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The Process of Separating Buckwheat and Wheat Grain in a Pneumatic Cone Separator in the Context of Sustainable Agriculture

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Abstract: In machines and devices used for separating and cleaning seed mixtures, the components of such mixtures can be separated in a stream of air. The efficiency of separation of a two-component (model) mixture containing wheat kernels and buckwheat nutlets was investigated. The main crop seeds and other crop seeds imitating impurities accounted for 80% and 20% (w/w), respectively. The experiment involved a pneumatic cleaning device with an immobile conical surface, designed by the authors, where mixture components are separated in a stream of air. The seed mixture was separated in a separator with the shape of an inverted cone, where the seeds were set into motion by a stream of air. The separation efficiency of the analyzed two-component mixture in the designed separator exceeded 78%. Regression equations describing the separation efficiency index of the entire seed mixture (ε) and the separation efficiency of the main crop seeds (η_p) and seeds imitating impurities (η_z) were derived. The coefficient of determination (R^2) for the above regression equations describing the separation efficiency of the mixture components (main crop seeds and seeds imitating impurities) and the separation efficiency index of the entire seed mixture ranged from 0.81 to 0.94. This result indicates that the developed equations were characterized by satisfactory and highly satisfactory fit to empirical data, and that they can be applied to accurately predict the quality of the seed separation process in the cleaning device designed by the authors. The developed equations can be effectively used to model and automatically control separation processes in the proposed separator.

Keywords: pneumatic separation; wheat; buckwheat; separation of a seed mixture

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1. Introduction

Food production is one of the most developed branches of the agricultural processing industry. Modern agriculture focuses on increasing yields and improving crop quality. Similar trends have also been observed for many years in the agri-food sector [1]. Seed cleaning plays a very important role in the storage and processing of grains. The cleaning and sorting of granular materials have been extensively researched [1–4]. Efficient separation of seed mixtures must be based on the separation traits of mixture components, which have been investigated by numerous authors [5–8].

Various quality requirements are imposed on the grain of the processed cereal species. "Safe" foods, such as gluten-free foods, can be used in preventing and treating various health issues, including celiac disease. Gluten-free food products are essential in the diets of consumers affected by gluten intolerance. Seed purity is the main criterion in the classification of seed batches for sowing or for the production of gluten-free foods containing less than 20 ppm (20 mg of gluten per kg of the product) [1,9]. These requirements are not always easy to meet in practice, which causes considerable losses in the main crop seeds, increases seed separation costs and renders seeds unfit for food production.

In conventional seed cleaning and sorting processes, impurities are removed from the main crop species based on their aerodynamic and geometric properties seeds [10,11]. Innovative machines and devices for cleaning and sorting seed mixtures rely on differences in the shape of the sorted components. Buckwheat nutlets can be sorted using mesh screens with triangular openings, cylindrical groove separators, grate separators and indented cylindrical separators [11,12], where seeds are separated, cleaned, and sorted based on differences in their shape.

In order to develop an effective method for separating seed (grain) mixtures, the separation traits that differentiate mixture components must be determined and appropriate seed separating devices must be applied [13]. Seeds are usually separated based on their aerodynamic properties, and terminal velocity is the most frequently used separation trait [14]. The behavior of the separated components of seed mixtures can be controlled by modifying the velocity of the vertical air stream. Aerodynamic forces that occur during relative motion between the air and the transported material exert different effects on mixture particles, depending on their shape, specific mass, and aerodynamic properties. Seed mixtures can be separated in a vertical stream of air only if their components have different aerodynamic properties. Lighter particles are lifted into the air, whereas heavier particles fall down into troughs in the cleaning device. Therefore, a detailed knowledge of the aerodynamic properties of mixture components is required in the processes of designing sorting and cleaning devices (with simultaneous removal of impurities from grain mixtures), cleaning and screening, or pneumatic transportation [15,16]. When pneumatic devices are used, the aerodynamic properties of mixture components have to be examined to determine the range of air stream velocities at which mixtures are most effectively separated [17,18].

Pneumatic separators are a large group of seed cleaning and sorting machines. New structures are constantly being proposed to improve the quality of the separation process [19]. In pneumatic separators, regardless of their structure (winnowing machines, separators with an aspiration channel, cyclone separators), seed mixtures are separated in a stream of air, and the terminal velocity of seeds is used as the separation trait [20–23]. Pneumatic separators consist of a hopper, a feeder, a separating (aspiration) chamber, collecting channels for seeds and impurities, and a fan with controlled air flow. These machines are widely used on account of their simple structure and operating principles [24,25].

Due to the unsatisfactory efficiency of the cleaning and separation of seed mixtures with conventional machines and cleaners where mixture components are usually separated based on a single separation trait, their structure is modified or new structural solutions are proposed. One of such solutions is a device for the pneumatic separation of seeds, equipped with a truncated-cone-like separating screen [26,27]. According to the literature [27,28], the advantages of a device with a conical separating screen include a small size, simple structure, and low energy inputs relative to the achieved outcomes, i.e., the high efficiency and quality of the cleaning process.

The objective of this study was to determine the effect of the operating parameters of a new cleaning device with an immobile conical surface, designed by the authors, where the components of a seed mixture are separated in a stream of air, on separation efficiency.

2. Materials and Methods

The experimental material was a model two-component mixture composed of the seeds of two crop species, i.e., kernels of spring bread wheat cv. Tybalt and nutlets of common buckwheat cv. Panda. The mixture was chosen based on the literature [11] which shows that in the threshed mass, buckwheat nutlets are mixed with impurities such as wheat, rye, oat, and barley seeds as well as segments of wild radish siliques. The problem of separating impurities from the threshed mass of buckwheat nutlets is particularly important in organic farming. The seeds used in the experiment were obtained from a seed production center in Olsztyn. Seeds of the analyzed species differed in shape. Wheat kernels were elongated, whereas buckwheat nutlets had a conical shape. The seed mixture weighed 500 g and contained 80% of the main crop species and 20% of impurities (w/w). The mixture was prepared in two variants where wheat kernels and buckwheat nutlets were the main crop species, respectively. The percentages of the components in the mixture (80% and 20%) were selected to demonstrate the efficiency of the separation process in the designed test stand.

The seeds were separated in a pneumatic separator with a conical screen, designed by the authors [23]. A general view and a schematic diagram of the test stand with a power inverter for controlling the rotational speed of a fan are presented in Figures 1 and 2, respectively. During the process, the seed mixture is poured onto the inner cone (1). The mixture is then transported by a stream of air supplied via the air channel (5) through the inlet whose width can be adjusted with a control knob (6) to the working channel between the outer cone (2) and the inner cone (1), which converges upward to ensure a constant flow rate of seeds. In the channel, mixture components are separated into fractions (as a result of differences in the external friction, mass, and aerodynamic properties of mixture components). The seed fractions then are deposited in the troughs (4) installed in the upper part of the cone. In the separator where air flows in the space between cones, the trajectory of falling mixture particles is modified, and the different aerodynamic properties of mixture components induce differences in the flight trajectory of individual grains. As a result, they are separated into fractions.

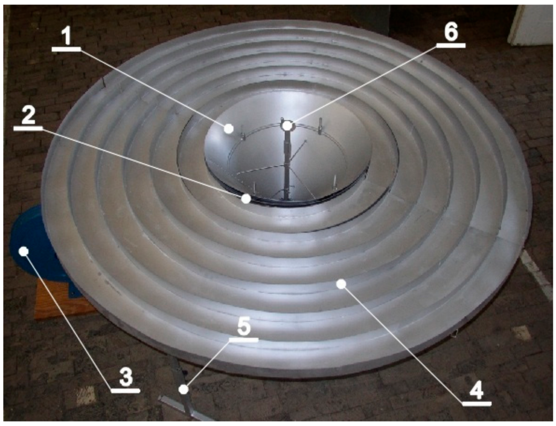

Figure 1. Test stand: 1—inner cone surface, 2—outer cone surface, 3—fan, 4—troughs, 5—base, 6—knob for infinitely variable adjustment of the charging slot.

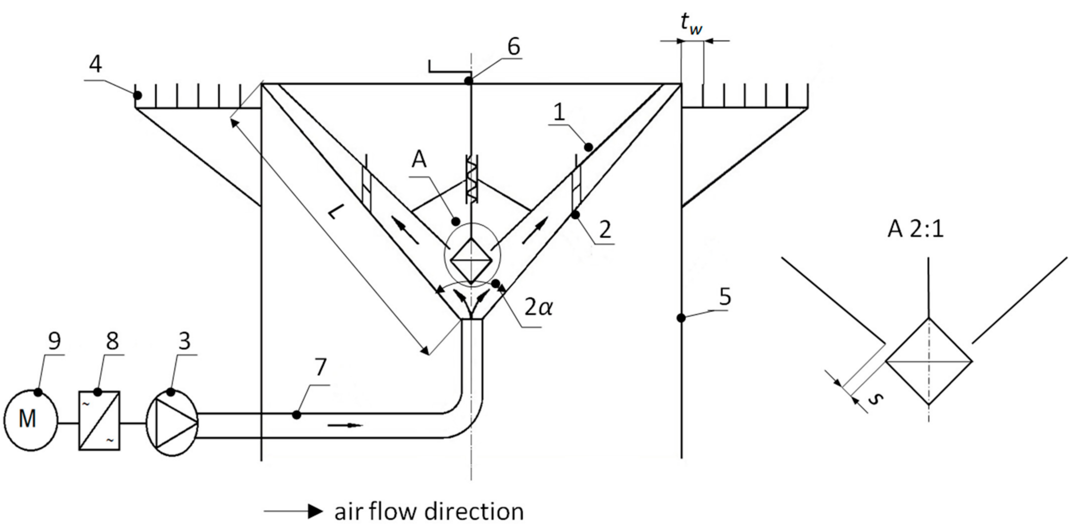

Figure 2. Diagram of the test stand: 1—inner cone working surface, 2—outer cone surface, 3—fan, 4—troughs, 5—base, 6—knob for infinitely variable adjustment of the charging slot, 7—air duct, 8—power inverter, 9—electric motor, 2α—cone's apex angle, L—length of the cone's generating line, s—width of the grain inlet, t_w—through width.

The following experimental factors were analyzed in the study:

1. Fixed factors:
   - width of the grain inlet, s = 10 mm;
   - sample mass, s_m = 500 g;
   - length of the cone's generating line, L = 500 mm;
   - trough width, t_w = 100 mm;
2. Variable factors:
   - air stream velocity, $v = 18.7 \div 19.5$ m $\times$ s^{-1}, insteps of 0.2 m $\times$ s^{-1};
   - moisture content of the model seed mixture, M = 10.1%; 13.7% and 17.3%;
   - cone's apex angle, $2\alpha = 60°$, $90°$, and $120°$;
   - model seed mixture, $m_{w/b}$—wheat and buckwheat, $m_{b/w}$—buckwheat and wheat.
3. Efficiency-related factors:
   - separation efficiency of mixture components: the main crop seeds and seeds imitating impurities (η)
   - separation efficiency index (ε).

The experimental methodology was described in detail by Choszcz et al. [27]. The width of the grain inlet was set and fan speed was adjusted using an inverter before the seed mixture was poured into the inner cone of the separator. The velocity of the air stream was determined by measuring the time when the seeds left the outer cone and were deposited outside the troughs. Seeds were removed from the troughs, and they were manually separated and weighed on the WPS 3100/C/2 laboratory weighing scale with an accuracy of 0.01 g. The measurements were performed for all combinations of independent variables in three replicates, according to the algorithm presented in Figure 3.

The seeds were weighed, and the separation efficiency of mixture components (η): the main crop seeds and seeds imitating impurities was determined using Formula (1) based on the mass of mixture components deposited in troughs [14]:

$$\eta = \frac{m_z}{m_c} \cdot 100 \tag{1}$$

where m_z and m_c—the mass of impurities separated from the model mixture and the mass of all impurities [g], respectively.

According to many authors, the separation efficiency index (ε) of a seed mixture is the most reliable measure of separation quality [11,13,29]. Based on the adopted separation parameters, the separation efficiency index (ε) for the analyzed mixture was calculated using Equation (2):

$$\varepsilon = \varepsilon_1 \cdot \varepsilon_2 \tag{2}$$

The partial values of the separation efficiency index, (ε_1) and (ε_2), were calculated using Equation (3) [13]:

$$\varepsilon_1 = \frac{m_z}{m_c} \tag{3}$$

where m_z and m_c—the mass of impurities separated from the model mixture and the mass of all impurities [g], respectively.

$$\varepsilon_2 = \frac{m_o}{m_n} \tag{4}$$

where m_o and m_n—the mass of the main crop seeds that were not separated from the mixture and the mass of the main crop seeds present in the mixture before the experiment [g], respectively.

The separation efficiency of mixture components (η) and the calculated values of the separation efficiency index (ε) were subjected to a statistical analysis using a quadratic polynomial multiple regression model with backward stepwise selection of non-significant variables. The influence of air stream velocity v, the cone's apex angle 2α, and moisture content M on the separation efficiency of mixture components was determined using aquadratic polynomial multiple regression equation with the following general form (5):

$$Y = b_1 \cdot v + b_2 \cdot \alpha + b_3 \cdot M + b_{12} \cdot v \cdot \alpha + b_{13} \cdot v \cdot M + b_{32} \cdot \alpha \cdot M + b_{11} \cdot v^2 + b_{22} \cdot \alpha^2 + b_{33} \cdot M^2 + b_0 \quad (5)$$

where:

Y—expected separation efficiency of mixture components,
b_0—model constant,
b_1, b_2, b_3—linear terms,
b_{12}, b_{13}, b_{23}—interaction terms,
b_{11}, b_{22}, b_{33}—quadratic terms.

The results were analyzed statistically using the Statistica PL v. 13.1 program [30,31].

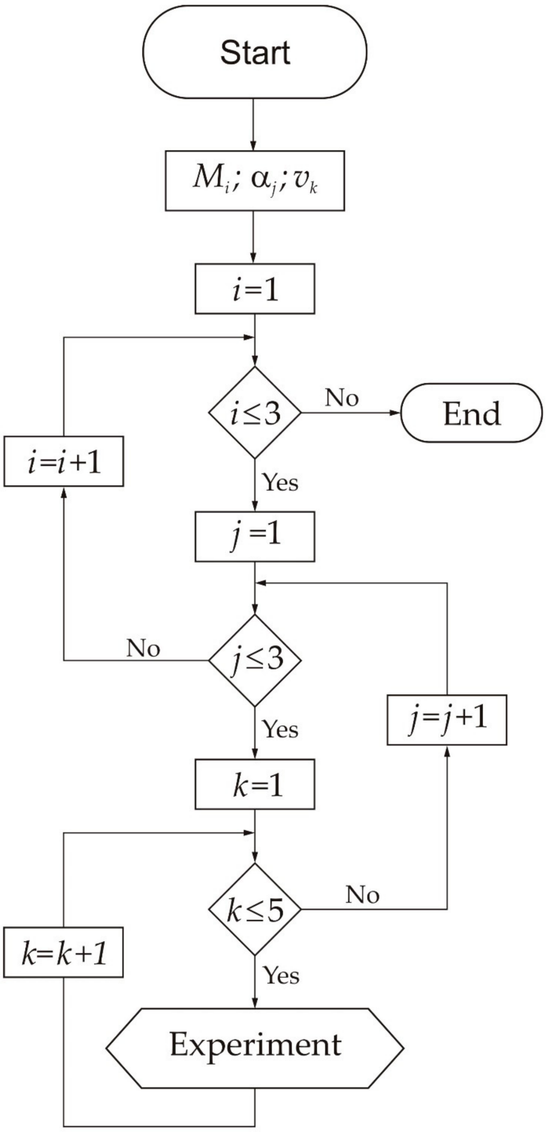

Figure 3. Algorithm for separating the seed mixture in a pneumatic conical separator: i, j, k—values of variable parameters (M, α,v).

3. Results

The statistical parameters describing the efficiency of the separation process (η) and the separation efficiency index (ε) are shown in Table 1. The average separation efficiency of both components, i.e., wheat (η_w) and buckwheat (η_b), in the mixture of wheat kernels and buckwheat nutlets, was 0.84. The average separation efficiency of wheat (η_w) in the mixture of buckwheat nutlets and wheat kernels also reached 0.84. The average separation efficiency of buckwheat (η_b) in the mixture of buckwheat nutlets and wheat kernels was 0.94. The average separation efficiency index (ε) reached 0.71 in the mixture of wheat kernel sand buckwheat nutlets, and 0.77 in the mixture of buckwheat nutlets and wheat kernels.

Table 1. Statistical parameters of the separation efficiency of seed mixtures.

Mixture	Indicator	Minimum	Maximum	Mean	Standard Deviation	Coefficient of Variation [%]
Wheat and buckwheat	ηw [%]	70.39	95.67	84.06	7.808	9.29
	ηb [%]	75.05	94.85	84.59	4.246	5.02
	$\varepsilon w/b$ [-]	0.62	0.78	0.71	0.043	6.02
Buckwheat and wheat	ηb [%]	75.95	98.9	93.90	5.982	6.37
	ηw [%]	66.52	95.67	84.56	8.281	9.79
	$\varepsilon b/w$ [-]	0.59	0.92	0.77	0.096	12.45

According to the literature, the physical properties of seeds change with an increase in their moisture content. Higher moisture content decreases the specific density of seeds and increases the value of the coefficient of external friction [32–35]. Moisture content, external friction, and density are physical attributes that exert the greatest effect on technological processes.

The average separation efficiency of a two-component mixture with different moisture content is presented in Figure 4. Separation efficiency increased with a rise in the moisture content of wheat kernels and buckwheat nutlets (within a range of 10.1–17.3%). Separation efficiency increased by 6% (from 0.67 to 0.73) in the mixture of wheat kernels and buckwheat nutlets, and by 16% (from 0.71 to 0.87) in the mixture of buckwheat nutlets and wheat kernels. The observed difference in separation efficiency resulted from changes in the physical attributes of wheat kernels and buckwheat nutlets that were induced by changes in their moisture content.

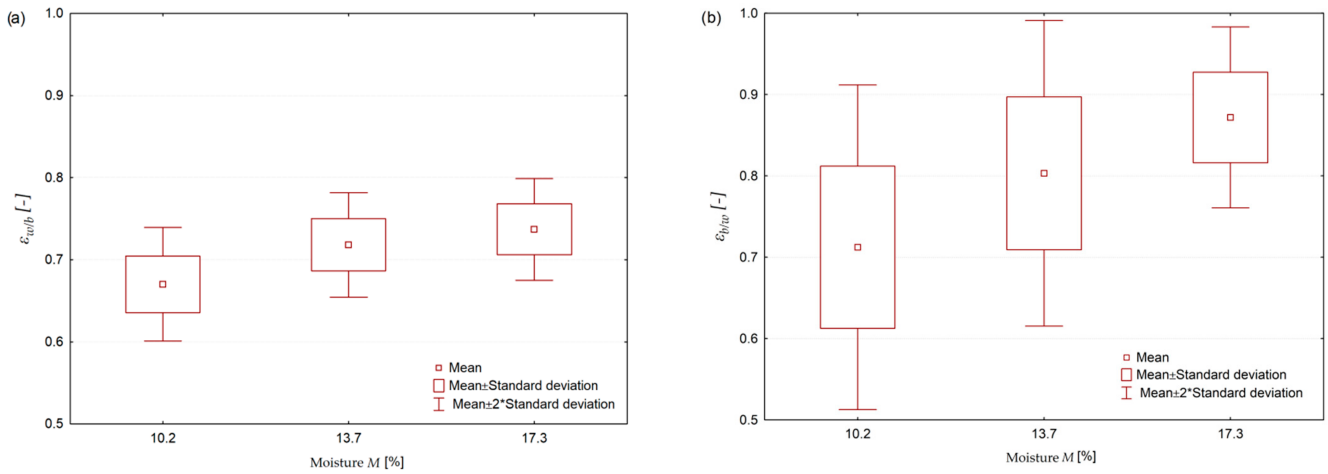

Figure 4. Mean values of separation efficiency ε, subject to the moisture M content of mixture components: (**a**)—mixture of wheat kernels and buckwheat nutlets ($\varepsilon_{w/b}$); (**b**)—mixture of buckwheat nutlets and wheat kernels ($\varepsilon_{b/w}$).

The study demonstrated that separation efficiency increases with a rise in the moisture content of mixture components (which leads to changes in the values of the coefficient of friction and the specific density of wheat kernels and buckwheat nutlets). The interaction between terminal velocity and the coefficient of friction influences separation efficiency at a constant value of terminal air stream velocity. The number of particles moving across the analyzed surface increases considerably when the coefficient of friction decreases.

The results of a statistical analysis of the functional relationship between the separation efficiency of mixture components the main crop seeds and seeds imitating impurities (η) and the separation efficiency index (ε) during seed separation in a pneumatic conical separator, depending on the moisture content M of seeds, air stream velocity v, and cone apex angle α, is presented in Table 2. The regression equations describing the separation efficiency of the main crop seeds (η) and seeds imitating impurities (η), and the separation efficiency index (ε) were characterized by high and very high fit to the empirical data. The coefficient of determination R^2 for the analyzed mixtures ranged from 0.81 to 0.94.

Table 2. Regression equations describing the separation efficiency of mixture components (the main crop seeds and seeds imitating impurities (η) and the separation efficiency index (ε).

Mixturetype	Indicator	Quadratic Equation for Two Independent Variables	F-Statistic 0.05	Coefficient of Determination R2 0.955	Adjusted R2	Standard Error of the Estimate 30.785	Probability (p)
Wheat and buckwheat	η_w [%]	$\eta_w = -0.1256{\cdot}\alpha + 0.0001{\cdot}\alpha^2 - 0.0068{\cdot}v^2 + 0.0060{\cdot}\alpha{\cdot}v + 0.0010{\cdot}v{\cdot}M + 3.3678$	59.350	0.884	0.869	0.031	0.00
	η_b [%]	$\eta_b = 0.11524{\cdot}\alpha + 0.00005{\cdot}\alpha^2 + 0.22267{\cdot}v + 0.02452{\cdot}M - 0.00058{\cdot}M^2 - 0.00592{\cdot}\alpha{\cdot}v - 0.00038{\cdot}\alpha{\cdot}M - 3.59746$	87.098	0.943	0.932	0.005	0.00
	$\varepsilon_{w/b}$ [-]	$\varepsilon_{w/b} = -0.0092{\cdot}\alpha + 0.0001{\cdot}\alpha^2 - 0.0013{\cdot}v^2 - 0.0012{\cdot}M^2 - 0.0002{\cdot}\alpha{\cdot}M + 0.0002{\cdot}v{\cdot}M + 1.0111$	26.812	0.809	0.779	0.015	0.00
Buckwheat and wheat	η_b [%]	$\eta_b = 0.0969{\cdot}\alpha - 0.0002{\cdot}\alpha^2 + 0.0047{\cdot}v^2 - 0.0005{\cdot}M^2 - 0.0047{\cdot}\alpha{\cdot}v + 0.0004{\cdot}\alpha{\cdot}M - 0.8521$	81.245	0.928	0.916	0.011	0.00
	η_w [%]	$\eta_w = -0.1606{\cdot}\alpha + 0.0001{\cdot}\alpha^2 - 0.0072{\cdot}v^2 + 0.0073{\cdot}\alpha{\cdot}v + 0.0004{\cdot}\alpha{\cdot}M + 3.8795$	79.130	0.910	0.899	0.027	0.00
	$\varepsilon_{b/w}$ [-]	$\varepsilon_{b/w} = -0.0664{\cdot}\alpha - 0.0028{\cdot}v^2 + 0.0028{\cdot}\alpha{\cdot}v + 0.0005{\cdot}\alpha{\cdot}M + 2.0820$	231,507	0.959	0.954	0.021	0.00

Separation efficiency increased with a rise in the moisture content of the seed mixture, whereas the influence of the second variable (cone apex angle 2α) was not significant. Two changes of the cone apex angle from 60° to 30° improved separation efficiency by up to 10% (from 70% to 80%).The quadratic equations describing the quality of the separation process (separation efficiency index—ε) of seeds with different moisture content M, sorted in a pneumatic conical separator at different air stream velocities v and different cone apex angles α are presented in Figures 5 and 6. The mixture of wheat kernels and buckwheat nutlets was most effectively separated at a maximum seed moisture content of M = 17.3%, air stream velocity of v = 18.9 m·s^{-1}, and cone apex angle of 2α = 60°. The mixture of buckwheat nutlets and wheat kernels was most effectively separated at a maximum seed moisture content of M = 17.3%, air stream velocity of v = 18.9 m·s^{-1}, and minimum cone apex angle of 2α = 60°.

In a study by Choszcz et al. [27], the separation efficiency index of a mixture of buckwheat nutlets and wheat kernels and a mixture of wheat kernels and buckwheat nutlets was determined at 0.81 on average. When a mixture of buckwheat nutlets and impurities was sorted in various devices based on one of the geometric properties of seeds, separation efficiency reached 96% [10]. In the work of Konopka et al. [36,37], the optimal value of the separation efficiency index (0.99) was also higher than the maximum values noted in several devices for sorting buckwheat nutlets [38–42], when seeds were separated based on their geometric properties. In numerous cases, considerable seed losses of up to 30% were reported when one of the geometric attributes of buckwheat nutlets was used as the main separation criterion in the process of sorting a mixture of buckwheat nutlets and impurities.

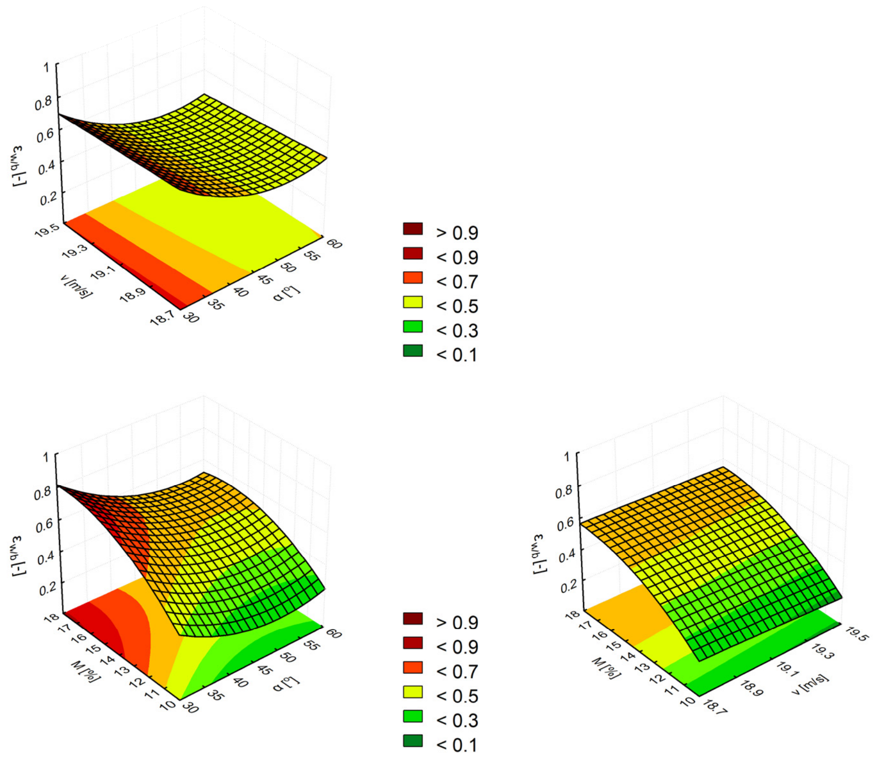

Figure 5. Separation efficiency index of the mixture of wheat kernels and buckwheat nutlets ($\varepsilon_{w/b}$) for seeds with different moisture content (M), separated at different air stream velocities (v), and different cone apex angles (α).

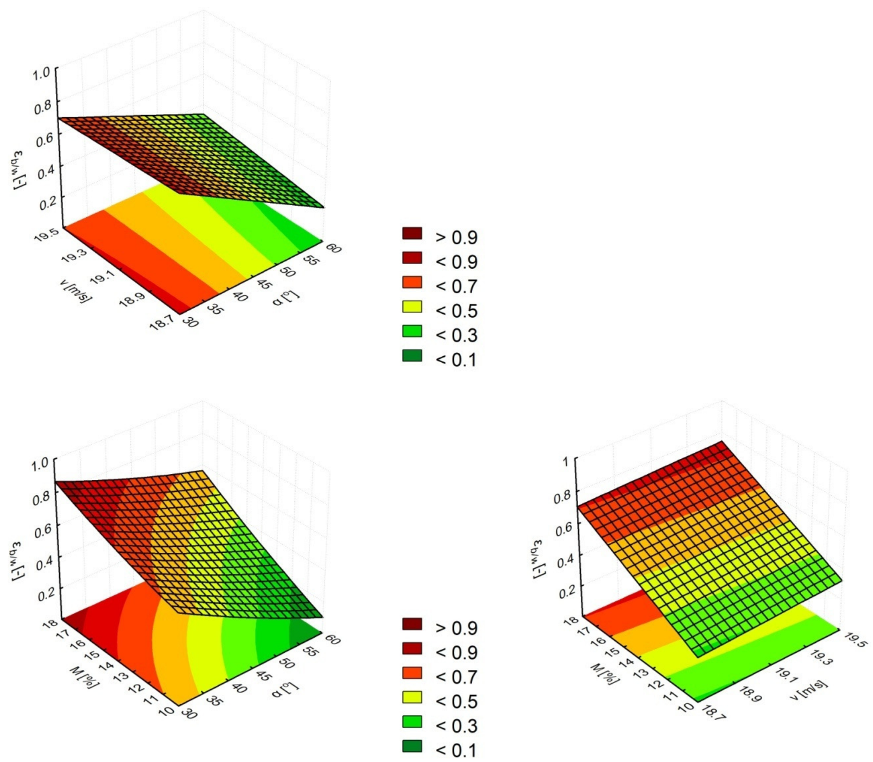

Figure 6. Separation efficiency index of the mixture of buckwheat nutlets and wheat kernels ($\varepsilon_{b/w}$) for seeds with different moisture content (M), separated at different air stream velocities (v), and different cone apex angles (α).

4. Conclusions

1. The separation efficiency index (ε) exceeds 0.78 when a two-component seed mixture composed of seeds of two cereal species–wheat kernels with an elongated shape and pyramid-shaped buckwheat nutlets–are sorted in a stream of air on an immobile conical surface in a pneumatic separator.
2. The efficiency (quality) of the separation process of a two-component (model) seed mixture in a pneumatic separator designed by the authors can be described with a quadratic multivariate polynomial. The regression equations describing the efficiency of mixture separation (ε) and the separation efficiency of the main crop seeds and seeds imitating impurities (η), in response to changes in the values of independent variables support accurate predictions of the parameters describing the quality of the seed separation process and can be effectively used to model and automatically control separation processes in the proposed pneumatic separator with an immobile conical surface.
3. In the agri-food industry, seed mixtures can be sorted with the use of the proposed separator after the geometric and aerodynamic properties of the processed mixture components (seeds) have been determined.

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