Highlights of Sustainability

ISSN 2696-628X, A Peer-Reviewed Open Access Journal by Highlights of Science
https://www.hos.pub/ho/sustainability

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Cite this Article

Bratoev, K. (2026). Theoretical Modeling and Geometric Optimization of Flat Sieves for Grain Mixture Separation. *Highlights of Sustainability*, *5*(1), 61–69.
https://doi.org/10.54175/hsustain5010005

Highlights of Science

Publisher of Peer-Reviewed Open Access Journals
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Barcelona, Spain

Highlights of Sustainability

Article

Theoretical Modeling and Geometric Optimization of Flat Sieves for Grain Mixture Separation

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Abstract The separation of grain mixtures using flat mechanical sieves is a probabilistic process that depends significantly on the separator's geometric parameters. This study investigates the relationship between the length-based separation coefficient $\mu(x)$ and the area-based separation coefficient $\mu(xy)$, emphasizing the critical role of the sieve's shape and working area. Through theoretical modeling, we demonstrate that the separation process follows an exponential decay pattern along the sieve length, while the overall efficiency is determined by the total sieving area. For sieves with equal diagonals, the square-shaped sieve maximizes the working area (at $\beta = \pi/2$) and minimizes grain losses, resulting in optimal separation performance. The area-based coefficient $\mu(xy)$ remains constant under fixed diagonal conditions, whereas the length-based $\mu(x)$ varies with the length x, as proven by the derived dependency $\mu(x)_e = \mu(xy)_e \cdot \sqrt{1 + tg^2(\alpha_e)}$. Experimental similarity criteria (π_1, π_2) confirm that grain losses are identical for rectangular and square sieves with equal diagonals; however, the square sieve provides a higher sieving probability per unit area. The study proposes a geometric optimization framework for flat sieves, recommending square configurations with dimensions derived from the equivalence $\mu(x)_0 \cdot x_0 = \mu(xy)_e \cdot r_e$. These results provide a theoretical foundation for designing high-efficiency separators, though experimental validation is suggested for future work.

Keywords flat sieves; separation coefficient; grain losses; geometric optimization; probabilistic modeling

1. Introduction

The separation of grain mixtures is a fundamental and critically important operation in post-harvest processing, directly affecting the quality of agricultural products and overall processing efficiency [1,2]. To achieve the required purity and minimize losses, various types of mechanical separators are employed, among which flat sieves remain widely used due to their design simplicity and operational reliability [2,3].

A key challenge in the design and operation of such separators lies in optimizing their geometric parameters—length, width, and overall shape—to maximize separation efficiency under given technological conditions [1]. The separation process itself is probabilistic, with the probability of a grain particle passing through the sieve depending on a complex interplay of factors including material properties, machine kinematics, and sieve geometry [4,5].

Fundamental research in this field has established that the separation process along the length of a sieve can be effectively described by an exponential decay model [4–6]. This model introduces the length-based separation coefficient, $\mu(x)$, which quantifies the separation intensity per unit length. However, the physical process occurs over the entire working surface of the sieve. This raises an important question: while the dependence on length is well-described, how does the separation efficiency depend on the total sieving area and its configuration? The relationship between the one-dimensional (length-based) and two-dimensional (area-based) characterization of the process remains insufficiently explored, creating a gap for a comprehensive geometric optimization framework.

Recent studies continue to highlight the significance of geometric and operational parameters for improving separator performance [1,2,7], and advanced modeling techniques are being applied to related separation processes [8]. Furthermore, the principles of similarity theory provide a proven methodological approach for analyzing and scaling agricultural machinery [9].

Building upon the established exponential model along the length [4,5], this study investigates the relationship between the length-based separation coefficient $\mu(x)$ and a proposed area-based separation coefficient $\mu(xy)$. The primary objective is to develop a theoretical model that links

Open Access

Received: 16 October 2025
Accepted: 16 January 2026
Published: 21 January 2026

Academic Editor
Christos A. Damalas, Democritus University of Thrace, Greece

these coefficients, thereby enabling the optimization of the sieve's shape and dimensions based on its total working area. The core hypothesis is that for a given sieve diagonal (representative of its size), the shape of the working area—particularly a square configuration—is decisive for achieving maximum separation efficiency and minimal grain losses.

Determining the interrelation between $\mu(x)$ and $\mu(xy)$ would allow for their equivalent use in calculating grain losses and provide a solid theoretical foundation for designing high-efficiency separators with optimized geometry.

This theoretical pursuit is highly relevant to contemporary engineering challenges. Recent comprehensive reviews confirm that improving the efficiency and adaptability of cleaning and separation systems remains a primary research and development focus in agricultural machinery [10]. This is further evidenced by ongoing work on novel technological implementations, such as improved two-aspiration cleaning systems designed to increase processing capacity [11]. The present study addresses this overarching goal by providing a fundamental geometric optimization principle derived from first principles.

2. Materials and Methods

The separation coefficient $\mu(x)$ defines separator performance and is inherently variable along its length, even under identical operating conditions. This phenomenon, first established by Mitkov [4] and later confirmed by Nepomnyashtiy [5], has also been observed in studies on specific crops like hybrid maize [12]. Physically, $\mu(x)$ quantifies the probability that an individual grain particle will pass through a sieve segment of unit length, as defined by the formula:

$$\mu(x) = \frac{q}{y \cdot \Delta x} = -\frac{\Delta y}{y \cdot \Delta x}, \tag{1}$$

where q/y represents the statistical probability that a single grain particle will pass through a sieve section of length Δx; q is the quantity of grain sieved in a section of length Δx; y is the quantity of unsieved but separable grain.

From Equation (1), the differential equation describing the sieving process along the length of mechanical separators is derived:

$$\frac{dy}{dx} = -\mu(x) \cdot y. \tag{2}$$

After integration, it takes the form:

$$y = e^{-\int \mu(x) \cdot dx}. \tag{3}$$

Taking into account the initial condition ($y = a$, where a is the quantity of separable grain at the beginning of the separator, i.e., $x = 0$), Equation (3) becomes:

$$y = a \cdot e^{-\varphi(x)}, \tag{4}$$

where $\varphi(x)$ is a function associated with the separation coefficient $\mu(x)$.

The presented relationships demonstrate that as the length of the separator increases and its separation efficiency improves, grain losses decrease significantly. This enhances the separation effect and, consequently, the operational quality of the separator. The probabilistic foundation of this model, where $\mu(x)$ represents the probability of passage per unit length, finds robust validation in modern computational research. Contemporary studies using advanced Discrete Element Method (DEM) and coupled CFD-DEM simulations directly analyze the microscopic interactions—such as particle sliding, rolling, and trajectory—that collectively determine this macroscopic probability [13,14]. These numerical experiments substantiate the core mechanistic assumptions underlying the exponential decay model. Furthermore, the principles of similarity theory applied here for scaling are congruent with the methodology of multi-parameter optimization sought in modern separator design studies [15].

However, the separation process must also be evaluated in terms of the geometric dimensions defining the separator's working area. This assertion is supported by the fact that separators of equal length may exhibit different separation coefficients due to variations in their widths, i.e., changes in the experimental probability of grain sieving.

Building upon the exponential decay model along the length, the separation process in three-dimensional space can be represented by the nonlinear surface shown in Figure 1.

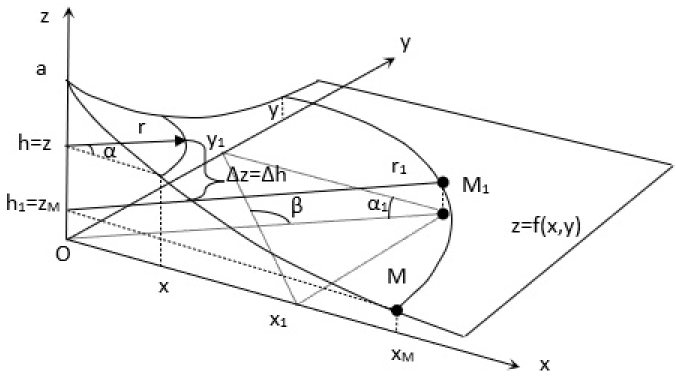

Figure 1. Surface of the sieving process over the separator's area. Here, x is the distance from the separator's inlet to any of its cross-sections; y is the distance from the separator's inlet to any of its longitudinal sections; z is the quantity of separable grain that has not been sieved through a section of length x; x_1 and y_1 are the Cartesian coordinates of the point M_1; r, α, h are the cylindrical coordinates of a point on the surface with the function $z = f(x, y)$; r_1, α_1, h_1 are the cylindrical coordinates of the point M_1; a is the quantity of separable grain fed at the separator's inlet ($x = 0$).

The curve $z = f(x)$, lying in the O_{xz} plane, is described by a dependency of the form Equation (4) and is considered the generatrix of the curvilinear surface representing the target function $z = f(x, y)$.

An arbitrarily chosen point (M) on the generatrix, when rotated around the *z*-axis by an angle $\alpha = \pi/2$, describes a circular arc. The position of a given point (M_1) along this arc can be determined using its cylindrical coordinates:

$$\left.\begin{aligned} r_1 &= \sqrt{x_1^2 + y_1^2} \\ \tan\alpha_1 &= \frac{y_1}{x_1} \\ h_1 &= z_M \end{aligned}\right\}. \tag{5}$$

The equality between coordinates z_M and h_1 indicates that the quantity of unscreened grain remains constant regardless of the rotation angle *a* of the generatrix. This leads to the following equation:

$$\left.\begin{aligned} \mu(x) &= \mu(r) \\ -\frac{\Delta z}{z \cdot \Delta x} &= -\frac{\Delta h}{h \cdot \Delta r} \end{aligned}\right\}. \tag{6}$$

Therefore, for the point M_1, Equation (4) takes the form:

$$h_1 = a \cdot e^{-\varphi(r)}, \tag{7}$$

where $\varphi(r)$ is a function related to the areal separation coefficient $\mu(r)$.

Let the Cartesian coordinates of the projection of the point M_1 onto the O_{xy} plane define the geometric dimensions of the separator. The resulting figure has equal diagonals, each matching the cylindrical coordinate r_1. The sieving area of the separator is given by:

$$S = \frac{r_1^2}{2} \cdot \sin\beta, \tag{8}$$

where β is the angle between the diagonals.

Equation (7) justifies the conclusion that if changes in coordinates x_1 and y_1 do not alter the coordinate r_1, the quantity of unsieved grain through the separator will remain constant. However, this will be accompanied by a change in the separator's working area, which according to Equation (8) will be maximized at $\beta = \pi/2$. Therefore, a separator with a square-shaped working area will operate at maximum capacity while maintaining unchanged grain losses.

The presented relationships (Equations (5)–(8)) demonstrate that the separation process in mechanical separators should be determined based on their working area, using the expression:

$$z = a \cdot e^{-\mu(r) \cdot r} = a \cdot e^{-\mu(xy) \cdot \sqrt{x^2 + y^2}}. \tag{9}$$

In this relationship, the coefficient $\mu(xy)$ remains constant under specific conditions ($r = \sqrt{x^2 + y^2} = const$), while the coefficient $\mu(x)$ has been proven to vary under these same conditions depending on x [5].

The determination of $\mu(xy)$ should be performed at the separator's maximum operating capacity, where grain losses do not exceed permissible limits. When determined this way, this coefficient enables optimization of the separator's geometric parameters.

The performance of mechanical separators is primarily characterized by grain losses at maximum productivity. It has been established that under conditions of constant specific area loading, a separator with a larger sieving area will be more productive. Among separators with equal diagonals, the one with a square shape will have the largest sieving area. The use of square-shaped separators is therefore recommended, with their dimensions considered optimal for quality separation of grain mixtures.

During the sieving process, the grain material moves toward the separator's end as a layer covering its entire working surface. Theoretically, it is reasonable to expect that grain losses would be identical whether determined by the length-based separation coefficient $\mu(x)$ or the area-based separation coefficient $\mu(xy)$. To verify this hypothesis, an approach comparing two flat sieves with different working surface shapes operating under identical conditions was used. One had a rectangular shape with dimensions x_0 and y_0, while the other was square-shaped with dimensions x_e and y_e (Figure 2).

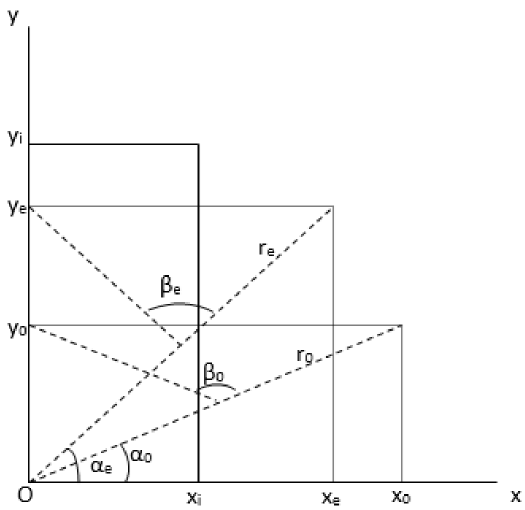

Figure 2. Working surface configurations of flat sieves.

Under specified initial operating conditions, the fundamental equation of the lengthwise sieving process for the rectangular sieve takes the form:

$$z_0 = a \cdot e^{-\mu(x)_0 \cdot x_0}, \tag{10}$$

where:

- $\mu(x)_0$ is the length-based separation coefficient of the rectangular sieve (m^{-1});
- x_0 is the sieve length (m).

A similar structure applies to the fundamental sieving equation expressed in terms of the area-based separation coefficient. For the square sieve with dimensions x_e and y_e, Equation (10) becomes:

$$z_e = a \cdot e^{-\mu(xy)_e \cdot r_e}, \tag{11}$$

where:

- $\mu(xy)_e$ is the area-based separation coefficient of the square sieve (m^{-1});
- r_e is the sieve diagonal (m).

When both sieves achieve identical grain losses under equal technological and kinematic conditions, their operational similarity can be established. Here, the relative grain losses serve as the similarity criterion [9]:

$$\pi_1 = \frac{z}{a} = idem, \tag{12}$$

with the similarity indicator:

$$\Delta_1 = e^{-\mu_c \cdot l_c} = 1, \tag{13}$$

where:

- μ_c is the ratio of the sieves' separation coefficients;
- l_c is the ratio of their linear dimensions (length to diagonal).

From these follows the equality:

$$\mu(x)_0 \cdot x_0 = \mu(xy)_e \cdot r_e. \tag{14}$$

For both sides of this expression, the following similarity criterion applies:

$$\pi_2 = \mu \cdot l = idem, \tag{15}$$

with the similarity indicator:

$$\Delta_2 = \mu_c \cdot l_c = 1. \tag{16}$$

Consequently, for the right-hand side of Equation (14), the following expression holds:

$$\mu(xy)_0 \cdot r_0 = \mu(xy)_e \cdot r_e, \tag{17}$$

where:

- $\mu(xy)_0$ is the area-based separation coefficient of the rectangular sieve (m^{-1});
- r_0 is the diagonal of the rectangular sieve (m).

By expressing the diagonal r_0 through the working surface area of the rectangular sieve, we obtain a relationship between its separation coefficients (length-based and area-based) in the general form:

$$\mu(x)_0 \cdot x_0 = \mu(xy)_0 \cdot \sqrt{\frac{2 \cdot S_0}{sin\beta_0}}\ , \tag{18}$$

where β_0 is the angle between the diagonals of the rectangular sieve. After algebraic transformations, this expression simplifies to:

$$\mu(x)_0 = \mu(xy)_0 \cdot \sqrt{1 + tg^2(\alpha_0)}\ , \tag{19}$$

where α_0 is the angle between the diagonal r_0 and the sieve length x_0. The angle α_0 belongs to the interval $0 \div \frac{\pi}{2}$.

From Equation (19), it is evident that across the entire range of angle α_0 variations, the coefficient $\mu(xy)_0$ will have a smaller value than the coefficient $\mu(x)_0$.

Applying the similarity criterion π_2 to Equation (14) and performing analogous transformations yields a corresponding relationship for the square sieve:

$$\mu(x)_e = \mu(xy)_e \cdot \sqrt{1 + tg^2(\alpha_e)}\ , \tag{20}$$

where:

- $\mu(x)_e$ is the length-based separation coefficient of the square sieve (m^{-1});
- α_e is the angle between the sieve's diagonal and its length (in degrees).

For sieves with equal diagonals, the relationship between their working areas is given by:

$$\frac{S_0}{S_e} = \frac{\frac{r_0^2}{2} \cdot \sin\beta_0}{\frac{r_e^2}{2} \cdot \sin\beta_e} = \frac{\sin\beta_0}{\sin\beta_e}, \tag{21}$$

where β_e is the angle between the diagonals of the square sieve (in degrees).

The assumption that both sieves operate under equal loading conditions implies that the reciprocal of Equation (21) represents the ratio of their specific area loadings:

$$\frac{q_{F0}}{q_{Fe}} = \frac{\sin\beta_e}{\sin\beta_0}, \tag{22}$$

where:

- q_{F0} and q_{Fe} are the specific area loadings of the rectangular and square sieves, respectively ($kg/(s \cdot m^2)$);
- β_0 and β_e are the angles between the diagonals of the rectangular and square sieves, respectively.

Expanding the left-hand side of Equation (22) yields:

$$\frac{\rho_0 \cdot V_0 \cdot h_0 \cdot y_0 \cdot x_e \cdot y_e}{\rho_e \cdot V_e \cdot h_e \cdot y_e \cdot x_0 \cdot y_0} = \frac{\sin \beta_e}{\sin \beta_0}, \tag{23}$$

where:

- $\rho_0(\rho_e)$—bulk density of grain material on the rectangular and square sieve, respectively (kg/m^3);
- $V_0(V_e)$—material flow velocity across the rectangular and square sieve, respectively (m/s);
- $h_0(h_e)$—grain layer height on the rectangular and square sieve, respectively (m);
- $x_0(x_e)$—length of the rectangular and square sieve, respectively (m);
- $y_0(y_e)$—width of the rectangular and square sieve, respectively (m).

Since both sieves operate under identical conditions, the final form of Equation (23) becomes:

$$\frac{h_0 \cdot x_e}{h_e \cdot x_0} = \frac{\sin \beta_e}{\sin \beta_0}. \tag{24}$$

This expression demonstrates how the grain layer height varies with changes in the sieve's working area and consequently, with changes in its specific loading. As the specific loading decreases, the material layer height on the sieve decreases correspondingly. This relationship can be expressed using the similarity criterion given in the literature [9]:

$$\pi_3 = \mu(x) \cdot h = idem, \tag{25}$$

with the similarity indicator:

$$\Delta_3 = \frac{\mu(x)_0 \cdot h_0}{\mu(x)_e \cdot h_e} = 1. \tag{26}$$

Substituting Equation (24) into the similarity indicator Δ_3 yields the relationship between the length-based separation coefficients of the two differently-shaped sieves:

$$\frac{\mu(x)_0 \cdot x_0 \cdot \sin \beta_e}{x_e \cdot \sin \beta_0} = \mu(x)_e. \tag{27}$$

By substituting this equality into Equation (20), we obtain:

$$\frac{\mu(x)_0 \cdot x_0 \cdot \sin \beta_e}{x_e \cdot \sin \beta_0} = \mu(xy)_e \cdot \sqrt{1 + tg^2(\alpha_e)}. \tag{28}$$

Given that for the square sieve $\beta_e = \pi/2$ and $\alpha_e = \pi/4$, the final form of Equation (28) becomes:

$$\frac{\mu(x)_0 \cdot x_0}{x_e \cdot \sin \beta_0} = \mu(xy)_e \cdot \sqrt{2}. \tag{29}$$

Analysis of the derived relationships, Equations (19)–(28), reveals that, under identical operating conditions, modifying the shape of the separator's working surface leads to increased values of both separation coefficients $\mu(x)$ and $\mu(xy)$. However, this trend persists only until the rectangular sieve with dimensions x_0 and y_0 transforms into a square sieve with dimensions x_e and y_e. If a rectangular sieve is converted to another rectangular sieve with the same diagonal but with a length x_i smaller than its width y_i (Figure 2), the aforementioned trend will continue only for the length-based separation coefficient, while the area-based separation coefficient will decrease. This implies that under identical operating conditions, the lowest grain losses will occur with a flat sieve having a square-shaped working surface, due to its higher area-based separation coefficient and increased working area.

Equation (29) enables the conversion of the length-based separation coefficient of a rectangular sieve to the area-based separation coefficient of a square sieve with an identical diagonal length. This demonstrates that by altering the shape and geometric dimensions of the sieve, the operational quality of such mechanical separators can be enhanced.

It is recommended to use an expression of the form (Equation (2)) when determining grain losses in flat sieves. The same expression is also suitable for calculating losses in rotary mechanical separators.

3. Discussion

Recent studies on separation processes continue to emphasize the importance of geometric and operational parameters, underscoring the relevance of the present theoretical optimization framework [1,2,7].

The performance of all mechanical separators is fundamentally governed by their geometric dimensions. Although a strong dependence on length is well-established, the separation process must be evaluated based on the total working area of the separator. In such cases, grain losses are appropriately described by an expression of the form given in Equation (9). As the parameter r (representative of the separator's area) increases, grain losses decay exponentially. Under specific conditions, the area-based separation coefficient $\mu(xy)$ can be considered constant, whereas the length-based coefficient $\mu(x)$ varies with x. The geometric configuration at which $\mu(xy)$ is determined represents the optimal design for the separator, which, as derived, corresponds to a square working area.

The principal distinction between the two coefficients lies in their response to changing underlying factors, extending the findings of [5]. The length-based coefficient $\mu(x)$ exhibits a consistent directional change when the separator length is modified. This behavior is not mirrored by the area-based coefficient $\mu(xy)$. It is this divergence that accounts for variations in separation intensity. Consequently, these findings indicate that not only the size but, critically, the shape of the separator's screening area is of paramount importance.

It is generally accepted that altering the length of a separator is crucial for its separation capability. However, this proven influence cannot be considered in isolation from the separator's working area. This conclusion follows directly from the analysis of Equation (20). According to this relationship, for a single flat sieve, the connection between its length-based and area-based separation coefficients is a function of the angle α_e. The value of this angle depends on the sieve's length-to-width ratio—that is, the shape of its working area.

Although the similarity criterion π_1 leads to identical grain losses for different shapes, transforming Equation (20) into the form of Equation (28) reveals that, under fixed operating conditions, the experimental probability of grain sieving per unit area is highest for a square sieve. Furthermore, Equation (28) provides a method to adjust the length-based separation coefficient of any sieve to this maximum unit-area sieving probability.

For flat sieves with diagonals of equal length, an increase in the angle α_e leads to a corresponding increase in the value of the length-based separation coefficient $\mu(x)$. In contrast, the area-based coefficient $\mu(xy)$ increases only until α_e reaches $\pi/4$. For angles larger than this, $\mu(xy)$ decreases. This behavioral difference, combined with the fact that a square sieve provides the largest possible area for a given diagonal length, results in the lowest grain losses under otherwise identical conditions. The proposed geometric optimization framework aligns with ongoing advancements in grain separation technology aimed at minimizing losses and enhancing efficiency [3].

While this study focuses on mechanical sieving, it is noteworthy that separation efficiency is a universal objective across different technologies, including electrostatic methods as explored for sunflower seeds [7].

The conclusions drawn regarding the relationship between the length-based and area-based separation coefficients of mechanical separators, as well as the process of separating grain mixtures across the surface of mechanical separators, should be further verified experimentally, employing modern modeling and simulation approaches as seen in studies like those of Petre & Kutzbach [8] and Panasiewicz et al. [2]. Future work could integrate the presented geometric optimization principles with digital control and sorting algorithms [16] to develop intelligent, adaptive separation systems.

The theoretical conclusion regarding the optimality of the square sieve configuration for a fixed diagonal provides a universal geometric design criterion. This finding rationalizes and generalizes the empirical objectives prevalent in contemporary separation research. While advanced numerical studies successfully employ methods like the Discrete Element Method to optimize specific complex sieve designs through parameter variation [15], the model presented herein offers a fundamental principle for maximizing the effective working area—and thus the statistical probability of sieving—under given spatial constraints. This analytical approach addresses the core challenge of improving separator efficiency, a priority clearly outlined in recent reviews of agricultural cleaning technology [10], and complements practical engineering innovations aimed at increasing processing capacity [11].

4. Conclusions

This study established a theoretical framework for modeling and optimizing the geometry of flat sieves for grain mixture separation. The core of the work defines the relationship between the length-based ($\mu(x)$) and area-based ($\mu(xy)$) separation coefficients, proving that the sieving process is better described and optimized by considering the total working area.

The key theoretical finding is that for sieves with diagonals of equal length, the square configuration is optimal. It maximizes the sieving area and provides the highest experimental probability of grain passage per unit area, leading to minimized grain losses under fixed operational conditions. This conclusion is derived from the fundamental relationship $(\mu(x)_0 \cdot x_0 = \mu(xy)_e \cdot r_e)$ and the subsequent similarity criteria, which confirm that while grain losses may be identical for different shapes with equal diagonals, the square sieve delivers superior separation efficiency.

Therefore, the proposed geometric optimization principle recommends designing flat sieves with a square working surface, where the side length can be determined from the equivalence of separation work $(\mu(x)_0 \cdot x_0 = \mu(xy)_e \cdot r_e)$.

The conclusions drawn from this theoretical model provide a solid foundation for the design of high-efficiency separators. Future work should focus on experimental validation of these principles using modern measurement techniques. Furthermore, integrating this geometric optimization approach with advanced control systems and sorting algorithms presents a promising path toward developing intelligent, adaptive separation equipment.

Furthermore, future research should focus on integrating this geometric optimization framework with digital technologies. Combining the presented analytical model with real-time control systems and the capabilities of digital twins, identified as key future trends [10], would pave the way for the development of intelligent, adaptive separation equipment. The synergy of a fundamental theoretical model, validated and parameterized by modern DEM/CFD-DEM simulations [17], with adaptive control algorithms represents a promising path toward next-generation high-efficiency separators.

Funding

The research was conducted within the European Union-Next Generation EU through the National Recovery and Resilience Plan of the Republic of Bulgaria, project No. BG-RRP-2.013-0001.

Data Availability

No new data were created or analyzed in this work. Data sharing is not applicable to this article.

Use of Generative AI and AI-Assisted Technologies

During the preparation of this manuscript, the author used ChatGPT Sci Space for translation assistance. The author has reviewed and edited the output and takes full responsibility for the content of this publication.

Conflicts of Interest

The author has no conflict of interest to declare.

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