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# MONODISPERSE SYSTEMS IN THE PRODUCTION OF COMPOUND (COMBINED) FERTILIZERS

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The research is aimed at the process of granulation of mineral fertilizers by roller and bulk methods, as well as in fluidized and suspension layers with active hydrodynamics of flow. It is emphasized that the improvement of the primary technological stages of the production of granulated fertilizers should be a priority task for optimizing the design of granulator equipment and establishing the most effective working and technological parameters for increasing productivity and reducing energy consumption. Key performance indicators of heat utilization granulation plants include economic costs, exergy losses, and minimized costs. The application of research results will allow choosing more effective parameters for the production of granules of complex fertilizers, which will ultimately increase the productivity and quality of products.

**Keywords:** granulation of mineral fertilizers, filling, rolling, active hydrodynamics, encapsulation, granulation.

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***Introduction***

Compound mixed fertilizers are comprehensive fertilizers created through a single technological process or by combining multiple existing technologies. These fertilizers contain two or three primary plant nutrients within a single granule, but in different chemical forms. They are produced by chemically and physically processing raw materials or combining various single and double-component fertilizers [1,2]. During production, chemical interactions between components can lead to the formation of new compounds. These compounds may be sparingly soluble and resistant to degradation in the soil, making them difficult for plants to absorb.

Ammonium nitrate and urea are commonly used nitrogen fertilizers in all soil-climatic zones. These fertilizers transform within the «soil–plant» system and participate in the nitrogen cycle, meeting the nitrogen needs of growing plants. However, they have significant drawbacks, including high water solubility, leaching from the arable layer, and contamination of surface water and groundwater. Additionally, excessive use of nitrogen fertilizers can lead to nitrate accumulation in agricultural products and soil, causing soil degradation and reduced product quality. Methods for improving fertilizers' quality are of great practical interest that they do not significantly complicate the technological production process and do not require the use of scarce and expensive reagents and conditioning additives. Hence, a particular type of complex mixed fertilizers that do not have the abovementioned disadvantages is encapsulated fertilizers [2,3].

***Results and discussion***

Innovative encapsulation (granulation) technologies are used to produce encapsulated fertilizers, resulting in a product with prolonged action that ensures the gradual (controlled) release of the target component (or several) from under the protective shell, reducing their contact with one another prior to entering the soil. The coating applied to the surface of the particles creates additional resistance to mass transfer during dissolution. As a result, the utilization rate of these fertilizers increases, allowing for a reduction in their quantitative application to the soil.

Various compositions can be used for coating fertilizer granules. For example, Gupta et al. [4] suggested coating urea with a sulfur shell. The coating process is carried out in rotating drums, where molten sulfur is sprayed over a layer of urea granules. After this, a wax containing a small amount of antiseptic resin is applied to the formed sulfur layer. Although sulfur is a micronutrient, its excessive application to the soil is toxic, adversely affecting soil microorganisms. Furthermore, the use of such fertilizers will result in secondary soil contamination with wax, which additionally contains antiseptic resin.

For urea encapsulation, urea-formaldehyde resin grade KFS-K is also used. This same substance is proposed [5] to prevent hygroscopicity. This method is exclusively applicable to substances with a relatively low level of caking, such as urea, nitrophosphate, and the like. Another drawback is the high content of a highly toxic substance – formaldehyde.

Baird et al. [1] described wax coating on potassium chloride fertilizer (MOP, 50% K). So, beeswax with nutritional microelements reduces moisture absorption by more than 65%, maintaining an uninterrupted supply of nutrients. Thus, such a hydrophobic coating can improve the physical characteristics of the fertilizer without compromising the nutrient release kinetics.

A known granular fertilizer [6] contains a mineral core and is coated with an inorganic substance-based shell – glauconite. The drawback of this invention is that glauconite, being a mineral, along with the core, which is also of mineral origin, enters the soil, contributing to increased soil acidity and creating high nutrient concentrations, which negatively affects plant development.

A known method [7] for producing encapsulated slow-release fertilizers involves applying a suspension of phosphogypsum in a 20–50% solution of urea-formaldehyde resin to the surface of granules at a temperature of 70–90$^0$C for 2–3 minutes. However, this method does not prevent the granules from clumping and caking, and the granules with a phosphogypsum coating do not exhibit high mechanical strength.

The formation of a continuous shell on the surface of mineral granules can occur as a result of the reaction of two or more substances. An example of such technology is an encapsulated particle, which consists of a core surrounded by a shell. The core contains mineral fertilizer, and the shell is made of a polyurethane layer, which is the product of the reaction between an aromatic isocyanate component and a polyol. The main disadvantage of such fertilizers is the presence of polyurethane, a chemical that decomposes very slowly in the soil, releasing toxic substances, and the difficulty in achieving a continuous polymer film on the surface of the granules.

In the United States, a patented process [8] involves coating granulated fertilizers with a layer of liquid sulfur and dissolved bitumen, followed by additional treatment with mineral powder to prevent sticking. The suggested mineral powders include limestone, chalk, talc, and silica. Other materials used for the shell include paraffin wax, synthetic and natural rubbers, polyolefins, solutions of sodium silicate, and calcium chloride. Most encapsulating materials do not dissolve under moisture, leading to increased soil contamination with each application of such fertilizers, thereby worsening the environmental condition. This trend has been observed to increase year by year.

This review consolidates recent progress in encapsulated fertilizer production. A key drawback of such formulations, compared to non-encapsulated ones, is the higher energy and material cost. To enhance competitiveness, it is necessary to use low-cost, natural-based materials that are safe for soil microbiota, create a porous coating for controlled nutrient release, and ensure sufficient mechanical strength to withstand transport and application.

A realistic strategy to reduce the dependency on conventional mineral fertilizers is the utilization of agricultural waste. In particular, organic waste from poultry farms in Ukraine and globally exceeds municipal waste volumes and presents serious storage and environmental challenges. Involving livestock waste in fertilizer production not only supports waste recycling but also broadens the raw material base for sustainable agriculture [2].

Animal manure, a traditional organic fertilizer, is rich in carbon, nitrogen, and phosphorus [9]. However, its direct application carries risks–odor nuisance, environmental contamination with trace elements, and food safety concerns related to microbiological agents and residues of antibiotics or hormones [9,10].

It should be noted that the practice of direct utilization of chicken manure as an organic fertilizer for soil conditioning puts the environment at jeopardy due to over-fertilization [11], but litter-free chicken manure meets all the above-mentioned requirements and can be used as a protective coating for nitrogen fertilizers. The resulting encapsulated product has prolonged action and nourishes plants more effectively over a long period, and due to the organic origin of the coating material, it does not contaminate the soil and environment [12].

A specialized installation for encapsulation of mineral fertilizers has been developed based on theoretical and experimental studies. Such parameters as humidity, temperature, particle size and chemical composition of the starting materials, as well as specific properties of the used organics, have been taken into account under installation development, which allows the uniformity of the granules and the stability of their properties [13].

Thus, the technology for producing compound mixed (combined) fertilizers in granulated form involves the following main technological stages:

1. Raw material preparation (crushing, classification, melt preparation, etc.).
2. Granulation.
3. Stabilization of the granule structure through convective cooling.
4. Separation of the commercial fraction (size classification, crushing of large fractions).
5. Coating the granule surface (encapsulation) of mineral fertilizers with organic matter.

It should be noted that enterprises already engaged in the production of granulated mineral fertilizers will not face significant challenges in redirecting their production to obtain complex mixed (combined) extended-release fertilizers. This requires supplementing their existing technological production scheme with an additional unit equipped with a fluidized bed apparatus.

The critical technological operation in obtaining monodisperse granules is the second stage, granulation. A well-organized process that yields a product with the most uniform size (mono-fraction) allows for the minimization or complete elimination of the fourth stage, enabling the immediate direction of cooled mineral fertilizer granules to encapsulation.

Granulated materials are produced using a variety of methods [14]. These include rolling, which involves agglomerating and layering particles to form granules. Liquids can also be dispersed into the free volume of the apparatus, where droplets crystallize as they cool. Another method is spraying liquid onto granules in a fluidized bed, followed by drying or cooling to solidify the surface layer. Granules may also form through chemical reactions in an active medium. Additional techniques include flaking (cooling the liquid on a surface and shredding the film), pressing powders into briquettes or tablets and crushing them, extrusion of pasty masses through dies, and sintering by heating, then crushing and sieving the agglomerates.

The comparative assessment of granulation technologies (Table) indicates that the most commonly applied approaches include melt dispersion with subsequent cooling in prilling towers, rolling combined with surface coating by dispersed liquids, and spraying of pulp or suspension into a fluidized or suspended layer.

To support the selection of optimal process conditions, an exergy-based evaluation methodology was developed. It enables estimation of energy consumption and thermal efficiency during granulation and convective cooling stages, accounting for process energetics and equipment performance.

In ref. [3], the results of exergy analysis of granulation processes under different operating conditions are presented. The study proposes technological solutions aimed at improving energy efficiency and systematically evaluates the performance of various cooler designs in terms of exergy losses. Based on this analysis, practical recommendations are provided for the use of granular fertilizer coolers across different industrial sectors. These measures can optimize cooling processes, reduce electricity consumption, and enhance overall production efficiency.

Research has established that for fertilizers, the melt for the production of which has a sufficiently low viscosity and the stages of crystallization occur in the granule, the pouring method is the most operationally reliable and cheap. This is also relevant in the production of food products. In addition, the claimed technology makes it possible to obtain a monodisperse product with a maximally spherical shape.

Another advantage of the sprinkling method is such a characteristic as the average irrigation density of the cross-section of the tower (Fig. 1).

Initially, this parameter was in the range of 100–200 $kg/m^2 \cdot h$. It has become possible to increase the irrigation density to 500–1000 $kg/m^2 \cdot h$ with the use of static and vibrating float sprinklers in granulation towers in combination with a fluidized bed cooler located in the lower part of the tower. This, in turn, allows one to increase the productivity of the unit volume of the granulation tower by 4–5 times [15].

Vibrating granulators have gained popularity for processing mineral fertilizer melts. By mechanically disrupting high-temperature liquid jets, these granulators

**Comparative analysis of granular production methods**

| Characteristic | Granular production method | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | rolling | prilling | in a fluidized bed | dispersing liquid into an active medium | flaking | pressing | extrusion | sintering |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| granule quality | irregular and porous surface structure, flowability, average degree of uniformity in granule size within 1–4 mm | a high degree of uniformity in the size of granules within 1–3 mm, flat and smooth surface | high quality granules, average degree of uniformity in granule size within 1–4 mm | homogeneous structure, granule size greater than 3 mm within 80– 90 % | high homogeneity and resistance to grinding | uniform size and shape of granules. different shape of granules | the probability of regulating the granules' size and the granules' shape | resistant to grinding and wear |
| evenness of substance (nutrient) distribution | provides | provides | provides | provides | provides | provides | provides | vulnerability to the heterogeneous structure formation |
| physical properties of granules | high mechanical strength | good mechanical strength | high granule density and good mechanical strength | good mechanical strength | good mechanical strength | high mechanical strength and granule density | good strength, high solubility and bioavailability | high mechanical strength |
| dust formation | low | moderate | moderate | moderate | low | low | extremely low | extremely low |
| granule resizability | provides | provides | provides | provides | provides | provides | provides | provides |
| energy expenditure | high | high | high | high | high | low | high | high |

Continued Table

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|
| critical control points of the technological process | humidity control | control of humidity, temperature and crystallization rate | control of humidity, temperature and gas flow rate | control of humidity, temperature and gas flow rate | requires highly skilled operators to control process parameters | pressure and temperature control, therefore, requires highly qualified operators | control of pressure and temperature and feed rate of raw materials | control of sintering temperature, therefore, requires highly qualified operators |
| additional requirements for raw materials | provides | provides | provides | provides | provides | raw material moisture control | provides | provides |
| method environmental friendliness | low | high | moderate | moderate | moderate | extremely high | moderate | moderate |
| the possibility of performing additional operations in the working volume of the granulator | partial implementation (drying in drum granulators and internal recirculation) | partial implementa-tion (cooling of granules) | full implementation | partial implementatio n (drying) | partial implementation (cooling) | impossible | impossible | partial implementati on (high temperature round drying) |
| prevalence of use in production | significant prevalence (phosphorus containing fertilizers)) | significant prevalence (nitrogen containing fertilizers) | significant prevalence (phosphorus containing, nitrogen containing and compound fertilizers) | very low prevalence (mainly research practice) | low prevalence | low prevalence (potassium fertilizers, micro- and organo mineral fertilizers) | low prevalence (microfertili zers) | low prevalence (microfertili zers) |
| productivity per equipment item | high (10–25 t/h) | extremely high (20–60 t/h) | medium (0.5–10 t/h) | extremely low (up to 0.5 t/h) | low (up to 5 t/h) | low (up to 5 t/h) | extremely low (up to 0.5 t/h) | extremely low (up to 0.5 t/h) |

produce finer, more uniform droplets, leading to a narrower particle size distribution and increased monodispersity.

The disintegration of jets into drops under the influence of forced mechanical oscillations is a rather complex process. As the pressure increases and a certain flow rate is reached, the liquid begins to form a continuous cylindrical stream. This jet remains continuous in the initial part of its movement, but at some distance from the opening, it begins to break up into drops. The process of such jet fragmentation is caused by instabilities arising from the interaction of inertial forces, surface tension forces, and gravity. As the flow rate increases, these instabilities intensify, leading to the disintegration of the continuous jet into individual droplets. The distance from the orifice to the point where the jet begins to break up depends on many factors, including pressure, orifice diameter, viscosity, and surface tension of the fluid.

As long as the speed is relatively low, the outflow has a laminar character, and the jet retains an axisymmetric shape until its disintegration (Fig. 2,a). However, with a further increase in speed, the aerodynamic effect of the external environment on the jet increases, and its axisymmetric shape turns into a wave shape (Fig. 2,b), which is characterized by crushing into drops of different sizes.

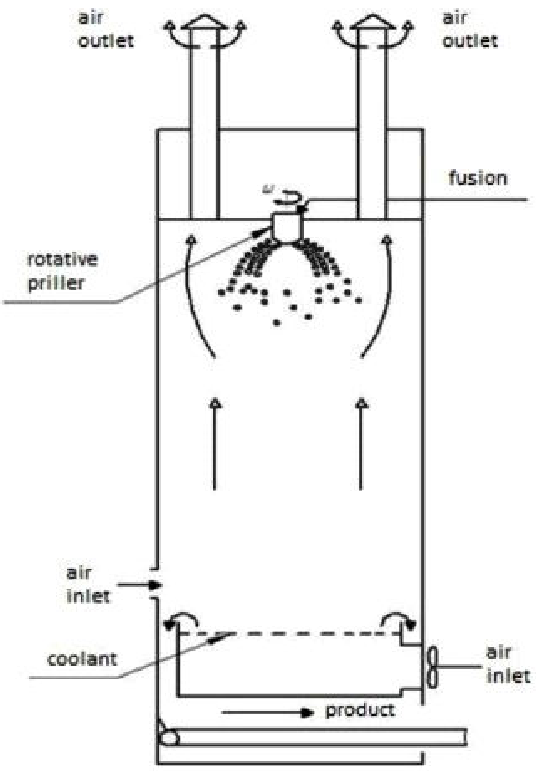


Fig. 1. Flow diagram of air and granules in the granulation tower

To mitigate agglomeration and promote uniform ingredient distribution within granulated products, it is essential to produce granules with a narrow size distribution. Monodisperse jet disintegration, induced by artificial regular disturbances, offers the potential to generate droplets spanning a wide size range, from 20–50 μm to 100–2000 μm. By carefully designing vibrating granulators, it is possible to further enhance product stability and physical properties.

An excessive increase in the oscillation frequency leads to a decrease in the length of the continuous jet. The increase in the amplitude of the oscillations first contributes to the increase in the size of the droplets, then causes the jet to split into two separate streams of droplets, and finally leads to the formation of droplets of irregular size.

At specific power $W=360$ W/m$^2$, as can be seen from Fig. 3, and, at the moment of jet disintegration, the drops have a pear-shaped shape. The pointed end of the drop is drawn into its main volume in 1/500 s, and the drop acquires a spherical shape (Fig. 3,b). At the same time, «satellites» are not formed. The production of pear-shaped drops is explained by a regular change in the speed of the liquid first in the jet, and then inside the drop, which occurs as a result of a periodic change in the speed of outflow from the canal under the influence of pressure pulses.

The uniformity of artificial jet disintegration is significantly influenced by the quality of the outflow orifice processing, the implementation of jet laminarization techniques, and the minimization of extraneous external disturbances that may induce turbulence. Proper shaping and polishing of the nozzle ensure a stable and symmetrical jet, which is crucial for achieving a controlled breakup into uniform droplets. In selecting the target granule size, one must consider the inherent hydrodynamic instability of molten droplets emerging from the jet. Under the influence of aerodynamic forces during flight, especially at high velocities or in the presence of uneven surrounding flow fields, larger droplets tend to deform due to surface tension gradients and internal pressure fluctuations. This deformation can lead to the formation of hollow, thin-walled shells that are particularly unstable. These shells ultimately disintegrate into a spectrum of smaller fragments, which reduces size uniformity and complicates downstream granule classification. A visual representation of this process is provided in Fig. 4, illustrating the stages of droplet deformation and breakup.

Causal analysis is a systematic methodology that facilitates the identification of potential root causes of undesirable events or problems. By categorizing potential conditioning factors – typically into areas such as materials, methods, equipment, environment, measurement, and personnel – this approach ensures a structured and comprehensive examination of all plausible hypotheses that may affect the outcome of a process or product quality parameter. This methodological rigor is particularly essential in high-precision industries, including fertilizer granulation, where product uniformity, mechanical strength, and nutrient encapsulation efficiency are sensitive to a multitude of interacting variables.

However, causal analysis alone does not confirm causation; it primarily serves as a hypothesis-generating framework. Empirical validation – through experimental trials, process monitoring, and statistical correlation – is required to verify which among the identified factors exert a dominant or synergistic influence on the observed anomalies.

To visualize and systematically assess the network of potential causes affecting the quality indicators of monodisperse compound fertilizer granules, an Ishikawa (fishbone) diagram was constructed (Fig. 5). This diagram enables the decomposition of complex process interdependencies and highlights key domains of concern. For instance, it maps how inconsistencies in melt temperature, deviations in nozzle geometry, insufficient jet laminarization, or external vibrations in the granulation zone can lead to deviations in granule sphericity, size distribution, and coating uniformity. Furthermore, factors related to material feedstock, such as the presence of fines or impurities, are also traced to their downstream effects on granule integrity and surface morphology.

By leveraging this visual tool in conjunction with process data, researchers and engineers can prioritize critical control points and implement targeted interventions, ultimately enhancing the reproducibility, sustainability, and performance of the fertilizer granulation process. The use of such a diagnostic framework aligns with contemporary principles of quality-by-design and supports continuous improvement in advanced manufacturing systems.

Bow-tie analysis is a structured qualitative method used to visualize and evaluate the pathways from initiating causes to final consequences of a hazardous event. It combines the logic of fault tree analysis (on the left side of the diagram, identifying potential root

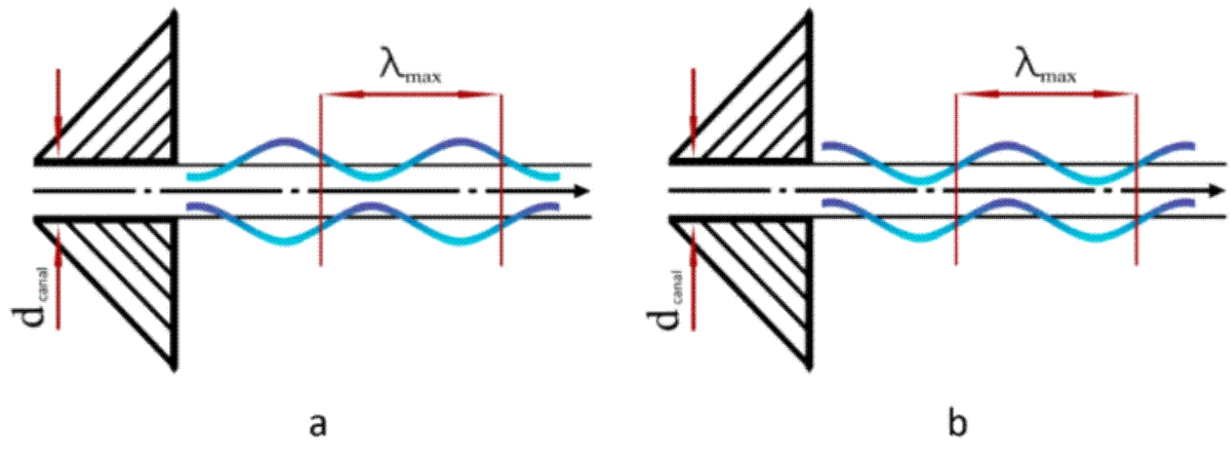


Fig. 2. Profile of jets before their breakup: a – axisymmetric jet with capillary waves; b – wave jet


Fig. 3. Formation of uniform droplets without «companions» during the application of regular pressure pulses from an oscillating membrane to the jet (specific power 360 W/m$^2$, f=584 Hz, $d_{canal}$=1.2 mm, pressure 0.54 m in water column meters, $\lambda$=6 mm): a – the first stage, formation of pear-shaped drops; b – the second stage, formation of spherical drops without «companions»

causes) and event tree analysis (on the right side, representing consequences), with a central event or critical failure mode at the core – the so-called "knot" of the bow tie. This approach is particularly valuable for illustrating the effectiveness of preventive and mitigative barriers across different stages of risk propagation.


Fig. 4. Disintegration of a liquid drop falling in the air

Unlike complex fault or event tree modeling, bow-tie diagrams are especially effective in cases where risks can be attributed to a limited number of distinct causal chains and where it is crucial to verify the presence and reliability of control measures. Typically developed through expert brainstorming, this method facilitates communication of risk logic and control strategies across interdisciplinary teams.

A practical implementation of this approach is demonstrated in Fig. 6, which presents a bow-tie diagram developed to assess the risk structure and control points in the granulation process of monodisperse compound fertilizers. The diagram illustrates the causal relationships between initiating factors and undesirable outcomes, while also highlighting the preventive and mitigating barriers intended to maintain process stability and product quality.

Building upon the structure presented in Fig. 6, the analysis demonstrates that the production of monodisperse compound fertilizers is subject to a complex set of interacting factors. These include internal causes such as equipment malfunction, insufficient staff qualification, and poor compliance with sanitary protocols, as well as external influences like unstable raw material supply, environmental fluctuations, and power interruptions. Each of these factors has the potential to disrupt process stability and compromise product quality.

The diagram highlights the importance of a comprehensive control strategy that integrates both preventive and corrective measures. Preventive actions such as raw material quality control, routine equipment inspection, and adherence to technological standards can reduce the likelihood of critical failures. Corrective and mitigating steps, including continuous monitoring, flexible production scheduling, and the implementation of circular economy principles, help to limit the severity of negative consequences when issues arise.

By identifying these key risk points and associated barriers, the bow-tie model provides a clear visual tool for managing process safety and performance. It also supports decision-making by revealing system vulnerabilities and offering a structured approach for improving resilience. In this context, the method serves not only as a diagnostic tool but also as a foundation for developing more robust, adaptive, and sustainable production systems.

***Conclusions***

The caking and agglomeration of fertilizers during transportation and storage remain a global challenge, leading to irreversible degradation of product quality, increased dust formation, operational blockages, and inconsistent application in the field. These issues highlight the urgent need to improve both the physical integrity and functional performance of compound fertilizers.

This study introduces a comprehensive methodological framework for assessing environmental risks associated with the entire life cycle of technological equipment used in the production of monodisperse compound fertilizers. The proposed approach integrates energy consumption analysis, environmental protection costs, and end-of-life

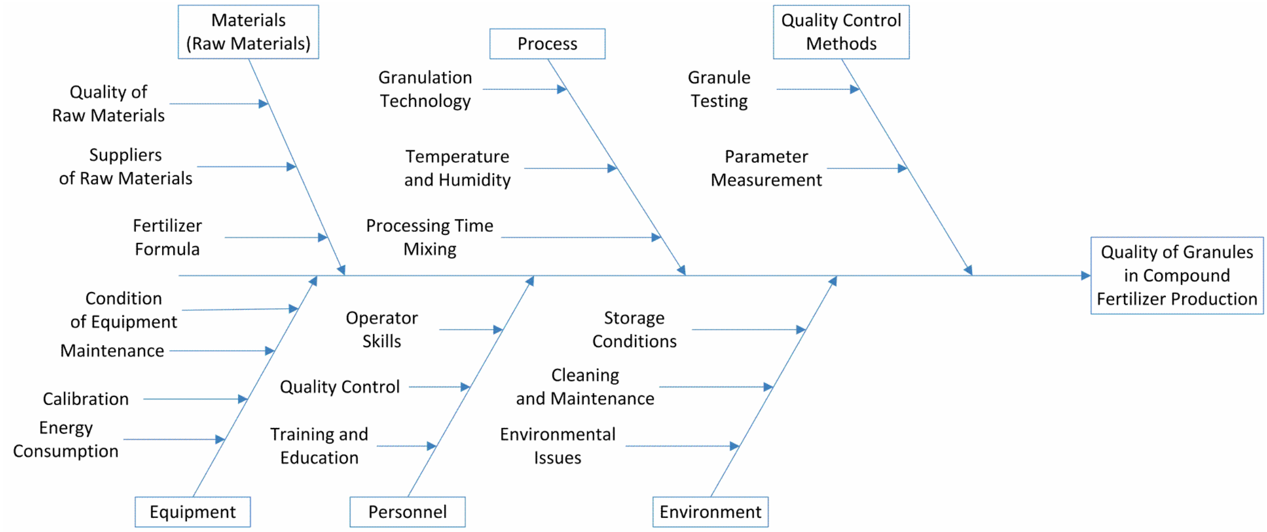


Fig. 5. Quality indicators of granules of monodisperse compound (combined) fertilizers

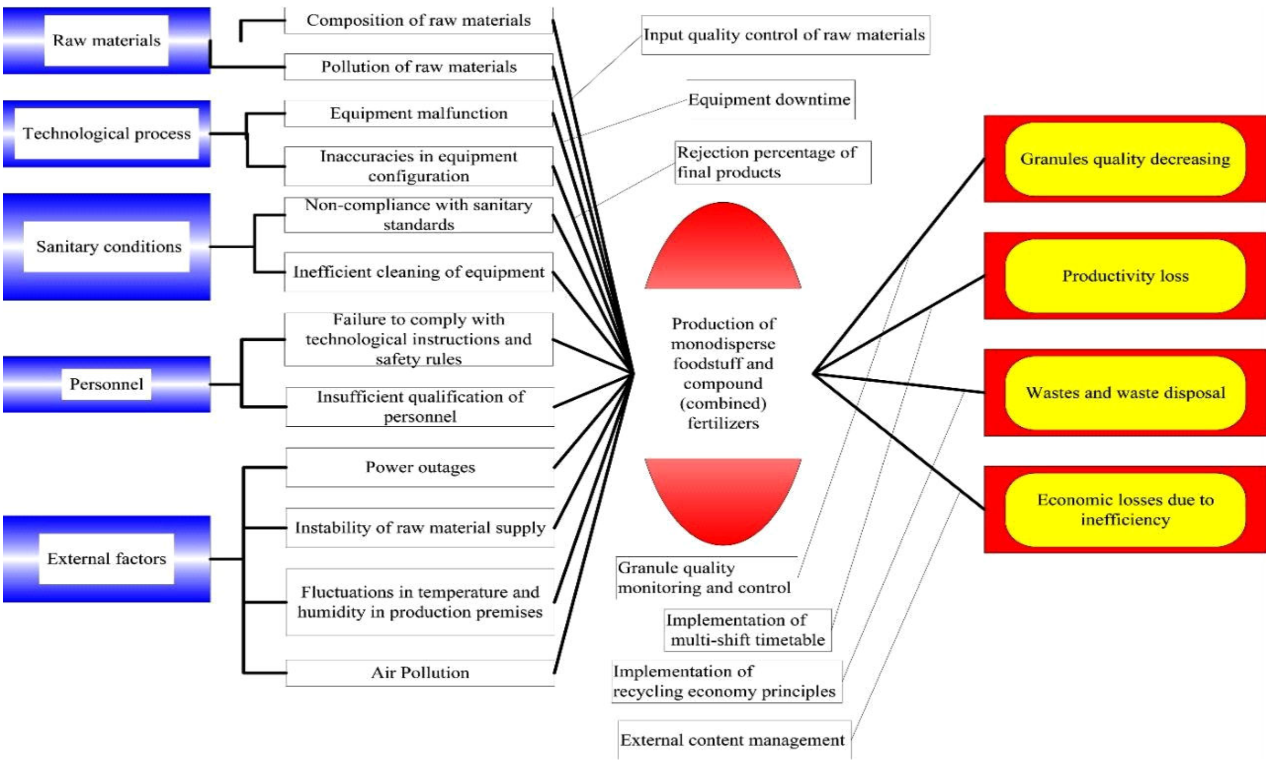


Fig. 6. Analysis of results using the bow-tie method

management – including dismantling and disposal.

By systematically evaluating both ecological impact and economic efficiency, this methodology enables a holistic optimization of granulation processes and equipment configurations. The findings contribute to advancing sustainable fertilizer technologies and align with the goals of circular economy and responsible resource use.

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## REFERENCES

1. *Hydrophobic* coatings for granular fertilizers to improve physical handling and nutrient delivery / Baird R.J., Kabiri S., Degryse F., da Silva R.C., Andelkovic I., McLaughlin M.J. // Powder Technol. – 2023. – Vol.424. – Art. No. 118521.

2. *Moure Abelenda A., Amaechi C.V.* Manufacturing of a granular fertilizer based on organic slurry and hardening agent // Inventions. – 2022. – Vol.7. Art. No. 26.

3. *Determination* of the energy efficiency of granulation equipment based on exergy analysis / Ostroha R., Yukhymenko M., Myshchenko D., Skydanenko M., Ivchenko O., Zhyhylii D., Ponomarova L., Bocko J. // Technology Audit and Production Reserves. – 2024. – Vol.5. – No. 1(79). – P.6-11.

4. *Microencapsulation* techniques and its application in pharmaceutical / Gupta S.K., Singhvi I.J., Shirsat M.K., Karwani G., Agarwal A, Aditi // Asian J. Pharm. Sci. Clin. Res. – 2011. – Vol.1. – No. 3. – P.67-77.

5. *Ukrainian* patent 43789. Granulovane mineralne dobryvo / Abramov S.M., Abramova M.S. – Kyiv: Derzhavne patentne vidomstvo Ukrainy; 2009.

6. *USA* patent 6039781 A. Precoated controlled release fertilizers and processes for their preparation / Goertz H.M., Timmons R.J., Johnson W.R. – Washington, DC: U.S. Patent and Trademark Office; 2008.

7. *USA* patent 20080111269 A1. Granules, tablets and granulation / Politi G., Heilakka E. – Washington, DC:U.S. Patent and Trademark Office; 2008.

8. *USA* patent 7674313 B2. Controlled release fertilizer and system and method / Jordon S., Jordan J. – Washington, DC: U.S. Patent and Trademark Office; 2010.

9. *Pajura R.* Composting municipal solid waste and animal manure in response to the current fertilizer crisis – a recent review // Sci. Total Environ. – 2024. – Vol.912. – Art. No. 169221.

10. *Management* of poultry manure in Poland – current state and future perspectives / Drozdz D., Wystalska K., Malinska K., Grosser A., Grobelak A., Kacprzak M. // J. Environ. Manage. – 2020. – Vol.264. – Art. No. 110327.

11. *Assessment* of the energy potential of chicken manure in Poland / Tanczuk M., Junga R., Kolasa-Wiecek A., Niemiec P. // Energies. – 2019. – Vol.12. – Art. No. 1244.

12. *A review* on treatment processes of chicken manure / Devendran Manogaran M., Shamsuddin R., Yusoff M.H.M., Lay M., Siyal A.A. // Clean Circ. Bioeconomy. – 2022. – Vol.2. – Art. No. 100013.

13. *Investigation* of the kinetic laws affecting the organic suspension granulation in the fluidized bed / Ostroha R., Yukhymenko M., Yakushko S., Artyukhov A. // East Eur. J. Enterprise Technol. – 2017. – Vol.4/1. – No. 88. – P.4-10.

14. *Shanmugam S.* Granulation techniques and technologies: recent progresses // Bioimpacts. – 2015. – Vol.5. – No. 1. – P.55-63.

15. *Formation* of liquid droplets at the prilling bucket outlet under free oscillations of the liquid jet / Yurchenko O., Ostroha R., Sklabinskyi V., Gusak O., Bocko J. // Advances in design, simulation and manufacturing VI. DSMIE 2023. – Lecture notes in mechanical engineering. – Cham: Springer, 2023.

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**МОНОДИСПЕРСНІ СИСТЕМИ У ВИРОБНИЦТВІ СКЛАДНИХ (КОМБІНОВАНИХ) ДОБРИВ**

***Р. Острога, М. Скиданенко, О. Івченко, Д. Жигилій, Л. Пономарьова, Й. Боцко***

Дослідження спрямовані на процес гранулювання мінеральних добрив валковим і насипним способами, а також у псевдозріджених і суспензійних шарах з активною гідродинамікою течії. Наголошується, що удосконалення первинних технологічних стадій виробництва гранульованих добрив має бути пріоритетним завданням оптимізації конструкції грануляторного обладнання та встановлення найбільш ефективних робочих і технологічних параметрів для підвищення продуктивності та зниження енергоємності. Ключові показники ефективності теплоутилізаційних грануляційних установок включають економічні витрати, втрати ексергії та мінімізовані витрати. Застосування результатів досліджень дозволить підібрати більш ефективні параметри для виробництва гранул комплексних добрив, що в кінцевому результаті підвищить продуктивність і якість продукції.

**Ключові слова**: грануляція мінеральних добрив, засипка, вальцювання, активна гідродинаміка, капсулювання, гранулювання.

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**Keywords:** granulation of mineral fertilizers; filling; rolling; active hydrodynamics; encapsulation; granulation.

**REFERENCES**

1. Baird RJ, Kabiri S, Degryse F, da Silva RC, Andelkovic I, McLaughlin MJ. Hydrophobic coatings for granular fertilizers to improve physical handling and nutrient delivery. *Powder Technol.* 2023; 424: 118521. doi: 10.1016/j.powtec.2023.118521.

2. Moure Abelenda A, Amaechi CV. Manufacturing of a granular fertilizer based on organic slurry and hardening agent. *Inventions.* 2022; 7: 26. doi: 10.3390/inventions7010026.

3. Ostroha R, Yukhymenko M, Myshchenko D, Skydanenko M, Ivchenko O, Zhyhylii D, et al. Determination of the energy efficiency of granulation equipment based on exergy analysis. *Technology Audit and Production Reserves.* 2024; 5(1(79)): 6-11. doi: 10.15587/2706- 5448.2024.311777.

4. Gupta SK, Singhvi IJ, Shirsat MK, Karwani G, Agarwal A, Aditi. Microencapsulation techniques and its application in pharmaceutical. *Asian J Pharm Sci Clin Res.* 2011; 1(3): 67-77.

5. Abramov SM, Abramova MS, inventors. *Granulovane mineralne dobryvo* [Granulated mineral fertilizer]. Ukraine patent UA 43789. 2009. (*in Ukrainian*).

6. Goertz HM, Timmons RJ, Johnson WR, inventors. *Precoated controlled release fertilizers and processes for their preparation.* USA patent US 6039781A. 2008.

7. Politi G, Heilakka E, inventors. *Granules, tablets and granulation.* USA patent US 20080111269A1. 2008.

8. Jordon S, Jordan J, inventors. *Controlled release fertilizer and system and method.* USA patent US 7674313B2). 2010.

9. Pajura R. Composting municipal solid waste and animal manure in response to the current fertilizer crisis – a recent review. *Sci Total Environ.* 2024; 912: 169221. doi: 10.1016/j.scitotenv.2023.169221.

10. Drozdz D, Wystalska K, Malinska K, Grosser A, Grobelak A, Kacprzak M. Management of poultry manure in Poland – current state and future perspectives. *J Environ Manage.* 2020; 264: 110327. doi: 10.1016/j.jenvman.2020.110327.

11. Tanczuk M, Junga R, Kolasa-Wiecek A, Niemiec P. Assessment of the energy potential of chicken manure in Poland. *Energies.* 2019; 12: 1244. doi: 10.3390/en12071244.

12. Devendran Manogaran M, Shamsuddin R, Yusoff MHM, Lay M, Siyal AA. A review on treatment processes of chicken manure. *Clean Circ Bioeconomy.* 2022; 2: 100013. doi: 10.1016/j.clcb.2022.100013.

13. Ostroha R, Yukhymenko M, Yakushko S, Artyukhov A. Investigation of the kinetic laws affecting the organic suspension granulation in the fluidized bed. *East Eur J Enterprise Technol.* 2017; 4/1(88): 4-10. doi: 10.15587/1729-4061.2017.107169.

14. Shanmugam S. Granulation techniques and technologies: recent progresses. *Bioimpacts.* 2015; 5(1): 55-63. doi: 10.15171/bi.2015.04.

15. Yurchenko O, Ostroha R, Sklabinskyi V, Gusak O, Bocko J. Formation of liquid droplets at the prilling bucket outlet under free oscillations of the liquid jet. In: Ivanov V, Pavlenko I, Liaposhchenko O, Machado J, Edl M, editors. *Advances in design, simulation and manufacturing VI. DSMIE 2023. Lecture notes in mechanical engineering.* Springer, Cham; 2023. doi: 10.1007/978-3-031-32774-2_18.