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DEVELOPMENT OF A COMPLEX TECHNOLOGY FOR REPLACING FOSSIL ENERGY CARRIERS WITH BY-PRODUCTS IN THE BIOETHANOL PRODUCTION

Introduction. *During the production of bioethanol, a significant amount of liquid waste, known as vinasse, is generated. Discharging vinasse leads to considerable environmental pollution and harm to living organisms. However, vinasse can be used as a fuel for industrial boilers when concentrated to 55—60% dry matter. The ash resulting from incineration is rich in minerals, particularly potassium salts, and can be utilized as fertilizer.*

Problem Statement. *The proposed and implemented technological solutions significantly reduce energy costs for biofuel production, achieving energy efficiency levels superior to global benchmarks. These conceptual solutions enable biofuel enterprises to achieve complete energy self-sufficiency by utilizing biomass waste as fuel.*

Purpose. *The purpose of this research is to develop a technology to replace fossil energy carriers at bioethanol enterprises with production waste for increasing fuel output based on renewable energy sources. This advancement supports Ukraine's energy independence and enhances environmental safety.*

Materials and Methods. *Dry matter in vinasse has been determined by the refractometric method and by drying to a constant mass at 105 °C. Ash content has been studied by incinerating a sample in a muffle furnace at 700—900 °C until complete ash formation, followed by quantifying the amount of unburned residue.*

Results. *The physical and chemical indicators for native and concentrated vinasse have been determined. The general view of evaporation plant and the mnemonic diagram of the automatic control system have been presented. Concentrated vinasse can be used as fuel for the process steam production at bioethanol plants.*

Conclusions. *Vinasse should be concentrated in vacuum evaporation units that are energetically integrated with ethanol distillation and rectification units. The developed and implemented technology enables the production of fuel to supply energy for the industrial production of bioethanol.*

Keywords: bioethanol, post-alcohol waste, waste, sugar beet vinasse, concentration, vinasse concentrate incineration, renewable energy feedstocks.

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Currently, six factories in Ukraine produce about 50,000 ton bioethanol per year, primarily from sugar molasses. According to the Laws of Ukraine on Alternative Fuels and Amendments to Certain Laws on Stimulating the Production of Motor Blended Gasolines, the annual demand for bioethanol is 300,000 tons. Bioethanol plants, while producing alternative fuel, consume fossil energy resources such as natural gas or fuel oil. Approximately 200—250 m^3 natural gas is required to produce one ton of bioethanol. Consequently, a significant portion of the energy used in green bioethanol production is derived from non-green sources, diminishing its value as an environmentally friendly energy resource. Additionally, rising prices for fossil energy carriers highlight the need to explore nonconventional energy sources for bioethanol plants.

During the production of bioethanol, a significant amount of liquid waste, known as post-alcohol bard or vinasse, is generated. Producing one ton of bioethanol results in the formation of 120—150 m^3 vinasse that contains about 10% of organic matter, with the remainder being water and inorganic substances. According to the preliminary estimates, 600,000 tons of vinasse were disposed in 2023 [1]. Vinasse, a hot (70—100 °C) dark brown liquid with an unpleasant odor, has a high chemical oxygen demand (COD) of up to 100 kg/m^3 [2—4]. When such wastewater enters reservoirs, its dark color negatively affects plant photosynthesis, and the high COD reduces the dissolved oxygen content in the water, leading to the death of aquatic flora and fauna [5].

Vinasse can also contaminate soils with phenols, sulfates, and heavy metals [6], contribute to the formation of greenhouse gases, and facilitate the reproduction of insects that adversely affect livestock breeding [7]. Consequently, enterprises that produce such biotechnological waste face constant pressure from environmental protection authorities and nearby residents, leading to periodic stoppage of production and legal liabilities. Currently, vinasse disposal is a significant problem. All bioethanol plants in Ukraine dump it in filtration fields, where as a result of microbiological decomposition, it emits harmful substances into the air and pollutes surface water bodies.

There are several methods for addressing the problem of vinasse disposal. Vinasse from maize, barley, and wheat has a high content of insoluble solids and can be used as livestock feed [2]. However, vinasse from beet pulp, sugar cane, grapes, agave, and sweet sorghum has a dark color, low pH values, and high concentrations of soluble organic substances, necessitating different disposal approaches [2]. Technological methods for treating such vinasse include biological processes (aerobic or anaerobic fermentation), physicochemical methods (coagulation/flocculation, electrocoagulation, adsorption, oxidation of organic substances, and membrane separation), and thermal processes (concentration and combustion) [2, 4].

Biomass burning is regarded as climate-neutral concerning emissions of CO_2 as a greenhouse gas (it does not contribute to excessive accumulation in the atmosphere), unlike fossil fuels [2, 8]. This is because the carbon dioxide released during biomass burning is absorbed by plants from the atmosphere and can be reabsorbed through the vegetation of other plants. The urgency of transitioning to climate neutrality is conditioned by Ukraine's high energy and carbon intensity, as well as by the reliance on outdated technological processes [9].

Vinasse can serve as a fuel for industrial boiler houses if concentrated to 50—60% dry matter [10]. The energy content of this fuel fully meets the needs of the bioethanol plant from which the vinasse is discharged. Concentrated organic waste substances can be combusted in boiler units, effectively replacing fossil energy carriers such as natural gas and fuel oil for producing process steam at the enterprise. The advantages of the thermal evaporation process include its adaptability to various feedstocks for combustion [10], the relative simplicity of industrial plants, and high productivity [11].

Concentrated vinasse has recently been utilized for energy supply in bioethanol production, particularly in Brazil and India, where sugarcane vinasse is often co-fired with sugarcane bagasse [12, 13]. This combined fuel is used in robust power units that generate 20—60 tons of steam per hour at a temperature of 400—450 °C. The high-pressure steam is utilized for electricity generation, while the low-pressure steam (having passed through the steam turbine) serves as process steam.

There are reports on combusting sugarcane vinasse, concentrated to 55—60% dry matter, in specially designed burners together with high-calorie fuel, constituting approximately 20% of the total heat load [14]. Given the differences between sugar-beet and sugarcane molasses, there is a necessity for technological advancements in burning sugar-beet molasses to produce process steam.

It is important to highlight that utilizing vinasse as an energy source in industrial enterprises aligns with the Sustainable Development Goals (SDGs) adopted by the UN General Assembly in September 2015. Specifically, it contributes to Goal 7 (ensuring access to affordable, reliable, sustainable, and modern energy for all), Goal 9 (building resilient infrastructure, promoting inclusive and sustainable industrialization, and fostering innovation), Goal 12 (ensuring sustainable consumption and production patterns), and Goal 13 (taking urgent action to combat climate change and its impacts).

Therefore, the goal of this study is to develop a technology for replacing fossil energy sources at enterprises that produce bioethanol with waste from its production, which should contribute to increasing the production of fuel based on renewable energy sources, as well as to raising the energy independence and environmental security of Ukraine.

The research is structured as follows to achieve its objectives:

1. Obtaining empirical data in laboratory conditions for calculating the primary scheme of the evaporation plant, including:
   - Determining the relationship between the density of beet pulp and the refractometric index.
   - Estimating the concentration depression as dry substance content changes during the evaporation process of vinasse.
2. Developing the primary diagram of the plant and designing the heat exchange equipment.
3. Calculating the key characteristics of the equipment and developing the necessary design documentation.
4. Designing and implementing an Automated Plant Management System (APMS).
5. Manufacturing the equipment, followed by its installation and commissioning at the enterprise.

In this research, we have utilized beet vinasse (oily post-alcohol bard) from Haisyn Distillery (Haisyn, Vinnytsia Oblast) stored in its original form at a temperature of 4 °C for no longer than three days. The vinasse is evaporated with the use of a rotary evaporator. The calculations have been made for the capacities of Haisyn Distillery that produces 120—140 m^3/day bioethanol, with approximately 1000 m^3/day molasses discharged to filtration fields. The study is structured according to the outlined method statement and has given the results as presented below.

Vinasse concentration control. The biochemical and physicochemical characteristics of vinasse depend on the type of plant material used for bioethanol production [1, 2]. For instance, beet pulp has a relatively high content of soluble dry matter [1, 2]. To facilitate automated control of the vinasse concentration process, it is essential to establish correleation between relationships among the key parameters, such as density, dry matter content, and refractometric index of concentrated vinasse. The content of moisture and matter is determined by drying a 5 g sample of vinasse at 105 °C in a drying cabinet, until a constant mass is achieved [15], and by the refractometric method [16]. Vinasse concentration is monitored based on the dry matter (or the moisture) content. For the moisture analysis being time-consuming and the dry matter indicators being quite unreliable for automated systems, it is more efficient to measure the refractive index or density of the product. The empirical dependencies of these parameters are illustrated in Fig. 1.

As already mentioned above, the obtained data have been subsequently used in the design of the

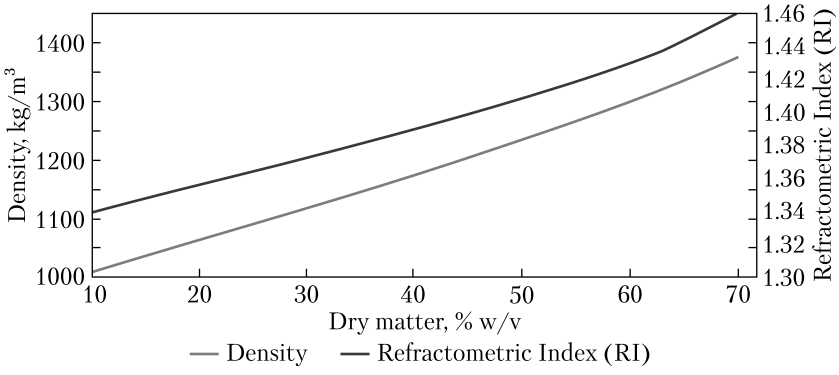

Fig. 1. Dependence of the sugar beet vinasse density and the refractometric index on the dry matter content

automated control system for the concentration plant process.

Determination of vinasse concentration depression. The results of the measurements have indicated that during the evaporation process, the concentration of vinasse dry matter varies in a wide range, from 12 to 65% wt. The difference between the boiling point of a liquid and the temperature of its vapor above it is significantly affected by the factors, such as concentration depression, particularly important in designing evaporation units for vinasse concentration. Experimental data on concentration depression (boiling point elevation) are crucial to design the evaporation unit. The results obtained are presented in Table 1. These data have been subsequently utilized to determine the required heat transfer surface area for the evaporators in a four-stage vacuum evaporation plant capable of evaporating 40 tons of evaporating moisture per hour at Haisyn Distillery.

Table 1. **Experimental Data on Vinasse Concentration Depression**

Vinasse dry matter concentration, % wt.	Temperature of the liquid, °C	Temperature of the steam, °C	Concentration depression, °C
25	101.7	99.0	2.7
30	102.3	99.5	2.8
45	104.8	99.5	5.3
50	105.5	99.5	6.0
60	107.9	99.5	8.4
70	111.2	99.5	11.7

Schematic diagram of the installation for concentration of vinasse. Given the substantial energy demands of the evaporation process, it is essential to devise an energy flow scheme for bioethanol production. This scheme aims to utilize thermal energy for vinasse concentration and to redirect secondary energy to the primary production process that is distillation and rectification of ethanol from fermentation liquid. Figure 2 illustrates the proposed schematic diagram of the plant, featuring vacuum distillation and rectification of bioethanol alongside four-stage evaporation of vinasse to achieve a dry matter content of 60%. The secondary steam generated from the second stage of the evaporation plant goes to the vacuum distillation plant.

The plant incorporates a thermocompressor (TVR) at the first stage of evaporation, which allows a significant reduction in the primary steam consumption. The distillation/rectification unit utilises secondary steam from the second stage of the evaporation plant, resulting in a specific steam consumption of 60 kg per ton of water evaporated. In contrast, a similar four-stage plant without integrated energy flows with distillation typically requires about 300 kg of steam per ton of evaporated water. The diagram shows the parameters crucial for designing the plant equipment, including heat exchange surface area, pipeline cross-sections, and collector volumes.

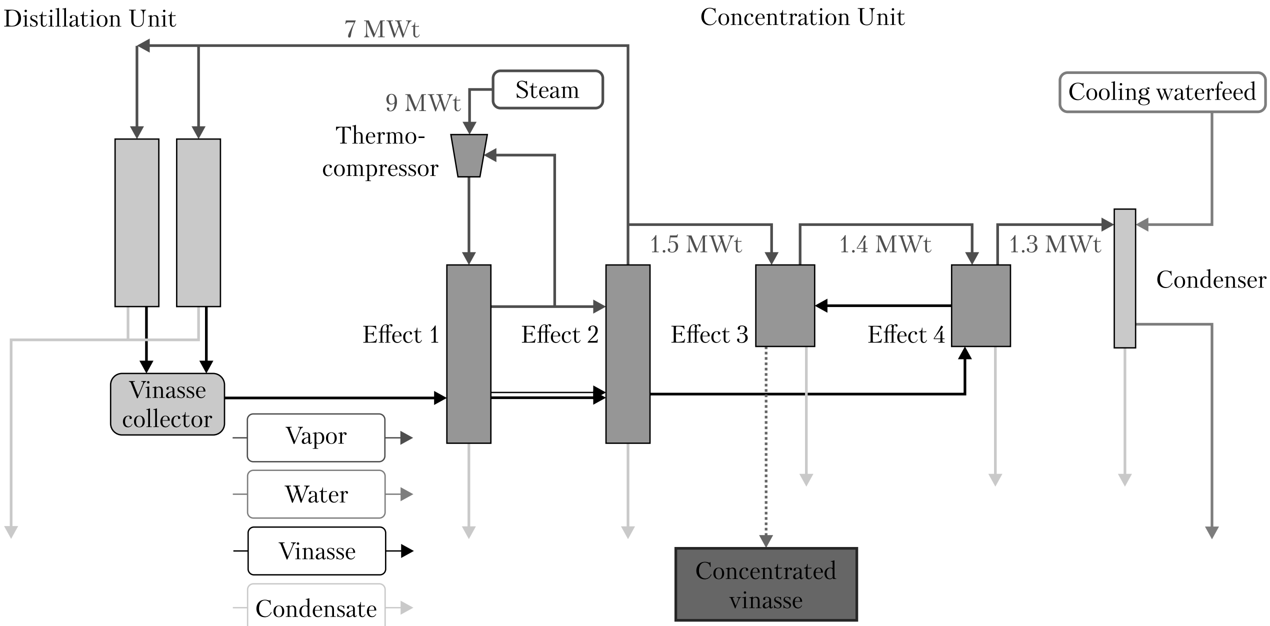

Fig. 2. Schematic diagram of the vinasse concentration plant

Condensates sufficiently purified during the vinasse concentration process can be recycled back into production for preparing fermentation media. This approach aligns with the environmental principle of *Zero Effluent*, which advocates for zero discharges as part of the circular economy concept. Circular economy principles emphasize maximizing resource utilization and extending their lifecycle, thereby reducing the demand for new resources and minimizing waste production [17, 18].

The arrangement of the evaporation plant equipment. The arrangement of the evaporation plant equipment is shown in Fig. 3. Such an evaporation plant is installed on the territory of the Haisyn Distillery. It occupies an area of 9 × 18 m, the height of the room is 18 m. The nominal capacity of the plant is 38 tons of evaporating moisture per hour. The nominal output of 60% vinasse concentrate is 200 tons per day. The 3D model of the evaporation plant has been built in the SketchUp program (Trimble Inc., California, USA).

Automatic control system of the evaporation plant. The evaporation unit is designed to concentrate vinasse through a four-stage evaporation

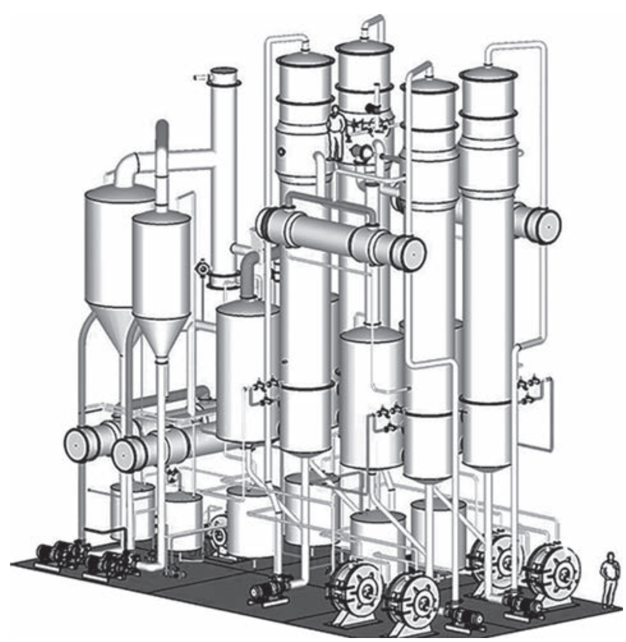

Fig. 3. Arrangement of evaporation unit equipment

process to remove excess moisture. The first and second stages of the evaporation plant are configured with two parallel lines. The liquid is fed to this plant by pumps with a nominal flow rate

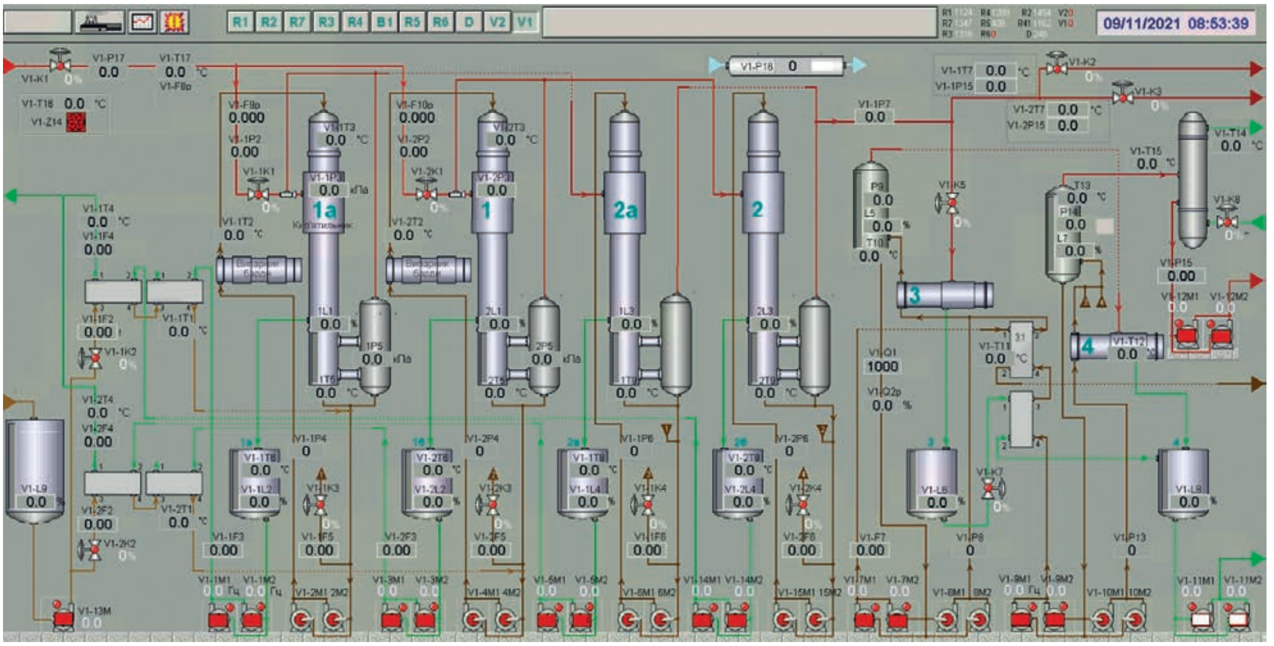

Fig. 4. Mnemonic scheme of the evaporation plant

Fig. 5. External view of the evaporation plant

Table 2. **Heat of Combustion of Vinasse Concentrate Sample**

Higher heat of combustion, kJ/kg (kcal/kg)	Lower heat of combustion, kJ/kg (kcal/kg)
16077 (3840)	14772 (3528)

of 50 m^3/h, divided into two streams of 25 m^3/h for each line. The parity of consumption between both lines is automatically maintained during bard evaporation. After the second stage of evaporation, the concentrated streams of vinasse from both parallel lines are consolidated into a single stream, subsequently entering the third and finally the fourth stage of evaporation.

The evaporation plant is fully automated, facilitating integration with distillation columns through heat flows. Operational control of the entire equipment complex is centralized, managed by a single operator from a unified terminal. Figure 4 depicts the mnemonic diagram of the evaporation plant, as displayed on the terminal.

Figure 5 shows the external view of the plant on the territory of the Haisyn Distillery.

An experimental batch of vinasse concentrate with the following physicochemical parameters: the moisture content is 45.41 ± 0.5%, the ash content is 16.96 ± 0.15%, the sulfur content is 0.22 ± 0.01%, pH is 6.95 ± 0.1, was produced during the commissioning and test operation of the concentration plant from December 2021 to mid-February 2022. The data were obtained in the production laboratory of the Haisyn Distillery, by standard methods [19].

A sample of this concentrate was sent to the specialized laboratory of *Dniprovska Politekhnika* National Technical University for a preliminary evaluation of the concentrate as a liquid fuel. The results of determining the heat of combustion of the analyzed vinasse concentrate sample are shown in Table 2. For comparison, the lower calorific value of vinasse concentrated to 60—65% dry matter from the processing of sugar cane molasses into ethanol is approximately 9500 kJ/kg [20].

The calculations have demonstrated that the quantity of vinasse concentrated to 55% dry matter required to support the production of bioethanol is 240 kg, while 250 kg is produced. This means that the production needs are fully met. The preliminary estimates suggest that concentrated vinasse with a dry matter content of 60% and more can be utilized as a fuel for industrial steam boilers, either with adding to it 10—15% of fuel oil or together with natural gas as an auxiliary fuel in appropriately designed burners.

The laboratory studies followed by industrial application have indicated that concentrated vinasse can be effectively used as a fuel for generating process steam at bioethanol plants, where it is produced as a by-product of biotechnological processes. This vinasse can be further utilized for energy needs of the same production facility by concentrating it in vacuum evaporation units that are energetically integrated with ethanol distillation and rectification units. The technology of vinasse concentration has been successfully implemented at the Haisyn Distillery, which allows obtaining fuel to support the primary production of bioethanol.

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РОЗРОБЛЕННЯ КОМПЛЕКСНОЇ ТЕХНОЛОГІЇ ЗАМІЩЕННЯ ВИКОПНИХ ЕНЕРГОНОСІЇВ ПОБІЧНИМИ ПРОДУКТАМИ ВИРОБНИЦТВА БІОЕТАНОЛУ

Вступ. При виробництві біоетанолу утворюється значна кількість рідких відходів — післяспиртової барди (вінаси), скиди якої призводять до суттєвого забруднення довкілля та загибелі живого. Вінасу можливо використовувати як паливо для промислових котелень при концентруванні її до вмісту 55—60 % сухих речовин. Зола після її спалювання багата на мінеральні речовини, зокрема солі калію, і може використовуватися як добриво.

Проблематика. Запропоновані і реалізовані технологічні рішення дозволяють значно скоротити енергетичні витрати на виробництво біопалив і вийти на вищий за світові аналоги рівень енерговитрат. Концептуальні рішення дають можливість підприємствам з виробництва біопалив повністю перейти на енергетичне самозабезпечення через використання відходів біомаси як палива.

Мета. Розроблення технології заміщення викопних енергоносіїв на підприємствах з отримання біоетанолу відходами його виробництва, що дозволить збільшити виробництво палива на основі відновлювальних джерел енергії та підвищити енергонезалежність й екологічну безпеку України.

Матеріали й методи. Сухі речовини у вінасі визначали рефрактометричним методом та методом висушування до постійної маси при температурі 105 °С. Зольність досліджували шляхом спалювання наважки у муфельній печі при температурі 700—900 °С до повного озолення із наступним визначенням кількості неспаленого залишку.

Результати. Визначено фізико-хімічні показники для нативної та концентрованої вінаси. Подано загальний вигляд, мнемосхему автоматизованої системи управління випарною установкою для концентрування вінаси, яку надалі можна використовувати як паливо для виробництва технологічної пари на біоетанольних заводах.

Висновки. Концентрування вінаси потрібно здійснювати на вакуум-випарних установках, енергетично інтегрованих із установками із дистилювання і ректифікації етанолу. Розроблена та впроваджена технологія дозволяє отримувати паливо з відходів для забезпечення енергонезалежності основного промислового виробництва біоетанолу.

Ключові слова: біоетанол, післяспиртова барда, відходи, бурякова вінаса, концентрування, спалювання концентрату вінаси, поновлювана енергетична сировина.