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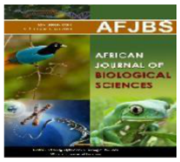

Developing an Energy-Efficient Drying Technology for Healthy Food Production

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Abstract

The reverse Carnot cycle was used to create an energy-efficient drying system for low-temperature vacuum drying with a heat pump. The advantage of this technology is reduced contact of the raw material with atmospheric air and the prevention of destructive oxidation processes during the evaporation of moisture. Lower drying temperatures help to preserve the natural shape, colour, taste, and nutritional properties of the dried product. This technology contributes to retaining nutritional value and, thus, helps to build favourable consumer perception. To control system processes and ensure the interaction of human-machine interfaces (HMI), programmable logic controllers are used. The developed system offers automatic temperature and pressure control in the drying chamber, as well as signal transmission and operator control. The developed technology can be used in the production of specialised products enriched with essential micronutrients for the prevention and complex treatment of widespread alimentary and infectious diseases. The recipe optimisation is carried out to ensure the right content of bioactive compounds.

Keywords: Drying technology, Low-temperature vacuum, Heat pump, Bioactive compounds

Introduction

Exploring innovative ways of applying energy and resource-saving technologies to natural raw materials processing and healthy food product production is important for researchers engaged in nutrition science (Sergun et al., 2021; Austrian et al., 2022; Vu et al., 2022; Zhang et al., 2022).

Inadequate handling of raw materials, and poor food processing techniques result in the loss of a great amount of agricultural produce (Iqbal et al., 2019).

One of the research areas is the development of sustainable rehydration processes that ensure effective preservation of the natural bioactive components, help save on transportation, limit waste, and increase shelf life (Calín-Sánchez et al., 2020).

These processes have to comply with Environmental, Social, and Corporate Governance (ESG) guidelines (Varadarajan, 2017; Korotkiy et al., 2021; Urbaniec et al., 2021).

Materials and Methods

An analysis of existing rehydration technologies for natural plant and animal raw materials was carried out. The low-temperature vacuum drying technology with a heat pump was found to be fully consistent with the key sustainability factors.

This technology is promising because of its high efficiency and intensity. Energy savings are achieved by employing a heat pump, which operates on the reversed Carnot cycle. The reuse of heat from the evaporated and humidified vapors in the condenser provides recuperation effects and enables the control of drying parameters. The use of waste heat is an environmental factor of sustainability, so it is very important to develop techniques providing for increased energy efficiency (Korotkiy et al., 2021; Salehi, 2021).

Quantitative data show that this technology lowers energy consumption by 60-80%, compared with conventional dryers operating under similar conditions (Korotkiy et al., 2021; Salehi, 2021).

A shorter processing time is a result of vacuum drying when the partial vapour pressure is below atmospheric pressure. The advantage of this technology is reduced contact of the raw material with atmospheric air and prevention of destructive oxidation processes during the evaporation of moisture. Lower drying temperature helps to preserve the natural colour of the dried product. This technology contributes to retaining nutritional value and, thus, helps to build favourable consumer perception.

During experiments, the heating temperature varied from 40 to 600 C, the vacuum pressure was up to 40 - 60 kPa. The exergy efficiency of using the heat of the return air was up to 25-30%. The structure of the product was highly porous to ensure better rehydration. The preservation of polyphenolic substances was directly related to the high antioxidant capacity of the original ingredients. The use of low temperatures improved the characteristics of dried products, namely organoleptic characteristics when compared with products dried with different methods.

Results and Discussion

In our experiments, we used our own drying complex, which operates in the following cycles: (1) heating, (2) vacuuming, and (3) drying in pulsed combined heating modes.

Guidelines for vacuum low-temperature drying of plant-based raw materials with specified technological parameters were developed. Siemens TIA Portal automation services were employed for control algorithms.

Using our prior research on the topic (Chojnacka et al., 2021), the proposed ways of reducing energy consumption include using the heat from the phase transition for preheating the raw material, performing the drying process under vacuum pressure, and applying oscillating pressure modes. The heat of the spent drying agent is utilised on the surface of the condenser for further use in heating the conductive surfaces of the installation. As the process is performed under a vacuum, the raw material components are preserved, and heat and mass transfer are greater when bound (including osmotic) moisture is removed. Water ring pumps are used to create vacuum.

The cyclic pressure changes ensure the uniform capillary-diffusion movement of the vapour-gas phase to the surface. For quality, the process requires compliance with certain sequences of exposure to the main drying parameters (duration, temperature, and pressure). For raw plant materials, we have determined the recommended values of the parameters.

To control system processes and ensure the interaction of human-machine interfaces (HMI), programmable logic controllers were employed.

Using Siemens Simatic controllers, we have developed a multifunctional control system that provides two-way data exchange via the Modbus TCP protocol of Simatic systems with conductive surface heating and chamber vacuum systems.

The control algorithm was programmed in the TIA Portal environment according to the specified processing parameters for various groups of raw materials. The software module for managing the drying process is shown in **Figure 1.**

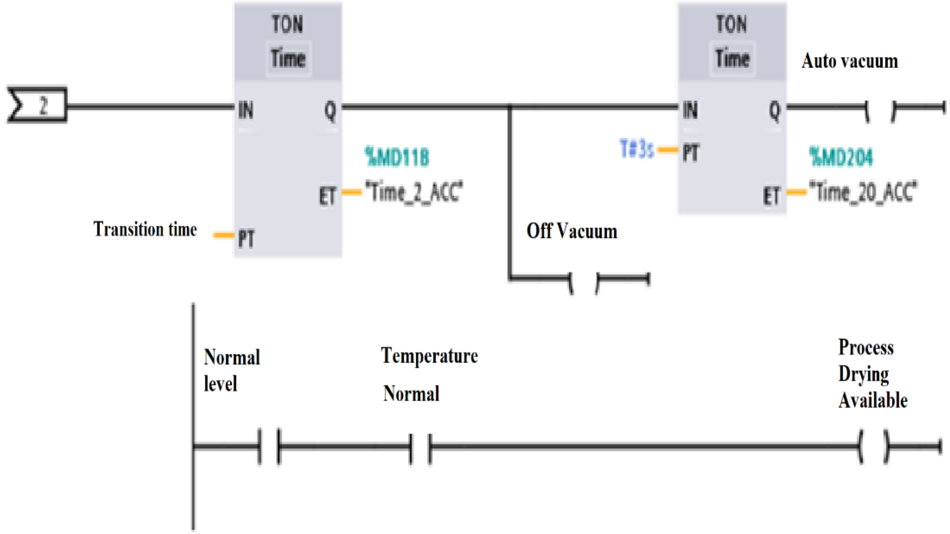

Figure 1. Diagram of the software module for managing the drying process

Primary data is set by the operator on the SIMATIC HMI control panel. For certain raw materials, the parameters are stored in the database management system. The screens of the operator panel display the current values and allow manual operation of the drying process. The technology of vacuum-pulse drying provides the opportunity to produce products comparable in terms of quality with sublimated ones. The advantage is a greater intensity of internal moisture transfer during vacuuming and better use of heat in the drying process.

The process is implemented in three stages. First, conductive heating (at a surface temperature of 600 C) of the prepared raw material is carried out at atmospheric pressure. At this stage, the moisture concentration is redistributed to the surface diffusion zone.

When moved away from the heating zone, a negative concentration gradient is observed due to thermal diffusion in raw material. At this stage, the dryer chamber is vacuumed to a

pressure of 0.1 kPa, the moisture gradients become aligned, and the diffusion flow can be considered stationary.

The duration of the second stage is limited by the onset of the falling rate period. For the studied berries, the duration of the first stage was up to 360 seconds, and the second stage lasted for up to 20 minutes. In the third stage, the heating is stopped; equalizing the pressure to atmospheric pressure takes 180 seconds. These processing parameters prevent changes in the shape of berries as well as the thermal decomposition of bioactive compounds.

The balanced sequence of changes in drying time, temperature, and pressure determines the preservation of natural shape, colour, taste, and nutritional properties. The sequence was programmed with Siemens TIA Portal automation services.

SCADA interface was adapted to be used for data exchange with SIMATIC controllers, and controlling and monitoring of the drying process were displayed on the SIMATIC HMI control panel.

To protect plant-based raw materials in potential emergencies, we have provided a function to disable conductive heating when the temperature parameters of the process are exceeded. The developed system ensures automatic temperature and pressure control in the drying chamber, as well as signal transmission and operator control.

Conclusion

The developed technology can be used in the production of specialised products enriched with essential micronutrients for the prevention and complex treatment of widespread alimentary and infectious diseases (Ikuta et al., 2012; Tokhiriyon et al., 2019, 2020, 2021; Gribova et al., 2020; Vekovtsev et al., 2020; Fedorenko et al., 2021; Strizhevskaya et al., 2021).

For food enrichment, a computer program is used to design and calculate composition with improved nutritional value. The composition is optimised with Pareto charts to achieve desired nutritional values and functional properties. For recipe optimisation, the content of specified bioactive compounds is taken into account (Kumar et al., 2021; Aguilar-Pérez et al., 2023; Bechoff et al., 2023; Elechi et al., 2023; Fanzo et al., 2023; Lee et al., 2023; Miano et al., 2023; Nartea et al., 2023; Peasley et al., 2023; Pourmohamadkhan et al., 2023; Rohner et al., 2023; Shi et al., 2024).

Application of innovative technology allowed us to design and develop an information and communication system for controlling the processes of vacuum low-temperature drying of raw materials of plant and animal origin in healthy food production.

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Conflict of interest: None.

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Ethics statement: The study was conducted according to the guidelines of the Declaration of Helsinki.

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