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PROSPECTS FOR APPLYING INNOVATIVE TECHNOLOGIES AND IMPROVING THE EFFICIENCY OF FRUIT AND GRAPE DRYING

Madaminjon Mo‘minjon o‘g‘li Ubaydullaev
Doctor of Agricultural Sciences,
Associate Professor,
Department of Food Technology and Safety,
Fergana State Technical University.
Shakhlokhon Ilkhomjon qizi Kadirova
Master’s student, group M40-26 (Technology
of Storage and Processing
of Agricultural Products).
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Abstract. This article analyzes conventional and innovative technologies for drying fruits and grapes on the basis of scientific literature. The operating principles, advantages, and limitations of solar, heat-pump, infrared, microwave, vacuum, and freeze-drying methods are examined. It is substantiated that drying efficiency should be assessed not only by the rate of moisture removal, but also by energy consumption, retention of product color, texture and flavor, rehydration capacity, and preservation of biologically active compounds. The importance of selecting appropriate grape-drying conditions according to cultivar, berry size, skin characteristics, and pretreatment is highlighted. For Uzbekistan, the introduction of hybrid systems such as solar–heat-pump and solar–infrared systems, sensor-based monitoring, and optimization of process parameters according to the type of raw material are proposed as promising directions.

Keywords: fruits, grapes, drying technology, innovative method, solar dryer, heat pump, infrared drying, microwave drying, vacuum drying, hybrid system, energy efficiency, product quality.

Introduction. Fruit and grape production is one of the agricultural sectors with considerable potential for generating high added value. However, the high moisture content of freshly harvested produce, continued respiration, and microbiological factors limit its shelf life. Drying reduces water activity by removing free moisture, restricts the growth of microorganisms, and decreases product weight and transportation costs. At the same time, if temperature and drying time are not properly selected, browning, texture hardening, loss of volatile aroma compounds, and degradation of heat-sensitive vitamins may occur (Mohammed et al., 2024). Although traditional open-air sun drying is simple and relatively inexpensive, maintaining consistent product quality is difficult because of weather dependence, dust, insects, and other external contaminants. Convective hot-air dryers provide greater control over the process; however, energy consumption and heat-induced quality losses remain important challenges. Therefore, alongside improvements to individual drying methods, increasing attention is being paid to hybrid technologies that combine several heat- and mass-transfer mechanisms (An et al., 2024; Saha et al., 2024).

Aim of the study. To conduct a comparative analysis of modern technologies used for drying fruits and grapes on the basis of scientific sources, assess their effects on energy efficiency and product quality, and substantiate promising technological solutions suitable for application under the conditions of Uzbekistan.

Materials and methods. This article is analytical in nature and does not present results from new laboratory or industrial experiments. The research material consisted of scientific review articles published in 2024–2025, as well as research findings on the solar–infrared drying of grapes. The sources were grouped according to drying mechanism, energy consumption, drying duration, product quality, process control, and criteria for economic implementation.

Comparative analysis, synthesis of scientific data, and a systems approach were used. Results reported in different sources were not interpreted as unified experimental indicators obtained using the same raw material, equipment capacity, and operating conditions. Accordingly, the tables summarize qualitative characteristics and application conditions of the technologies; they should not be regarded as guaranteed technical specifications or standard operating regimes for any particular piece of equipment.

Results and discussion. The main purpose of drying is to reduce the moisture content of a product to a level at which microbiological and enzymatic spoilage processes are slowed. Heat transfer to the product and moisture migration from its inner layers to the surrounding environment occur simultaneously and are interrelated. The drying rate depends on product shape, slice thickness, initial moisture content, tissue structure, air temperature, relative humidity, and air velocity. In grapes, the density of the skin resists the outward movement of water; therefore, cultivar characteristics and pretreatment affect drying kinetics.

Table 1.

Comparative characteristics of modern technologies for drying fruits and grapes

Technology	Operating principle	Main advantage	Limitation / consideration
Solar	Moisture removal using solar radiation and heated air	Renewable energy; relatively low operating costs	Weather-dependent; variable temperature
Heat-pump	Cooling moist air to condense moisture, followed by reheating the air	Controlled drying at low temperatures; heat recovery	Equipment and maintenance costs; need for automation
Infrared	Transfer of radiant energy to the product surface	Rapid surface heating; compact equipment	Possibility of uneven heating in thick layers
Microwave	Volumetric heating inside the product in an electromagnetic field	May accelerate internal moisture migration	Field non-uniformity and localized overheating
Vacuum	Evaporation of moisture at a lower temperature under reduced pressure	Potential to reduce oxidation and thermal effects	Equipment complexity and investment requirements
Freeze-drying	Sublimation of ice from a frozen product under vacuum	May preserve porous structure and rehydration properties	Long processing time and high cost
Hybrid	Combination of two or more drying mechanisms	Balance between speed, quality, and energy consumption	Complex control; regime must be adapted to the raw material

Solar dryers, compared with drying products in the open air, provide a protected chamber, control of airflow, and more efficient use of solar heat. In an indirect solar dryer, air heated in a collector is supplied to the drying chamber; in mixed-mode dryers, the product is exposed to both solar radiation and heated air. However, solar radiation varies throughout the day. Therefore, hybrid systems combined with thermal energy storage or an auxiliary heat source can improve the continuity of the drying process (Saha et al., 2024).

In heat-pump systems, moist air is cooled in an evaporator, causing its moisture to condense; the air is then reheated and returned to the drying chamber. Reusing heat in a closed or semi-closed cycle increases energy efficiency. Since these systems operate at controlled temperatures, they are suitable for heat-sensitive products. Zhu et al. (2025) identify temperature and humidity control, automation, and improved product-quality retention among the advantages of heat-pump drying. At the same time, equipment cost, compressor efficiency, and the reliability of the sensor system affect implementation costs.

Table 2.

Selection of drying methods suitable for fruit and grape products

Raw material / product	Suitable approach	Main control factors	Expected result
Thinly sliced fruits	Convective + infrared or solar hybrid	Slice thickness, air velocity, surface temperature	Higher drying rate and batch uniformity
Heat-sensitive fruits	Heat-pump or vacuum drying	Low temperature, relative humidity, final moisture content	Better retention of color, aroma, and bioactive compounds
Apples, pears, and stone fruits	Hot-air or heat-pump drying	Enzymatic browning, slice thickness	Stability of appearance and texture
Grapes (raisin cultivars)	Solar, solar–infrared, or heat-pump hybrid	Cultivar, berry size, skin, pretreatment	Reduced drying time and quality control
High-value specialty products	Freeze-drying or vacuum drying	Freezing regime, pressure, product temperature	Preservation of porous structure and rehydration properties
Small-scale batches from farms	Modular solar dryer with thermal energy storage	Solar radiation, air exchange, hygiene	Use of local energy and reduced contamination

In infrared drying, energy is transferred to the product surface through electromagnetic radiation. This method can rapidly heat the surface layer and shorten drying time; however, temperature gradients may develop in thick or unevenly arranged products. In microwave drying, an electromagnetic field generates volumetric heating inside the product and may accelerate internal moisture migration. Nevertheless, an uneven field can cause localized overheating. For this reason, these methods are often used in combination with convective or vacuum drying (Mohammed et al., 2024). In vacuum drying, reduced pressure lowers the boiling point of water, making it possible to dry products at relatively low temperatures. In freeze-drying, the product is first frozen, after which ice crystals are removed under vacuum by sublimation, without passing through the liquid phase. As a result, the porous structure and rehydration properties may be better preserved; however, the process is complex, time-consuming, and requires high energy and capital expenditure. Therefore, these technologies should be selected on an economic basis for products requiring high quality and added value. In their study of grape drying, Çoban et al. (2024) investigated the possibility of combining solar heat with an infrared heating film for seedless Sultana grapes. Their findings showed that the combined use of solar and infrared energy can accelerate the drying process. This demonstrates the practical importance of hybrid energy sources in grape drying; however, before applying a specific regime to other cultivars or regions, it must be tested in view of the raw material characteristics and local climatic conditions.

Table 3.

Criteria for assessing drying efficiency and monitoring directions

Criterion	What it determines	Monitoring method	Significance
Drying duration	Time required to reduce moisture to the specified level	Recording mass and moisture content over time	Productivity and batch turnover
Specific energy consumption	Energy consumed per unit of moisture removed	Electricity and heat meters	Selection of an energy-efficient technology
Final moisture content / water activity	Condition affecting storage stability	Moisture analyzer and water-activity meter	Shelf life and microbiological stability
Color and appearance	Browning, color changes, and uniformity	Colorimeter or standardized visual assessment	Commercial appearance and market requirements
Texture and rehydration	Hardness, brittleness, and water absorption	Texture analyzer and rehydration test	Consumer acceptability
Bioactive compounds	Vitamins, phenolic compounds, antioxidant activity	Product-specific laboratory analysis	Nutritional and functional value
Economic efficiency	Equipment, energy, labor, and maintenance costs	Analysis of capital and operating costs	Investment decision-making
Food safety	Contamination, hygiene, and storage-related hazards	Sanitary control and storage monitoring	Production of safe products

Pretreatment before drying is also an important stage affecting final product quality. Sorting, washing, grading, peeling or slicing fruits, applying permitted treatments to limit enzymatic browning, and removing excess surface moisture improve process stability. For grapes, cultivar, berry size, skin thickness, and wax layer should be taken into account. When chemical or physical pretreatments are selected, food safety, residue limits, and the product's consumer qualities must be assessed together.

Drying rate alone should not be used as the principal criterion when selecting a technology. Energy consumption, energy used per kilogram of moisture removed, product rehydration, color and texture, retention of bioactive compounds, equipment capacity, maintenance costs, and seasonal workload must all be considered. An et al. (2024) emphasize the importance of evaluating drying systems through energy analysis, including comparisons between conventional and hybrid technologies.

Recommendations for selecting innovative technologies. In regions of Uzbekistan with high solar radiation, it is advisable to combine small- and medium-capacity solar dryers with thermal energy storage or a heat pump. This approach increases the use of solar energy and helps stabilize drying conditions during cloudy periods or in the evening. For high-quality products intended for export, heat-pump, vacuum, or staged hybrid drying options may be selected on the basis of an economic assessment.

It is recommended that temperature and relative-humidity sensors, scales for monitoring product mass, and instruments for measuring airflow velocity be installed in the drying chamber. The control system should adjust temperature, air velocity, and drying stages according to the type of raw material. Automatic termination of the process should be based not only on time but also, preferably, on the final moisture content or water activity of the product.

Before implementation in production, a process specification should be developed for each fruit type and grape cultivar. It should define raw-material requirements, pretreatment, piece size, temperature and

air-humidity ranges, intermediate drying controls, final moisture content, cooling, packaging, and storage conditions. After the parameters have been tested in small experimental batches, the technology should be scaled up to industrial production.

Conclusions

1. The introduction of innovative technologies for drying fruits and grapes creates important opportunities to stabilize product quality, control the process, and reduce energy consumption.

2. Solar dryers make it possible to use renewable energy, while heat-pump systems are distinguished by more precise temperature and humidity control and heat recovery. Infrared and microwave methods are promising as components of hybrid systems.

3. Vacuum and freeze-drying can be used for high-quality, heat-sensitive products; however, their economic efficiency must be assessed together with equipment costs and energy consumption.

4. In grape drying, cultivar characteristics, skin permeability to water, berry size, and pretreatment are important factors determining the technological regime. Hybrid approaches should be tested using local cultivars.

5. Under the conditions of Uzbekistan, it is recommended to introduce modular dryers combining solar energy, heat pumps, and sensor-based automatic control in stages, while assessing energy, quality, and economic indicators together.

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