UNIVERSIDADE FEDERAL DE LAVRAS

PAULA GIAROLLA SILVEIRA

EFFECTS OF ETHANOL PRETREATMENT ON THE PROPERTIES OF YACON SLICES SUBJECTED TO DIFFERENT DRYING METHODS

LAVRAS-MG
2025

PAULA GIAROLLA SILVEIRA

EFFECTS OF ETHANOL PRETREATMENT ON THE PROPERTIES OF YACON SLICES SUBJECTED TO DIFFERENT DRYING METHODS

Tese apresentada à Universidade Federal de Lavras, como parte das exigências do Programa de Pós-Graduação em Ciência dos Alimentos, para a obtenção do título de Doutora.

Prof. Dr. Jefferson Luiz Gomes Corrêa
Orientador

Prof. Dr. Irineu Petri Júnior
Coorientador

LAVRAS-MG
2025

Ficha catalográfica elaborada pelo Sistema de Geração de Ficha Catalográfica da Biblioteca Universitária da UFLA, com dados informados pelo(a) próprio(a) autor(a).

Silveira, Paula Giarolla.
Effects of ethanol pretreatment on the properties of yacon slices subjected to different drying methods/ Paula Giarolla Silveira. - 2025.
122 p. : il.

Orientador(a): Jefferson Luiz Gomes Corrêa.
Coorientador(a): Irineu Petri Júnior.
Tese - Universidade Federal de Lavras, 2025.
Bibliografia.

1. Frutooligossacarídeos. 2. Micro-ondas. 3.Secagem convectiva. I. Corrêa, Jefferson Luiz Gomes. II. Petri Júnior, Irineu. III. Título.

PAULA GIAROLLA SILVEIRA

EFEITOS DO PRÉ-TRATAMENTO COM ETANOL NAS PROPRIEDADES DE FATIAS DE YACON SUBMETIDAS À DIFERENTES MÉTODOS DE SECAGEM

EFFECTS OF ETHANOL PRETREATMENT ON THE PROPERTIES OF YACON SLICES SUBJECTED TO DIFFERENT DRYING METHODS

Thesis submitted to the Federal University of Lavras as part of the requirements of the Graduate Program in Food Science for obtaining the title of Doctor.

Aprovada em 14 de fevereiro de 2025.

Prof. Dr. Jefferson Luiz Gomes Corrêa	UFLA
Prof. Dr. Roney Alves da Rocha	UFLA
Profa. Dra. Maria José Valenzuela Bell	UFJF
Prof. Dr. Rafael Augustus de Oliveira	UNICAMP
Profa. Dra. Nádia Rosa Pereira	UENF

Prof. Dr. Jefferson Luiz Gomes Corrêa
Orientador

LAVRAS-MG
2025

Aos meus pais, que sempre priorizaram a minha educação e me forneceram o amor mais puro e genuíno.

Dedico

AGRADECIMENTOS

Agradeço primeiramente a Deus, que, ao longo de toda a minha jornada, abriu portas para que meus sonhos se tornassem realidade. Sem Ele ao meu lado, eu nada seria.

Aos meus pais, Valdemir e Talise, por serem meu refúgio nos dias difíceis e por sempre me incentivarem a seguir meus sonhos. Amo vocês.

À minha querida vó, Clere, obrigada por sempre me apoiar. A sua vida é uma dádiva para mim.

Ao meu amado irmão, Gabriel, por todo o amor dedicado a mim. Sem dúvida, dividir a vida com você torna tudo mais leve; amo poder contar sempre com você.

À minha cunhada, Aline, por ser minha irmã, conselheira e confidente. Além disso, agradeço pelo maior e mais amável presente que eu poderia receber: Pedro e Ana Elisa, meus amados sobrinhos.

À minha doce e amada sobrinha, Ana Elisa, que, mesmo tão pequenininha, é capaz de me mostrar um amor gentil e puro, que muitas vezes me deu forças para seguir em frente. Como eu amo você, minha pequena!

Ao meu namorado, Felipe Lino, por sempre me apoiar, torcer por mim e trazer alegria aos meus dias. Com você, a vida é mais leve e feliz. Amo você.

À minha querida amiga, Jana, por estar comigo desde o meu primeiro dia na UFLA e por me ensinar o valor de uma amizade verdadeira. Obrigada por sempre me apoiar.

Aos meus queridos amigos, Bruna, Ramon e Paulinha, por sempre estarem ao meu lado. Sinto-me realmente privilegiada por ter a amizade de vocês.

Ao meu querido orientador, Jefferson, por ter me ensinado tanto ao longo desses anos. Seus ensinamentos vão além da vida acadêmica; você me ensinou sobre generosidade, bondade e paciência. Escrever aqui não seria suficiente para expressar toda a minha gratidão, mas deixo o meu muito obrigado por me conduzir até aqui e por me dar tantas oportunidades.

Ao meu coorientador e grande amigo, Irineu, por sempre me ensinar com tanto carinho. Ter sua coorientação foi uma dádiva; obrigada por me ajudar a chegar até aqui.

Ao professor Roney, por ter se tornado meu amigo e por me ajudar tanto nesta jornada.

Aos meus amigos do laboratório de secagem, Amanda, Jhenifer, Matheus Cruz e Guilherme, por terem sempre me dado apoio.

À UFLA e ao DCA, pela oportunidade de aprendizado.

À CAPES, pelo auxílio financeiro.

RESUMO GERAL

Yacon é uma raiz tuberosa amplamente consumida devido ao seu alto teor de frutooligosacarídeos (FOS). Contudo, seu elevado teor de umidade (~89% b.u.) faz com que ele seja altamente perecível. A secagem é uma alternativa que promove a redução do teor de umidade, prolongando a vida útil do produto, mas degradações também ocorrem. Pré-tratamentos de secagem, como imersão em etanol, podem ser utilizados para melhoria do processamento e obtenção de um produto de qualidade. Além disso, métodos de secagem como micro-ondas intermitente são capazes de garantir menor tempo de secagem e uma maior manutenção do valor nutricional. Portanto, o presente trabalho visou investigar o efeito de diferentes métodos de secagem aplicados a fatias de yacon, bem como, o efeito do uso do etanol como pré-tratamento. Desse modo, o trabalho foi divido em três partes: no primeiro artigo foi realizada uma revisão bibliográfica abrangente sobre métodos de secagem e pré-tratamentos aplicados ao yacon, destacando lacunas e avanços na literatura; O segundo artigo investigou o impacto do pré-tratamento com etanol, na secagem convectiva e nas propriedades (cor, encolhimento, FOS, atividade antioxidante, fenóis totais, análise micro estrutural) de fatias de yacon; e o terceiro artigo trata da secagem por micro-ondas intermitente de fatias de yacon, utilizando o etanol como pré-tratamento. Neste trabalho, também foi investigado o efeito do etanol na secagem e nas propriedades. Nos ensaios de secagem convectiva, o pré-tratamento com etanol reduziu o tempo de secagem em até 28,00% e o consumo de energia em 22,72%, preservando os parâmetros de cor e encolhimento. Além disso, observou-se que temperaturas mais altas levaram à degradação de compostos bioativos. O melhor tratamento neste caso foi a secagem a 50 °C sem o uso de etanol, pois apresentou maior retenção de FOS (51,00%). Nos ensaios de secagem intermitente por micro-ondas, o uso do etanol reduziu ainda mais o tempo de secagem em até 34,62% e o consumo de energia em 32,41%, além de manter a capacidade antioxidante, os compostos fenólicos totais e a retenção de FOS especialmente. O melhor tratamento neste caso foi a 52°C com o uso do etanol. Além disso, vale ressaltar que o uso combinado do etanol e secagem por micro-ondas promoveu uma abordagem mais eficiente e sustentável, alinhada aos Objetivos de Desenvolvimento Sustentável (ODS) da ONU.

Palavras-chave: antioxidantes; secagem convectiva; frutooligossagarídeos; secagem por micro-ondas intermitente.

GENERAL ABSTRACT

Yacon is a tuberous root widely consumed due to its high content of fructooligosaccharides (FOS). However, its high moisture content (~89% w.b.) makes it highly perishable. Drying is an alternative that reduces moisture content, extending the product shelf life, although some degradation also occurs. Pre-drying treatments, such as ethanol immersion, can improve processing efficiency and contribute to obtaining a higher-quality product. Additionally, drying methods such as intermittent microwave drying can ensure shorter drying times and better preservation of nutritional value. Therefore, this study aimed to investigate the effect of different drying methods applied to yacon slices, as well as the effect of ethanol pretreatment. The work was divided into three parts: the first article presented a comprehensive literature review on drying methods and pretreatments applied to yacon, highlighting gaps and advancements in the literature. The second article investigated the impact of ethanol pretreatment on convective drying and the properties (color, shrinkage, FOS content, antioxidant activity, total phenolics, and microstructural analysis) of yacon slices. The third article addressed intermittent microwave drying of yacon slices, also using ethanol as a pretreatment. The effects of ethanol on drying and product properties were further investigated. In the convective drying trials, ethanol pretreatment reduced drying time by up to 28.00% and energy consumption by 22.72%, while preserving color and shrinkage parameters. Additionally, higher drying temperatures led to the degradation of bioactive compounds. The best treatment in this case was drying at 50°C without ethanol pretreatment, as it resulted in higher FOS retention (51.00%). In the intermittent microwave drying trials, ethanol pretreatment further reduced drying time by up to 34.62% and energy consumption by 32.41%, while preserving antioxidant capacity, total phenolic compounds, and FOS retention. The best treatment in this case was drying at 52°C with ethanol pretreatment. Furthermore, it is worth emphasizing that the combined use of ethanol pretreatment and intermittent microwave drying provided a more efficient and sustainable approach, aligning with the United Nations Sustainable Development Goals (SDGs).

Keywords: antioxidants; convective drying; fructooligosaccharides; prebiotic; intermittent microwave drying.

INDICADORES DE IMPACTO

A presente pesquisa tratou de técnicas de secagem (secagem convectiva e secagem por micro-ondas intermitente) aplicadas ao yacon, utilizando de etanol como pré-tratamento. Cabe ressaltar que a pesquisa trouxe impactos em diversas áreas, contribuindo para avanços sociais, tecnológicos e econômicos. O uso do etanol como pré-tratamento no processo de secagem foi determinante para reduzir tanto o tempo necessário quanto o consumo energético, otimizando o processo e contribuindo para uma produção mais sustentável e eficiente. Além disso, a tecnologia de secagem por micro-ondas intermitente combinada com a imersão em etanol foi capaz de manter uma maior quantidade de compostos bioativos no yacon seco quando comparada a secagem convectiva. Os impactos sociais dessa pesquisa são notáveis, visto que, a pesquisa atende as metas estabelecidas pelos Objetivos de Desenvolvimento Sustentável (ODS) das Nações Unidas. O trabalho apoia diretamente as seguintes métricas: ODS 2, "Fome Zero e Agricultura Sustentável", ao aprimorar técnicas que preservam alimentos perecíveis, diminuindo as perdas pós-colheita e possibilitando maior acesso a alimentos nutritivos ao longo do tempo; ODS 3, "Saúde e Bem-Estar", uma vez que o consumo de yacon traz benefícios à saúde; ODS 9, "Indústria, Inovação e Infraestrutura", pois promove inovações no processamento de alimentos ao incorporar novas técnicas e pré-tratamentos que tornam o processo de secagem de yacon mais eficiente e sustentável; ODS 12,"Consumo e Produção Responsáveis", pois a diminuição do consumo de energia no processo revela uma abordagem moderna para o setor alimentício. Finalmente, ao reduzir o consumo de energia, especialmente com o uso do etanol para acelerar a secagem, o trabalho contribui para o ODS 7 e 13, “Energia limpa e acessível” e "Ação Contra a Mudança Global do Clima", demonstrando que é trazer melhorias para os processos industriais, reduzir o desperdício e minimizar a pegada de carbono associada à produção de alimentos, avançando em direção a um futuro mais sustentável.

IMPACT INDICATORS

This research addressed drying techniques, specifically convective drying and intermittent microwave drying, applied to yacon, using ethanol as a pretreatment. The study had significant impacts across various fields, contributing to social, technological, and economic advancements. The use of ethanol as a pretreatment in the drying process was crucial in reducing both drying time and energy consumption, optimizing the process and supporting a more sustainable and efficient production approach. Furthermore, intermittent microwave drying technology combined with ethanol immersion was able to preserve a higher amount of bioactive compounds in dried yacon compared to convective drying. The social impacts of this research are noteworthy, as it aligns with the goals established by the United Nations' Sustainable Development Goals (SDGs). The study directly supports several metrics, including SDG 2, "Zero Hunger and Sustainable Agriculture," by enhancing techniques that preserve perishable foods, reducing post-harvest losses, and enabling greater access to nutritious foods over time. It also addresses SDG 3, "Good Health and Well-Being," since yacon consumption provides health benefits. In addition, the research aligns with SDG 9, "Industry, Innovation, and Infrastructure," by promoting innovations in food processing through the incorporation of new techniques and pretreatments that make yacon drying more efficient and sustainable. The reduced energy consumption achieved during the drying process also supports SDG 12, "Responsible Consumption and Production," by highlighting a modern approach for the food sector. Finally, by reducing energy consumption, especially through the use of ethanol to accelerate drying, this study contributes to SDG 7, "Affordable and Clean Energy," and SDG 13, "Climate Action." It demonstrates that industrial processes can be improved to minimize waste and reduce the carbon footprint associated with food production, advancing toward a more sustainable future.

LIST OF FIGURES

FIST PART

SECOND PART – ARTICLES

LIST OF TABLES

SECOND PART – ARTICLES

SUMÁRIO

FIST PART

1 GENERAL INTRODUCTION

Profound changes in the global landscape, driven by factors such as population growth, climate change, and multiple crises (wars, geopolitical conflicts, and the pandemic), have significantly altered consumer behavior (Galanakis, 2023). These changes intensified the pressure on resource management asked for the production of safe, nutritious, and sustainable food (Galanakis, 2024). In this context, scientific goals have been established to encourage research focused on the production of functional and nutrient-rich foods, particularly those abundant in bioactive compounds (Galanakis, 2023). Furthermore, the rising demand for high-nutritional-value foods is closely linked to the prevalence of chronic diseases as a leading global cause of mortality, prompting individuals to adopt health-oriented strategies. Consequently, consumers have increasingly turned to the active role of natural supplements (Boyaci-Gunduz *et al.*, 2021).

In response to these changes, prebiotic foods like yacon became significantly. Yacon (*Smallanthus sonchifolius*) is a tuberous root with fructooligosaccharides (FOS) as its storage primarily carbohydrates. FOS are associated with modulating blood insulin levels, inhibiting gluconeogenesis in liver cells, and promoting weight loss, making it a suitable low-calorie sweetener (Zambrana *et al.*, 2021). Additionally, yacon is a source of antioxidants, which, as noted by Sharma *et al.* (2024), confer anti-carcinogenic properties to the food.

The consumption of yacon dates back to 1615 in the Andes region (Oliveira *et al.*, 2021). However, its global popularity is merged to recent consumer trends, making it available in countries like Brazil, the Czech Republic, Germany, Japan, and New Zealand (Reis *et al.*, 2021). Despite its availability, yacon consumption remains seasonal due to its limited harvest period and its highly perishable nature, the latter primarily attributed to its high moisture content (approximately 89% w.b.). This highlights the need for technologies that extend its shelf life, improving the logistic aspect (Silveira *et al.*, 2024b).

Food drying is one of the oldest techniques used to extend the shelf life of foods by reducing their moisture content. Thereby, it, decreases susceptibility to microbial spoilage and chemical reactions (Corrêa *et al.*, 2021). Despite, prolonged drying times or excessively high temperature are used to degrade heat-sensitive compounds, leading to nutritional losses (Silveira *et al.*, 2024b). Thus, it is essential to develop methods that get around the drying disadvantages and preserve the nutritional value of foods.

Marques *et al.* (2023, 2022) and Lisboa *et al.* (2018) studied the convective drying of yacon slices but did not evaluate the impact of processing on its nutritional value, such as FOS content, antioxidant capacity, and total phenolics. Lopes *et al.* (2024) investigated microwave drying of yacon slices following vacuum pulse osmotic dehydration. While they assessed FOS content, they did not examine changes in the food antioxidant potential. Therefore, further exploration of the effects of drying on yacon nutritional value is needed.

Macedo *et al.* (2021) emphasize that intermittent microwave drying (IMWD) is an effective method for preserving nutritional value by preventing overheating and protecting heat-sensitive compounds. Additionally, the authors used ethanol pretreatment that reduced drying time and energy consumption. The Marangoni effect that occurs due to the immersion in ethanol caused by the surface tension gradient between moisture and ethanol. It aids, the evaporation of the moisture from the food internal layers during drying (Guedes *et al.*, 2021). The combined application of those technologies to yacon slices were still unexplored.

Given this background, the present study aimed to: 1 - conduct a literature review on drying techniques and pretreatments applied to yacon roots; and 2 - evaluate the effects of ethanol pretreatment in two drying methods: convective drying and intermittent microwave drying. Additionally, this study seeks to assess the impact of the pretreatment on quality parameters (color, shrinkage, FOS retention, antioxidant capacity, and total phenolics) and process parameters (drying time, energy consumption, and drying kinetics) for both drying techniques.

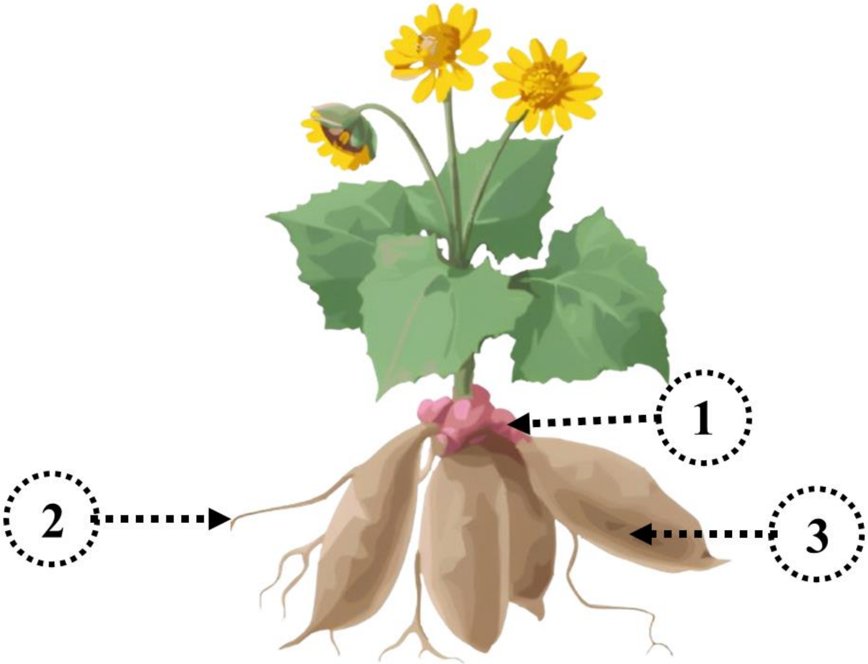
2 THEORETICAL FRAMEWORK

Understanding the characteristics of the product and the processes involved in drying ethanol-pretreated yacon slices requires a thorough literature review.

2.1 Yacon

Yacon (*Smallanthus sonchifolius*) (Figure 1) is a species in the Asteraceae family that can grow up to 2.5 m tall in its mature stage (Kamp *et al.*, 2019). The mature plant features a root system composed of three main structures: rhizophores, roots, and tuberous storage roots (Silva *et al.*, 2018). Each plant develops 4 to 20 tuberous roots, measuring 10 to 25 cm in diameter and weighing between 200 and 2000 g per unit. These tuberous roots are the most valued parts for human consumption (Reis *et al.*, 2021).

Figure 1 – Illustration of a yacon plant.



Caption: Rhizophores (1), Roots (2), Tuberous root (3).
Source: Author (2024).

Yacon tuberous roots contain between 10% and 20% dry matter, with carbohydrates as their primary component (Lopes *et al.*, 2024). These roots predominantly store carbohydrates in the form of FOS, which are inulin-type fructans with a low degree of polymerization. Fructans are fructose polymers that play a crucial role as carbohydrate reserves (Mendonça *et* *al.*, 2016). In addition to FOS, simple sugars such as fructose, glucose, and sucrose are also found in yacon storage tissues (Zambrana *et al.*, 2021). However, the composition of these sugars can vary significantly depending on factors such as the cultivar, planting and harvesting season, and post-harvest temperature and time conditions (Oliveira; Nashimoto, 2005).

FOS are considered non-toxic, non-digestible, and contribute a sweet flavor to vegetables. Moreover, these fructans give yacon its prebiotic character, as they serve as fermentable substrates for beneficial bacteria in the gut microbiota of the large intestine (Sharma *et al.*, 2024). These bacteria produce short-chain fatty acids (SCFAs) as secondary metabolites, which have a modulatory effect on metabolism. SCFAs are transported via the bloodstream to the liver, where they regulate lipid metabolism. This process also contributes to lowering the pH in the large intestine, eliminating putrefactive microbiota that produce toxic metabolites such as ammonia, indole, phenols, and nitrosamines (Silva *et al.*, 2018). Additionally, FOS are responsible for reducing blood glucose levels (Zambrana *et al.*, 2021).

In this context, the consumption of yacon stands out for its importance in promoting human health. Therefore, the use of technologies to make this food more accessible worldwide and extend its shelf life is essential.

2.1.1 Stability of bioactive compounds in yacon roots

The primary bioactive compounds in yacon roots are FOS and phenolic compounds. The concentration of FOS varies according to the plant developmental stage, as the sugar profile changes due to polysaccharide depolymerization (Marques *et al.*, 2021). The ideal harvesting time for yacon, in terms of FOS content, is approximately eight months after planting (Oliveira; Nashimoto, 2005).

Harvesting activates the enzyme fructan hydrolase, leading to the hydrolysis of FOS molecules into simple sugars (glucose and fructose), which may compromise the functional properties of yacon (Sanín; Navia; Serna-Jiménez, 2020). After one week of storage at room temperature (25°C), about 30–40% of the FOS are converted into simple sugars (Marques *et al.*, 2021). Refrigerated storage (5–10°C) at a relative humidity of approximately 80% reduces depolymerization rates, thereby extending the product shelf life. However, even under refrigerated conditions, FOS degradation cannot be entirely prevented (Oliveira; Nashimoto, 2005).

Phenolic compounds in yacon roots are susceptible to changes during post-harvest stages due to oxidation or enzymatic browning caused by cutting, processing, or storage of the tuberous roots (Silveira *et al.*, 2024a). These reactions are catalyzed by the highly active enzymes polyphenol oxidase (PPO) and peroxidase (POD) in yacon. PPO oxidizes phenolic compounds into orthoquinones, which polymerize into dark pigments known as melanins (Lopes *et al.*, 2024). POD contributes to undesirable flavor development in vegetables by utilizing hydrogen peroxide as a substrate or oxygen as a hydrogen acceptor during oxidation reactions (Macedo *et al.*, 2022).

Various techniques have been employed to preserve the post-harvest quality of yacon, such as drying (Lopes *et al.*, 2024), osmotic dehydration (Mendonça *et al.*, 2016; Corrêa *et al.*, 2021; Oliveira *et al.*, 2016), and blanching (Martins *et al.*, 2022; Campos; Aguilar-Galvez; Pedreschi, 2016). Among these, drying stands out as the most effective method for extending the shelf life of yacon. However, no studies in the literature have explored the use of ethanol as a pretreatment combined with convective drying or IMWD. This approach could be a promising alternative, accelerating the drying process and reducing energy consumption.

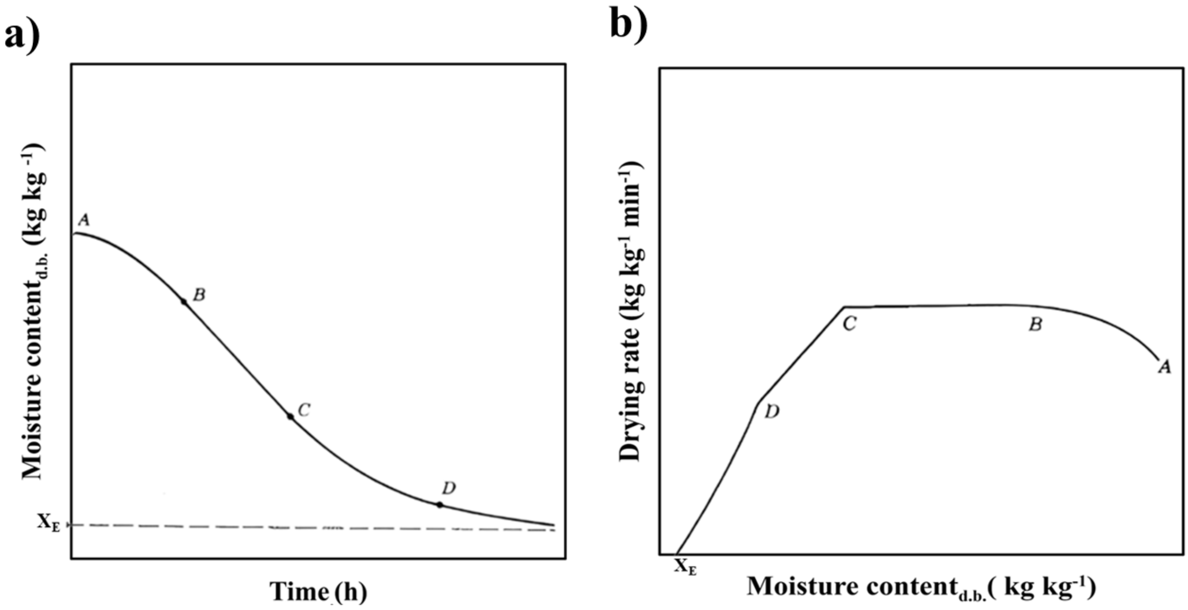
2.2 Drying

Drying is a unit operation aimed at reducing moisture content, thereby slowing microbial or enzymatic degradation reactions (Corrêa *et al.*, 2017; Silveira *et al.*, 2024a). This process involves transferring water from the material to an unsaturated gas phase. Generally, moisture removal occurs through evaporation, requiring the application of thermal energy to induce a phase change from liquid to vapor (Tadini *et al.*, 2016).

Drying curves, under constant air velocity, temperature, and relative humidity conditions, exhibit three distinct periods: transient (A→B), constant rate (B→C), and falling rate ($C \rightarrow X_E$) (Figure 2a) (Foust *et al.*, 1982). The transient period (A→B) corresponds to the initial heating of the material and an increase in the drying rate. During the constant rate period (B→C), moisture is primarily removed from the surface, where it is most readily available. This stage continues until the internal moisture is sufficiently reduced, limiting it diffusion to the surface. For materials where mass transport occurs by diffusion, such as fibrous organic solids, this interval is generally short and dependent on air conditions (Geankoplis, 2006). According to Mujumdar (2014), the constant rate period may not occur in all materials, as it depends on physical and structural characteristics, such as porosity and the type of moisture bonding.

During the falling rate period ($C \rightarrow X_E$), water is extracted from internal regions, where it is more strongly bound, requiring higher energy for removal. The moisture content versus drying rate curve (Figure 2b) also illustrates these stages, aiding in characterizing the material behavior during the process.

Figure 2 - Drying kinetics.



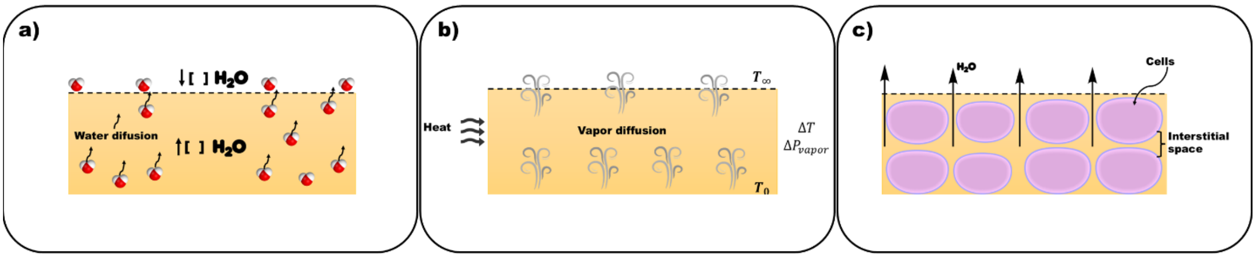
Caption: Drying time versus moisture content curve of the solid (a) and drying rate versus moisture content curve (b).

Source: Author (2024).

If the resistive forces to mass transfer exceed the energy required for water vaporization at the solid surface, a decrease in the drying rate is observed, as shown in the C→D interval in both graphs. Since less energy is required to vaporize the remaining moisture, the solid temperature begins to rise. Beyond point D, the moisture content in the solid is very low, and no saturated area remains on its surface. Drying continues until it reaches the equilibrium moisture content (X_E), where the vapor pressure within the solid equals the partial vapor pressure in the air (Foust *et al.*, 1982).

During the drying stages, the following mechanisms of water removal occur: liquid diffusion, vapor diffusion due to partial vapor pressure gradients, liquid movement driven by capillary forces, and liquid or vapor movement caused by total pressure differences. These mechanisms are illustrated in Figure 3.

Figure 3 - Internal mechanisms of water removal.



Source: Author (2024).

In liquid diffusion (Figure 3a), water moves through the solid due to a concentration gradient, from the inner regions of the solid, where water concentration is high, to the surface, where it is lower.

In vapor diffusion driven by partial vapor pressure gradients (Figure 3b), water migrates within the solid in vapor form due to these gradients. A temperature gradient created by heating generates a vapor pressure gradient. The movement of vapor can be explained by the Knudsen diffusion mechanism, which states that vapor flow depends on the concentration and diffusivity of vapor within the solid. These properties are influenced by the average pore diameter, porosity, tortuosity, and geometric shape of the solid. Knudsen diffusion is governed by collisions between gas molecules and pore walls, prevailing when the mean free path of molecular collisions exceeds the pore diameter. In this case, molecules collide more frequently with pore walls than with other molecules. This mechanism is significant only under high vacuum conditions, such as in freeze-drying or vacuum oven drying (Tadini *et al.*, 2016).

Capillary-driven liquid movement (Figure 3c) occurs as liquid flows through interstices and capillaries due to molecular attraction between the solid and the liquid. As water is removed from the pores, the curvature of the liquid–gas interface increases, creating capillary pressure that drives liquid suction into the capillaries (Guedes *et al.*, 2021; Rojas; Augusto; Cárcel, 2021).

Liquid or vapor movement caused by total pressure differences arises from factors such as external forces, shrinkage, high temperatures, and capillarity. High temperatures can significantly increase pressure, and this pressure gradient acts as the driving force for vapor movement. The vapor, in turn, exerts pressure on the liquid, inducing liquid flow within the porous material (Rojas; Augusto; Cárcel, 2021).

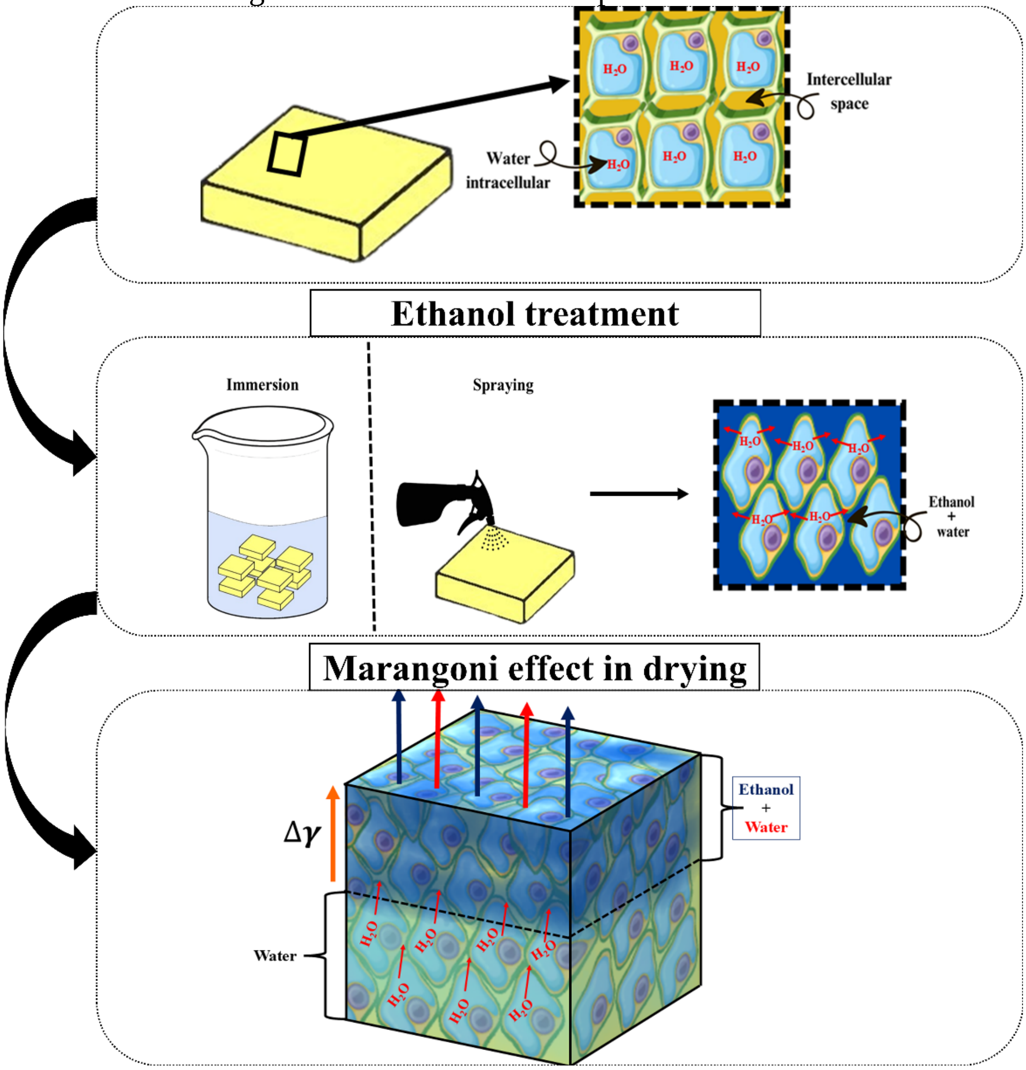
In this context, these mechanisms not only explain the drying dynamics but also help in understanding the transformations foods undergo during the process. Drying inevitably extends beyond simple water removal, leading to physical, sensory, and nutritional changes, which are often undesirable and irreversible, even after rehydration (Macedo *et al.*, 2021). This underscores the complexity of a process that must be tailored to the specific needs of each food. Over the years, various drying methods have been developed, aiming not only for efficient water removal but also for minimizing these changes, thereby preserving the beneficial properties of the product as much as possible (Corrêa *et al.*, 2021; Oliveira *et al.*, 2021; Silveira *et al.*, 2024a, 2024b).

2.2.1 Ethanol pretreatment

In recent years, the use of drying pretreatments has become increasingly widespread (Mello *et al.*, 2021). Techniques such as ultrasound application (Mello *et al.*, 2020), pulsed electric fields (Alam *et al.*, 2018), high pressures (Codina-Torrella, 2018; Evelyn; Silva, 2019; Irna *et al.*, 2018), or ethanol pretreatments (Araújo *et al.*, 2022; Bitencourt *et al.*, 2022; Corrêa *et al.*, 2012; Souza *et al.*, 2018; Macedo *et al.*, 2023, 2021; Silveira *et al.*, 2024a, 2024b) do not involve high temperatures but can reduce drying time, improve the final product quality, and decrease energy consumption. Thus, they are considered more environmentally friendly technologies (Guedes *et al.*, 2021).

Ethanol has been widely used as a pretreatment due to its low cost and non-toxic properties (Guedes *et al.*, 2021). Adding ethanol as a pretreatment can induce the Marangoni effect (Figure 4), which promotes mass transfer at the interface between two fluids with different surface tensions. This effect can occur during drying, where ethanol vaporizes first, leaving water on the sample surface and creating a water/ethanol concentration gradient. This process generates a constant flow until a surface tension equilibrium is achieved (Macedo *et al.*, 2023).

Figure 4 - Effects of Ethanol pretreatment.



Source: Author (2024).

The structural changes caused by ethanol use can be attributed to the extraction of certain components from the cell wall and/or membrane, thinning these structures (Santos *et al.*, 2021). Additionally, cells lose turgor, altering their original shape and becoming more distorted and compact. These permanent structural modifications facilitate water removal during drying (Guedes *et al.*, 2021; Silveira *et al.*, 2024a).

The plant cell wall and membrane have diverse compositions. According to Rojas, Augusto and Cárcel (2021), ethanolic solutions can extract polyphenols, certain proteins, and lipids from the cell walls and/or membranes. However, compounds related to the structural integrity of the cell wall, such as cellulose, lignin, and hemicellulose, remain intact. Maintaining the overall cellular structure while thinning the walls prevents collapse and ensures better water flow during drying.

Given ethanol effects on cell wall composition and thickness, osmotic dehydration during pretreatment, and the Marangoni effect, studies by Araújo *et al.* (2022), Guedes *et al.* (2021), Macedo *et al.* (2023, 2021), Rojas, Augusto and Cárcel (2021), and Santos *et al.* (2021) attribute ethanol ability to reduce drying time and, consequently, increase drying rates. This reduction in drying time is evident from changes in the slope of the moisture variation curve over time, particularly during the initial drying phase when temperature and drying rates increase.

Junqueira *et al.* (2021) evaluated the effects of ethanol on antioxidant capacity and phenolic content in dried taioba leaves. While ethanol positively reduced drying time, it also decreased antioxidant activity and phenolic content. According to the authors, these effects result from structural changes induced by ethanol. Phenolic compounds, typically stored within vacuoles alongside enzymes and oxygen, are released due to irreversible structural alterations, leading to decompartmentalization. This triggers the release of enzymes, primarily polyphenol oxidase and peroxidase, which facilitate degradative reactions, ultimately reducing total phenolic content. Furthermore, antioxidant activity loss is associated with damage to the food matrix. In contrast, Macedo *et al.* (2023) found that ethanol positively preserved antioxidant capacity and phenolic content. Ethanol role in preserving bioactive compounds and antioxidants may be linked to its ability to reduce drying time, thereby limiting exposure to hot air. Additionally, shorter immersion times during pretreatment help avoid bioactive compound leaching and extraction.

Cunha *et al.* (2020) observed that ethanol could alter food color, particularly reducing the L^* parameter (lightness), indicating darkening in treated samples. This effect may be related to the reduction of photochemically active compounds, such as carotenoids.

Studies have also reported beneficial effects of ethanol pretreatment on the drying of apples (Rojas; Augusto; Cárcel, 2020), melons (Cunha *et al.*, 2020), dragon fruit (Araújo *et al.*, 2022), and potatoes (Guedes *et al.*, 2021). These studies highlighted reduced drying time and improved preservation of bioactive compounds in these foods. In this context, ethanol pretreatment emerges as a promising strategy for reducing drying time and energy consumption while preserving bioactive compounds, resulting in highly nutritious dried foods.

2.2.2 Convective drying

Convective drying is the most common method used to extend the shelf life of food products (Corrêa *et al.*, 2021). In this process, heated air is directed toward the food, creating a moisture gradient that acts as the driving force for mass transfer (Junqueira *et al.*, 2021). During the initial drying stage, as surface moisture is removed, the solid surface reaches the wet-bulb temperature, which corresponds to the air local temperature and humidity. In the falling rate period, as free water diminishes and heat transfer is no longer controlled by surface evaporation, the solid temperature rises and can approach the dry-bulb temperature of the drying air (Mujumdar, 2014).

Operational parameters such as air temperature and velocity play a crucial role in convective drying processes, as they control the thermal driving force and evaporation rate. Air velocity regulates vapor removal efficiency from the surface, directly impacting the drying rate during the initial stage (Corrêa *et al.*, 2017). Thus, controlling these parameters significantly affects drying time and changes in the properties of dried foods, including color, texture, and nutritional value (Macedo *et al.*, 2023). In addition to operational parameters, structural changes in the food matrix caused by pretreatments can also influence drying kinetics and the quality of the dried product (Silveira *et al.*, 2024a).

Santos *et al.* (2024) investigated the convective drying of acerola residues in a wind tunnel at air velocities of 1 m/s and temperatures of 40°C and 60°C. They observed that 60°C was more efficient, reducing internal resistance to moisture removal due to increased water molecule mobility and a greater mass transfer driving force.

Menezes *et al.* (2013) explored the convective drying of yellow passion fruit peel in a fixed bed, evaluating temperatures (35, 45, 55, and 65°C) and air velocities (0.8, 1.0, and 1.3 m/s). They found that temperature was the most influential factor, significantly reducing drying time, increasing drying rates, and enhancing effective diffusivity. The combination of 55°C and 1.3 m/s was deemed the most efficient, balancing lower energy consumption with reduced drying time.

Junqueira *et al.* (2017) studied the effects of physical pretreatments (rapid freezing with liquid nitrogen and slow freezing) and chemical pretreatments (immersion in an alkaline solution of ethyl oleate) on the convective drying of cape gooseberries. The pretreatments reduced drying time by up to 30%, with ethyl oleate being the most effective. Additionally, pretreatments decreased shrinkage, improved rehydration capacity, and preserved ascorbic acid while reducing water activity. However, they also caused more pronounced changes in texture and color, particularly with physical pretreatments. The authors concluded that ethyl oleate is the best option for optimizing efficiency and quality in the convective drying of cape gooseberries.

Macedo *et al.* (2021) evaluated the impact of different pretreatments, including osmotic dehydration-OD, pulsed vacuum osmotic dehydration-PVOD, and ethanol immersion-ET, on the convective drying of strawberries. Their study focused on drying kinetics and final product quality. Principal component analysis showed that strawberries pre-treated with ethanol, without osmotic dehydration, exhibited the best results in preserving bioactive compounds. The authors concluded that ethanol pretreatment is a promising strategy for optimizing convective drying, while osmotic dehydration is better suited for enriching the product with isomaltulose.

Silveira *et al.* (2024a) investigated the convective drying of yacon slices in a wind tunnel at different temperatures (50°C and 70°C), with a constant air velocity of 1 m/s, both with and without ethanol pretreatment-ET. The authors found that ET reduced drying time by up to 28% and energy consumption by 22.72%. While drying at 50°C without ET retained the highest FOS content (55.11%), ET at 50°C achieved a balance between energy savings and antioxidant preservation.

In conclusion, convective drying is an excellent method for extending the shelf life of food products. Process parameters have a significant influence on drying kinetics and the quality of the final product. Furthermore, the use of pretreatments, such as ethanol immersion, has proven to be an effective strategy to enhance the process by reducing energy consumption, preserving nutritional value, and improving product quality, as demonstrated by Macedo *et al.* (2021).

2.2.3 Microwave drying

Microwaves are electromagnetic waves with frequencies ranging from 300 to 300,000 MHz. According to the United States Federal Communications Commission (FCC), microwaves are categorized into three bands: Ultra High Frequencies (300–3,000 MHz), Super High Frequencies (3,000–30,000 MHz), and Extra High Frequencies (30,000–300,000 MHz) (Alves; Petri Júnior, 2021).

The frequency range used for microwaves must comply with FCC regulations and international radio laws, where permitted frequencies are divided into categories for industrial (915 MHz), domestic (2,450 MHz), and medical (5,800 and 24,125 MHz) applications. The predominant frequency for domestic microwave ovens is 2,450 MHz, as this frequency aligns with the resonance of water molecules (Silveira Felipe *et al.*, 2022).

Microwave heating occurs through the rotation of molecular dipoles. As an electromagnetic wave propagates through space, it generates oscillations in the electromagnetic field of the region it traverses. Dipoles in molecules tend to align with the magnetic field, following the electromagnetic wave. This rotation increases the kinetic energy of the molecules, raising the temperature (Petri Júnior *et al.*, 2019). Additionally, charged particle oscillation can occur, where heat is generated through frictional losses caused by the migration of dissolved ions under the influence of an electromagnetic field. These losses depend on factors such as the size, charge, and conductivity of the ions, as well as their interaction with the solvent. As a result, microwave heating is considered selective, as molecules with a higher affinity for microwaves heat more quickly than those with lower affinity (Petri Júnior, 2017).

Polar compounds, such as H_2O, HCl, and CH_3OH, generally exhibit high microwave absorption capacity. In contrast, less polar compounds or those with zero dipole moments, such as C_7H_{16}, CCl_4, and CO_2, have low microwave absorption. Crystalline materials with highly organized structures are considered transparent to microwaves, as they allow electromagnetic waves to pass through with minimal absorption (insulators). Metals, on the other hand, reflect electromagnetic waves (conductors) and are not heated by them, making them suitable for constructing waveguide cavity walls (Silveira Felipe *et al.*, 2022).

Materials are classified as insulators or conductors based on their dielectric properties, which quantify their interaction with an applied electromagnetic field. These properties determine how quickly a material will heat when exposed to electromagnetic waves, making them a key factor in distinguishing good absorbers from poor absorbers (Gu *et al.*, 2021).

The main dielectric properties are relative electric permittivity (ε), relative dielectric constant (ε'), relative dielectric loss factor (ε''), and loss tangent (tan δ) (Ran *et al.*, 2019). Relative electric permittivity is defined by Equation 1.

$$\varepsilon = \varepsilon' + j\varepsilon'' \qquad (1)$$

Where j represents the imaginary unit.

The loss tangent (tg δ) indicates a material ability to convert absorbed energy into heat. Materials with tg δ > 0.1 efficiently absorb microwave energy and transform it into heat. Conversely, materials with tg δ < 0.1 are considered insulators, meaning they are transparent to microwaves. Therefore, the higher the tg δ value, the better the material is at absorbing microwave energy (Ma *et al.*, 2020). The loss tangent (tg δ) is defined by Equation 2.

$$\mathrm{tg}\,(\delta) = {}^{\varepsilon''}/_{\varepsilon'} \qquad (2)$$

When a material is considered a microwave absorber, the parameter known as penetration depth (D_{p}) must be evaluated. This parameter indicates the distance from the material surface at which the absorbed energy decreases to $^{1}/_{e}$ $(0{,}368)$ of the energy value at the surface. D_{p} can be calculated using Equation 3.

$$D_{\mathrm{p}} = \frac{\lambda}{2\pi\sqrt{2\varepsilon'}}\frac{1}{\sqrt{\{[1+(tg\ (\delta))^{2}]^{0,5}-1\}}} \tag{3}$$

Where λ corresponds to wavelength and can be calculated by Equation 4.

$$\lambda = {^{c}/_{f}} \tag{4}$$

Where *c* corresponds to the speed of light in a vacuum (299,792,458 m/s) and *f* is the wave frequency.

If ε" ≤ ε', Equation 4 can be simplified to Equation 5 with a margin of error of 10%

$$D_{p} = \frac{\lambda\sqrt{\varepsilon'}}{2\pi\varepsilon''} \tag{5}$$

Microwave drying has proven to be an excellent method for obtaining nutrient-rich dried foods. Several studies have demonstrated its effectiveness for drying various products, including strawberries, yacon, Peruvian carrots, carrots, and sweet potatoes. Macedo *et al.* (2023) investigated intermittent microwave drying (IMWD) and hot air drying (HAD) of fresh strawberries impregnated with isomaltulose (35% osmotic solution). They found that IMWD significantly reduced drying time by up to 64.91% and energy consumption by 73.16%, while maintaining a target temperature of 60°C. Although osmotic impregnation extended drying time, it minimized shrinkage, while untreated strawberries dried with IMWD retained higher levels of bioactive compounds, including 47.46% of anthocyanins, 70.26% of phenolics, and 81.18% of antioxidant capacity.

Silveira *et al.* (2024b) evaluated IMWD combined with ethanol pretreatment, focusing on the preservation of bioactive compounds and process efficiency. Ethanol immersion at 99.8% for 2 minutes at 25°C reduced drying time by 34.62% and energy consumption by 32.41%. This pretreatment also enhanced the retention of total phenolics (up to 77.5%), antioxidant capacity (73.9%), and fructans (64.1%). Lopes *et al.* (2024) investigated vacuum microwave drying (MWV) of yacon slices with and without pulsed vacuum osmotic dehydration (PVOD) as a pretreatment. The PVOD, performed with a sorbitol solution at 38 °Brix under a pressure of 681 mmHg for 10 minutes, reduced drying time by 36.5%, improved FOS retention up to 95.74%, and minimized sample shrinkage.

Mendonça *et al.* (2023) explored the impact of different drying methods on the quality of Peruvian carrot chips. They compared microwave (MW), MWV, and convective drying (CD). The MWV method, particularly at 400 W under 26.5 kPa pressure, stood out by preserving phenolics, β-carotene, and color while significantly reducing drying time to as little as 6 minutes, compared to 120 minutes for CD at 70°C. The MWV at 100 W was identified as the optimal method, ensuring superior nutritional and physical quality, including lower volumetric shrinkage, crispier texture, and greater retention of heat-sensitive nutrients.

Souza *et al.* (2022) assessed the effects of osmotic dehydration followed by hybrid microwave and hot air drying on carrot slices. Operating conditions included osmotic dehydration in a ternary solution (sucrose and sodium chloride) at 35°C for 300 minutes, microwave drying at three power levels (55.7, 167.9, and 336.8 W), and final hot air drying at 70°C and 1.5 m/s. The hybrid approach improved moisture diffusivity and carotenoid retention, reducing total drying time by up to 54% compared to hot air drying alone.

Junqueira *et al.* (2022) examined the effects of osmotic dehydration as a pretreatment for sweet potato slices followed by microwave drying. They tested two osmotic agents (sucrose and sorbitol) and different power densities (5.1 and 10 W/g). Sucrose at 10 W/g proved most effective, reducing drying time to 360 minutes, lowering specific energy consumption to 7.702 MJ/kg of water, and achieving the highest energy efficiency at 29.30%. The pretreatment enhanced water loss, increased effective diffusivity, and shortened drying time.

These studies highlight the potential of microwave drying as a promising alternative for obtaining dried foods with high nutritional value. The combination of this technology with pretreatments, such as ethanol immersion, presents a particularly effective approach. Further investigations into this synergistic combination are necessary to optimize the process and enhance its benefits.

REFERENCES

ALAM, Md Rizvi *et al*. Effect of pulsed electric field pretreatment on drying kinetics, color, and texture of parsnip and carrot. **Journal of Food Science**, [United States], v. 83, n. 8, p. 2159–2166, July 2018.

ALVES, Gabrielle Medeiros; PETRI JÚNIOR, Irineu. Microwave remediation of oil-contaminated drill cuttings – A review. **Journal of Petroleum Science and Engineering**, [Netherlands], v. 207, Dec. 2021.

ARAÚJO, Cintia da Silva. *et al*. Influence of pretreatment with ethanol and drying temperature on physicochemical and antioxidant properties of white and red pulp pitayas dried in foam mat. **Drying Technology**, [United States], v. 40, n. 3, p. 484–493, Sept. 2022.

BITENCOURT, Bruna Sousa *et al*. Valorization of pineapple pomace for food or feed: Effects of pretreatment with ethanol on convective drying and quality properties. **Waste and Biomass Valorization**, [Netherlands], v. 13, p. 2253–2266, Jan. 2022.

BOYACI-GUNDUZ, Cennet Pelin *et al*. Transformation of the food sector: Security and resilience after the COVID-19 pandemic. **Foods**, [Switzerland], v. 10, n. 3, Feb. 2021.

CAMPOS, David; AGUILAR-GALVEZ, Ana; PEDRESCHI, Romina. Stability of fructooligosaccharides, sugars and colour of yacon (*Smallanthus sonchifolius*) roots during blanching and drying. **International Journal of Food Science and Technology**, [England], v. 51, n. 5, p. 1177–1185, May 2016.

CODINA-TORRELLA, I. *et al*. Microbiological stabilization of tiger nuts' milk beverage using ultra-high pressure homogenization: A preliminary study on microbial shelf-life extension. **Food Microbiology**, [England], v. 69, p. 143–150, Feb. 2018.

CORRÊA, Jefferson Luiz Gomes *et al*. The influence of ethanol on the convective drying of unripe, ripe, and overripe bananas. **Drying Technology**, [United States], v. 30, n. 8, p. 817–826, May 2012.

CORRÊA, Jefferson Luiz Gomes *et al*. Dried yacon with high fructooligosaccharide content. **Journal of Food Process Engineering**, [United States], v. 44, n. 1, Oct. 2021.

CORRÊA, Jefferson Luiz Gomes *et al*. Influence of ultrasound application on both the osmotic pretreatment and subsequent convective drying of pineapple (*Ananas comosus*). **Innovative Food Science & Emerging Technologies**, [Netherlands], v. 41, p. 284–291, June 2017.

CUNHA, Renata Masur Carneiro da *et al*. Effect of ethanol pretreatment on melon convective drying. **Food Chemistry**, [England], v. 333, Dec. 2020.

EVELYN, Evelyn; SILVA, Filipa V. M. Heat assisted HPP for the inactivation of bacteria, moulds and yeasts spores in foods: Log reductions and mathematical models. **Trends in Food Science & Technology**, [England], v. 88, n. 8, p. 143–156, June 2019.

FOUST, Alan S. *et al*. **Princípios das operações unitárias.** 2. ed. Rio de Janeiro: LTC, 1982. 670 p.

GALANAKIS, Charis M. The “Vertigo” of the food sector within the triangle of climate change, the post-pandemic world, and the Russian-Ukrainian war. **Foods**, [Switzerland], v. 12, n. 4, Feb. 2023.

GALANAKIS, Charis M. The future of food. **Foods**, [Switzerland], v. 13, n. 4, Feb. 2024.

GEANKOPLIS, Christie J. **Transport Processes and Unit Operations**. 3rd ed. New Jersey: Prentice-Hall International, Inc., 2006. 921 p.

GU, Yuxiang *et al*. Cold plasma enzyme inactivation on dielectric properties and freshness quality in bananas. **Innovative Food Science & Emerging Technologies**, [Netherlands], v. 69, May 2021.

GUEDES, Jaqueline S. *et al*. Structural modification on potato tissue and starch using ethanol pretreatment and drying process. **Food Structure**, [Netherlands], v. 29, July 2021.

IRNA, Cicy *et al*. Comparison between high-pressure processing and chemical extraction: Astaxanthin yield from six species of shrimp carapace. **Journal of Dietary Supplements**, [Netherlands], v. 15, n. 6, p. 805–813, Nov. 2018.

JUNQUEIRA, João Renato de Jesus *et al*. Ethanol pretreatment in taioba leaves during vacuum drying. **Ciência e Agrotecnologia**, Lavras, v. 45, Nov. 2021.

JUNQUEIRA, João Renato de Jesus *et al*. Convective drying of cape gooseberry fruits: Effect of pretreatments on kinetics and quality parameters. **LWT - Food Science and Technology**, [England], v. 82, p. 404–410, Sept. 2017.

JUNQUEIRA, João Renato de Jesus *et al*. Microwave drying of sweet potato: Drying kinetics and energetic analysis. **Australian Journal of Crop Science**, [Australia], v. 16, n. 10, p. 1185–1192, Jan. 2022.

KAMP, Larissa *et al*. Plant growth, tuber yield formation and costs of three different propagation methods of yacon (*Smallanthus sonchifolius*). **Industrial Crops and Products**, [Netherlands], v. 132, p. 1-11, June 2019.

LISBOA, Cícera G. C. de *et al*. Effective diffusivity in yacon potato cylinders during drying. **Revista Brasileira de Engenharia Agrícola e Ambiental**, Campina Grande, v. 22, n. 8, p. 564–569, Aug. 2018.

LOPES, Francemir José *et al*. Microwave-vacuum drying of pulsed vacuum osmotic dehydration-pretreated Yacon as an alternative for preserving fructo-oligosaccharides. **Ciência e Agrotecnologia**, Lavras, v. 48, Apr. 2024.

MA, Xiaotong *et al*. Microwave power control scheme for potatoes based on dielectric loss factor feedback. **Journal of Food Engineering**, [England], v. 288, Dec. 2020.

MACEDO, Leandro Levate *et al*. Process optimization and ethanol use for obtaining white and red dragon fruit powder by foam mat drying. **Journal of Food Science**, [United States], v. 86, n. 2, p. 426–433, Feb. 2021.

MACEDO, Leandro Levate *et al*. Convective drying with ethanol pretreatment of strawberry enriched with isomaltulose. **Food and Bioprocess Technology**, [United States], v. 14, n. 6, p. 2046–2061, Nov. 2021.

MACEDO, Leandro Levate *et al*. Use of ethanol to improve convective drying and quality preservation of fresh and sucrose and coconut sugar-impregnated strawberries. **Food and Bioprocess Technology**, [United States], v. 16, p. 2257-2271, Mar. 2023.

MACEDO, Leandro Levate *et al*. Intermittent microwave drying and heated air drying of fresh and isomaltulose (Palatinose) impregnated strawberry. **LWT - Food Science and Technology**, [England], v. 155, Feb. 2022.

MARQUES, Bianca *et al*. Evidence of iso-volume deformation during convective drying of yacón: An extended van Meel model adapted to large volume reduction. **Journal of Food Engineering**, [England], v. 341, Mar. 2023.

MARQUES, Bianca Cristine *et al*. Convective drying of yacón (*Smallanthus sonchifolius*) slices: A simple physical model including shrinkage. **LWT - Food Science and Technology**, [England], v. 159, Apr. 2022.

MARQUES, Caroline *et al*. Long-term storage of yacon (*Smallanthus sonchifolius*) juice: Phytochemical profile, in vitro prebiotic potential, and discriminant bioactive properties. **Food Bioscience**, [Netherlands], v. 41, June 2021.

MARTINS, Alisson F. L. *et al*. Use of ultrasound and ethanol to improve the drying of yacon potato (*Smallanthus sonchifolius*): Effect of chemical and thermal bleaching. **LWT - Food Science and Technology,** [England], v. 162, n. 8, Apr. 2022.

MELLO, Ronaldo E. *et al*. Ultrasound-assisted drying of orange peel in atmospheric freeze-dryer and convective dryer operated at moderate temperature. **Drying Technology**, [United States], v. 38, n. 1-2, p. 259–267, July 2020.

MELLO, Ronaldo E. *et al*. PEF as pretreatment to ultrasound-assisted convective drying: Influence on quality parameters of orange peel. **Innovative Food Science & Emerging Technologies**, [Netherlands], v. 72, Aug. 2021.

MENDONÇA, Kamilla Soares de *et al*. Optimization of osmotic dehydration of yacon slices. **Drying Technology**, [United States], v. 34, n. 4, p. 386–394, Jan. 2016.

MENDONÇA, Kamilla Soares de *et al*. Peruvian carrot chips obtained by microwave and microwave-vacuum drying. **LWT - Food Science and Technology,** [England], v. 187, p. 115346, 2023.

MENEZES, Maraísa Lopes de *et al*. Análise da cinética e ajustes de modelos matemáticos aos dados de secagem do bagaço do maracujá-amarelo. **Revista Engevista**, [*s.l.*], v. 15, n. 2, p. 237–247, jan. 2013.

MUJUMDAR, Arun S. **Handbook of industrial drying.** 4th ed. Boca Raton: CRC Press, 2014. 1348 p.

OLIVEIRA, Letícia Fernandes de *et al*. Drying of ‘yacon’ pretreated by pulsed vacuum osmotic dehydration. **Revista Brasileira de Engenharia Agrícola e Ambiental**, [Campina Grande], v. 25, n. 8, p. 560–565, Aug. 2021.

OLIVEIRA, Letícia Fernandes de *et al*. Osmotic dehydration of yacon (*Smallanthus sonchifolius*): Optimization for fructan retention. **LWT - Food Science and Technology,** [England], v. 71, n. 4, p. 77–87, Mar. 2016.

OLIVEIRA, Marcelo Alvares de; NISHIMOTO, E. K. Evaluation of the development of yacon (*Polymnia sonchifolia*) plants and characterization of storage carbohydrates using HPLC. **Brazilian Journal of Food Technology**, Campinas, v. 7, n. 2, p. 215–220, Jan. 2005.

PETRI JÚNIOR, Irineu. **Descontaminação de cascalhos de perfuração utilizando um secador micro-ondas semi-industrial em regime contínuo.** 2017. 148 f. Tese (Doutorado em Engenharia Química) - Universidade Federal de Uberlândia, Uberlândia, 2017.

PETRI JÚNIOR, Irineu *et al*. Development and performance of a continuous industrial microwave dryer for remediation of drill cuttings. **Journal of Petroleum Science and Engineering,** [Netherlands], v. 176, p. 362–368, May 2019.

RAN, Xin-Li *et al*. Dielectric properties of carrots affected by ultrasound treatment in water and oil medium simulated systems. **Ultrasonics Sonochemistry**, [England], v. 56, p. 150–159, Sept. 2019.

REIS, Felipe Richter *et al*. Effect of processing methods on yacon roots health-promoting compounds and related properties. **Trends in Food Science & Technology**, [England], v. 113, p. 346–354, May 2021.

ROJAS, Meliza Lindsay; AUGUSTO, Pedro Esteves Duarte; CÁRCEL, Juan Andrés. Combining ethanol pre-treatment and ultrasound-assisted drying to enhance apple chips by fortification with black carrot anthocyanin. **Journal of the Science of Food Agriculture**, [*s.l.*], v. 101, n. 5, p. 2078–2089, Mar. 2021.

ROJAS, Meliza Lindsay; AUGUSTO, Pedro Esteves Duarte; CÁRCEL, Juan Andrés. Ethanol pre-treatment to ultrasound-assisted convective drying of apple. **Innovative Food Science & Emerging Technologies**, [Netherlands], v. 61, Jan. 2020.

SANÍN, Alejandra, NAVIA, Diana P.; SERNA-JIMÉNEZ, Johanna A. Functional Foods from Crops on the Northern Region of the South American Andes: The Importance of Blackberry, Yacon, Açai, Yellow Pitahaya and the Application of Its Biocompounds. **International Journal of Fruit Science**, [United States], v. 20, n. 3, p. S1784–S1804, Oct. 2020.

SANTOS, A. A. L. *et al*. Acerola processing waste: Convective drying with ethanol as pretreatment. **Food Research International**, [United States], v. 190, Aug. 2024.

SANTOS, Karoline Costa *et al*. 2021. Enhancing carrot convective drying by combining ethanol and ultrasound as pre-treatments: Effect on product structure, quality, energy consumption, drying and rehydration kinetics. **Ultrasonics Sonochemistry**, [England], v. 70, Jan. 2021.

SHARMA, Divyanshi *et al*. Functional oligosaccharides as a promising food ingredient: a gleam into health apprehensions and techno-functional advantages. **Food Measure,** [United States], Dec. 2024.

SILVA, Diego M. N. *et al*. Physical and chemical characterization of yacon tuberous roots at different altitudes and planting times. **Horticultura Brasileira,** [Brasília], v. 36, p. 199-204, Apr./June 2018.

SILVEIRA, Paula Giarolla *et al*. Innovative strategies in yacon drying: Ethanol pretreatment and intermittent microwave drying. **Journal of Food Science**, [United States], v. 89, n. 8, p. 4941–4952, Aug. 2024b.

SILVEIRA, Paula Giarolla *et al*. Process and quality parameters of convective dried yacon: Influence of ethanol treatment. **Food Research International**, [United States], v. 176, Jan. 2024a.

SILVEIRA FELIPE, André *et al*. Development of hotspot mapping technique in microwave cavity using resistive sheet. **Brazilian Journal of Chemical Engineering,** [São Paulo], v. 39, n. 2, p. 463–471, Jan. 2022.

SOUZA, Amanda Umbelina de *et al*. The influence of ethanol and vacuum on okara drying. **Journal of Food Chemistry & Nanotechnology**, [*s.l.*], v. 4, n. 4, p. 83–88, Jan. 2018.

SOUZA, Amanda Umbelina *et al*. Hybrid microwave-hot air drying of osmotically treated carrots. **LWT - Food Science and Technology**, [England], v. 156, Feb. 2022.

TADINI, Carmen Cecília *et al*. **Operações Unitárias na Indústria de Alimentos.** São Paulo: Grupo GEN, 2016. Disponível em: https://integrada.minhabiblioteca.com.br/#/books/9788521632689/. Acesso em: 24 maio 2023.

ZAMBRANA, Silvia *et al*. Efectos reductores de la glucemia de las plantas nutracéuticas bolivianas. **Ars Pharmaceutica,** [Espanha], v. 62, n. 1, p. 52-65, dic. 2021.

SECOND PART – ARTICLES

ARTICLE 1 - DRYING OF YACON ROOTS: A REVIEW

Scientific Journal Standards: Trends in Food Science & Technology
ISSN: 1879-3053
(Preliminary version)

Paula Giarolla Silveira[1*], Jefferson Luiz Gomes Correa[1], Carlos Ramon de Paula Silva[1], Amanda Aparecida Santos Lima[1], Matheus Souza Cruz[1], Fernanda Rezende Abrahão[1], Irineu Petri-Júnior[2]

[1] Department of Food Science, Federal University of Lavras, Campus Universitário, P. box 3037, Lavras-MG, 37200-000, Brazil, pagiarolla@gmail.com; jefferson@ufla.br

[2] Department of Chemical and Materials Engineering, Federal University of Lavras, Campus Universitário, P. box 3037, Lavras-MG, 37200-000, Brazil, irineupetri@gmail.com

Abstract

Yacon (*Smallanthus sonchifolius*) is known for its high content of fructooligosaccharides (FOS) and low glycemic index, making it a valuable functional food with numerous health benefits. However, its high moisture content carries out to a short shelf life, requiring effective drying techniques to preserve nutritional value and extend the availability of this root. This review explored various drying methods applied to yacon, such as convective drying, freeze drying, and microwave-assisted drying, among others. The impacts of each technique on the physical, chemical, and nutritional properties of yacon were examined, with a focus on the retention of bioactive compounds, such as FOS and phenolic compounds. The importance of optimizing drying parameters to maintain the quality of the dehydrated product was highlighted, showing advantages for future research and industrial applications.

Keywords: Bioactive compounds, fructooligosaccharides; prebiotic; antidiabetic; anti-obesity

1. Introduction

Yacon (*Smallanthus sonchifolius*) is a tuberous root from the Asteraceae family, native to Andian American countries. The name "yacon" is derived from the Quechua indigenous word “yaku”, meaning "watery," due to its high moisture content. Although its origin is Andean, it has been cultivated in Brazil, the Czech Republic, Ecuador, Germany, Japan, and New Zealand (Almeida Paula; Abranches; Ferreira, 2015; Caetano *et al.*, 2016).

The yacon grows at altitudes between 1,000 and 3,200 meters above sea level, in both warm and cold climates, and is not prone to usual diseases or pest problems (Almeida Paula; Abranches; Ferreira, 2015; Cao *et al.*, 2018; Reis *et al.*, 2021). Its tuberous root presents various sizes and shapes, with a thin brown skin, sweet taste, crunchy and juicy texture (Takenaka *et al.*, 2003). The root is commonly consumed raw (Khajehei; Hartung; Graeff-Hönninger, 2018b; Reis *et al.*, 2021), in juices, extracts, and cooked dishes (Almeida Paula; Abranches; Ferreira, 2015; Cao *et al.*, 2018; Lago; Norena, 2015). Despite its sweet taste, it contains low molecular weight carbohydrates and is therefore considered a low-calorie food (Cao *et al.*, 2018; Lago; Norena, 2015).

The low molecular weight carbohydrates in yacon are saccharides, mainly fructooligosaccharides (FOS), which are non-digestible prebiotic carbohydrates. FOS do not carries out to a glycemic impact. The regular ingestion of yacon is said to provide various health benefits, such as reducing chronic diseases, controlling glucose levels, regulating body weight, and lowering the risk of colon cancer (Caetano *et al.*, 2016). Despite being a food with high nutritional value, yacon consumption is still limited to regions with high production due to its high perishability. The high moisture content of yacon makes it susceptible to microbial degradation and post-harvest senescence (Silveira *et al.*, 2024). Therefore, it is important to study techniques that could increase shelf-life aiding, making the access to this FOS-rich food possible.

In this context, the present study aimed to review drying methods applied to yacon roots to explore the existing literature and propose further research on the subject, so that such a nutritionally rich food may become more widespread worldwide.

2. Composition and Importance of Yacon

The main substances present in yacon are water, carbohydrates stored in the form of fructooligosaccharides (FOS) and other free sugars, proteins, lipids, and ash (Almeida Paula;

Abranches; Ferreira, 2015; Yan *et al.*, 2019). The moisture content of the fresh root is about 8.63%±1.62% (d.b.) (Silveira *et al.*, 2024). The proximate composition on a dry basis of yacon roots is presented in Table 1 (Leidi *et al.*, 2018). Yacon root contains a considerable amount of potassium, ascorbic acid (Almeida Paula; Abranches; Ferreira, 2015), flavonoids, and antioxidant compounds such as phenols, with chlorogenic and caffeic acids being the most concentrated, and p-coumaric and protocatechuic acids, as well as tryptophan, found in smaller concentrations (Lago & Norena, 2015; Reis *et al.*, 2018; Leide *et al.*, 2018) Given its composition, yacon can be considered a multifunctional food, with antioxidant, antimicrobial, anticancer, and anti-inflammatory activities (Almeida Paula; Abranches; Ferreira, 2015; Lago; Norena, 2015).

Table 1 - Proximate composition of yacon (%), dry basis.

Component (%)	**Leidi *et al.* (2018)**	**Gonzales *et al.* (2023)**	**Choque Delgado *et al.* (2013)**
Proteins	2.8	8.91	8.00 -8.16
Lipids	0.3 – 0.6	0.13	0.77 - 0.97
Starch	0.4 – 2	ND	ND
FOS	38 – 64	ND	ND
Sugars	11 – 29	ND	ND
Fibers	3.9 – 4.2	ND	3.34 – 3.58
Ash	2.8	3.18	2.39 – 2.67
Total Carbohydrates	ND	77.97	86.13

Where: ND: means Not Determined

The biochemical composition of yacon indicates a high carbohydrate content (77.92–86.13%), along with values ranging from 2.39–3.18% for ash, 2.80–8.91% for proteins, and 0.13–0.97% for lipids. On the other hand, low mineral and vitamin contents have been reported (Gonzales *et al.*, 2023; Choque Delgado *et al.*, 2013). The most abundant mineral is potassium, present in significant quantities, averaging 230 mg per 100 g of fresh edible matter or 1~2% of dry weight. Smaller amounts of calcium, phosphorus, magnesium, sodium, iron, zinc, manganese, and copper are also found (Chessum *et al.*, 2022).

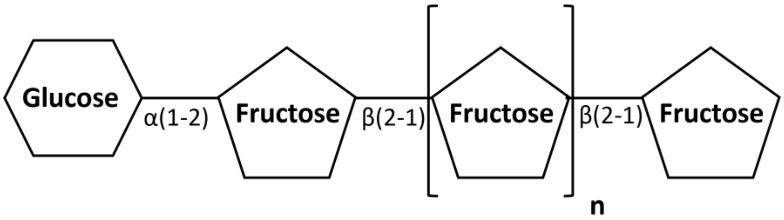
Some vitamins found in yacon are generally present as trace elements. These include retinol, carotene, thiamine, riboflavin, and niacin. Another compound reported is tryptophan, found in average amounts of 14.6 ±7.1 μg g^{-1} (Kim *et al.*, 2013). Compared to sweet potatoes, cassava, and yams, yacon presents lower amounts of carbohydrates, proteins, and fibers (Caetano *et al.*, 2016; Kim *et al.*, 2013; Histifarina *et al.*, 2023; Nwankwo, 2018; Brito *et al.*, 2015).

When analyzing the antioxidant profile of yacon, the main phenolic compounds identified are chlorogenic acid, caffeic acid, p-coumaric acid, protocatechuic acid, and tryptophan. Yacon roots contain a significant amount of phenolic compounds (about 200 mg per 100 g of fresh edible matter), standing out compared to other roots and tubers, such as carrots (Yan *et al.*, 2019). Studies have shown that, although carrots are rich in carotenoids, yacon also has a high concentration of polyphenols and phenolic compounds that contribute to its antioxidant action (Chessum *et al.*, 2022).

Yacon stands out among tubers and roots for its unique nutritional characteristics, especially in terms of moisture and carbohydrates. With a moisture content exceeding 70% of its fresh weight, yacon has a low energy value (46~56 kcal/100 g), in contrast to tubers such as sweet potato (123 kcal/100 g), potato (77 kcal/100 g), cassava (300 kcal/100 g), and yam (198-203 kcal/100 g), which have higher caloric density due to the storage of carbohydrates in the form of starch (Caetano *et al.*, 2016; Kim *et al.*, 2013; Histifarina *et al.*, 2023; Nwankwo, 2018; Brito *et al.*, 2015). Although its high moisture content contributes to its low caloric value, this characteristic also limits its shelf life, making it susceptible to damage during harvest, transport, and storage (Caetano *et al.*, 2016). The most notable difference among yacon and other tubers lies in the type of predominant carbohydrate. While roots like potatoes and cassava accumulate starch as an energy reserve, yacon stores fructooligosaccharides (FOS).

The carbohydrates present in yacon are primarily fructooligosaccharides (FOS), with smaller amounts of inulin. The main difference between FOS and inulin lies in the number of fructose molecules that form the polysaccharide chains (Almeida Paula; Abranches; Ferreira, 2015). FOS represent about 0.7% to 13.2% of the fresh root weight (38% to 64% of dry matter), depending on the crop, location, time of year, and post-harvest treatment (Caetano *et al.*, 2018; Leide *et al.*, 2018). These are oligofructans composed of a glucose monomer linked by β (2-1) bonds to fructose units, forming short linear chains of 2 to 10 fructose molecules (Figure 1) (Almeida Paula; Abranches; Ferreira, 2015; Caetano *et al.*, 2018). They are non-reducing sugars, not susceptible to Maillard reactions, stable at pH levels above 3, and at temperatures up to 140 °C (Almeida Paula; Abranches; Ferreira, 2015).

Figure 1 - Representation of the structure of inulin-type fructans.



Source: Almeida Paula; Abranches; Ferreira (2015)

The FOS are non-digestible sugars. They act as prebiotics, promoting gut health by stimulating the growth of bifidobacteria in the colon (Gonzales *et al.*, 2023). There are sufficient evidences to support the classification of FOS as prebiotics (Caetano *et al.*, 2016). Utami *et al.* (2013) observed that FOS promoted the growth of Lactobacillus and Bifidobacteria, increased the production of short-chain fatty acids (SCFA) in the rat cecum. Those authors observed that the consumption of yacon tuber could play a significant and slightly different role in maintaining colon health compared to other FOS sources. When compared with Jerusalem artichoke (*Helianthus tuberosus*), another root known for its prebiotic properties, both improved gut health, but yacon showed a higher concentration of FOS, suggesting a stronger prebiotic effect (Topolska *et al.*, 2018; Ali *et al.*, 2016). Besides, its comparison with yam reinforces the role of inulin and FOS in yacon as modulators of gut health, while yam, being richer in starch, presents a more traditional profile of energy and satiety (Yuniastuti & Iswari, 2019).

The FOS content gives yacon an extra advantage in terms of glycemic control, as its impact on blood sugar levels is much lower than that of tubers like cassava and yams. Those tubers contain high levels of starch, serving as an energy source (Jiménez & Sammán, 2014; Ferraro *et al.*, 2016). The ingestion of yacon is recommended for reducing chronic diseases, lowering glycemic levels, regulating body weight, and reducing the risk of colon cancer.

Comparisons with beetroot indicated that while both vegetables are rich in antioxidants, beetroot stands out for its nitrate content, while yacon contributes phenolic compounds and dietary fibers (Caetano *et al.*, 2016). Both yacon and sweet potato exhibit significant antioxidant activities, but sweet potato is often highlighted for its richness in carotenoids, compounds that help combat oxidative stress and prevent chronic diseases, whereas yacon is valued for its phenolic compounds and functional properties (Drapal & Fraser, 2019).

In terms of sensory aspects, yacon tuberous root presents a flavor similar to fruits like pear and melon, with slightly yellowish, crunchy, and watery flesh, distinguishing it from other tubers and roots. This may be related to the sweetness of yacon, which is predominantly caused by fructose, which is about 70% sweeter than sucrose (Nishino & Kiyohara, 2013; Kim *et al.*, 2012; Vasconcelos *et al.*, 2020).

3. Extending Yacon Shelf Life

According to Arango Torres *et al.* (2019), the shelf life of yacon roots is closely related to the preservation of their nutritional value. In this case, the nutritional value is primarily correlated with the FOS content present in the root. Oliveira and Nashimoto (2005) observed that postharvest storage temperature can either extend or shorten the shelf life of yacon. When stored at room temperature (approximately 20 °C) for a period of 7 days, there was a 30 to 40% conversion of FOS into simple sugars. Additionally, the same authors found that when stored under refrigeration (4–10 °C), this conversion into simple sugars occurs more slowly, allowing storage for up to 14 days. Thus, strategies aimed at prolonging the retention of FOS are necessary. Drying emerges as a promising strategy to extend the shelf life of yacon. This process inhibits microbial growth and enzymatic activity, which lead to spoilage, by reducing water activity, while preserving the food nutritional and sensory characteristics (Rodrigues *et al.*, 2014). Furthermore, drying reduces the weight and volume of the food, making it more economical for transportation and storage, especially in bulk shipments and long-term storage, minimizing packaging and handling costs.

Various methods are used to dehydrate yacon, including convective drying, solar drying, foam-mat drying, spray drying, microwave drying, heat pump drying, and freeze-drying. The choice of drying method depends on several factors, such as production scale, available resources, desired product quality, and method efficiency (Qu *et al.*, 2022). The main studies on yacon drying are presented in Table 2.

Table 2 - Research on yacon drying techniques.

Drying Parameters	**Drying Time**	**Reference**
CONVECTIVE DRYING		
T = 50–70 °C; H_R = 10%–30%	5–7 h	(Marques *et al.*, 2023)
T = 60, 70 and 80 °C; v = 0.87 m/s	ND	(Baldeón *et al.*, 2024)
T = 50 and 70 °C; v = 1 m/s	3.2–7.1 h	(Silveira *et al.*, 2024a)
H_R = 6%–13%; T = 45, 50, 55 and 60 °C; v = 2, 3, and 4 m/s	3.1–6.1 h	(Salinas *et al.*, 2018)
T = 50, 60, and 70 °C; v = 1.0, 1.5, and 2.0 m/s	7.2–13.3 h	(de Lisboa *et al.*, 2018)
T = 50 and 60 °C; H_R = 20%–30%; v = 4 m/s	6 h	(Marques *et al.*, 2022)

T = 50 and 75 °C; v = 2 m/s	2.5–10 h	(Bernstein & Noreña, 2014)
T = 50, 65, and 80 °C; v = 1.8 m/s	7–10.5 h	(Campos *et al.*, 2016)
T = 40, 50, and 60 °C;	5–11.5 h	(Oliveira *et al.*, 2021)
T = 40, 50, 60, and 70 °C; v = 0.5 m/s;	2–10 h	(Corrêa *et al.*, 2021)
SUN DRYING		
$T_{\text{Mechanical dryer}}$ = 60 °C; $T_{\text{Solar dryer}}$ = 20–38 °C; $T_{\text{Sun drying}}$ = 33–67 °C	7.4 h (mechanical); 18.4 h (solar); 21.6 h (sun)	(Gangta *et al.*, 2023)
T = 40, 50, and 60 °C	120 h	(Castro *et al.*, 2012)
FOAM-MAT DRYING		
T = 50, 60, and 70 °C; thickness: 0.5, 1.0, and 1.5 cm; v = 4 m/s	1.5–8 h	(Franco *et al.*, 2017)
T = 50, 60, and 70 °C; thickness: 0.5, 1.0, and 1.5 cm; v = 4 m/s	ND	(Franco *et al.*, 2016)
T = 50, 60, and 70 °C; thickness: 0.5, 1.0, and 1.5 cm; v = 4 m/s	1–5.3 h	(Franco *et al.*, 2015)
SPRAY DRYING		
T = 140 °C; Air pressure = 3.5 kgf/cm²; Air flow rate = 40.5 L/h; Air flow rate = 0.6 L/h	ND	(Lago & Noreña, 2017)
T = 140–160 °C	ND	(Brites *et al.*, 2016)
T_{in} = 100 °C; T_{out} = 40 °C; Air pressure = 1 kgf/cm²; Flow rate: 10 mL/min	10–60 s	(Bisinella *et al.*, 2016)
Flow rate: 0.60 L/h; T_{in} = 140–160 °C; Air pressure: 3.5 kgf/cm²; Air flow = 40.5 L/h; T_{out} = 90 °C	ND	(Lago & Noreña, 2016)
T_{in} = 140–160 °C; T_{out} = 75–85 °C	ND	(Arango-Torres *et al.*, 2024)
MICROWAVE DRYING		
T = 52 °C and 72 °C; M_p: 505.6 W	2.3–4.3 h	(Silveira *et al.*, 2024b)
Vacuum pressure = 0, 300, and 600 mmHg; P_d= 3.6, 6.3, and 9.9 W/g	ND	(Lopes *et al.*, 2024)
HEAT PUMP DRYING		
T = 15.0–45.0 °C; v = 1.00–2.00 m/s	ND	(Shi *et al.*, 2014)
T = 42.7 °C; v = 1.69 m/s	ND	(Shi *et al.*, 2015)
FREEZE-DRYING		
T= -80°C	48h	(Lancetti *et al.*, 2014)

T: temperature; T_{in} : temperature inlet; T_{out}: temperature outlet; T_M : temperature mechanical dryer; T_{solar}: temperature solar dryer; T_{sun} : temperature sun dryer; v: velocity; P_d: power density; M_p: microwave power; H_R: relative humidity

As described in Table 2, each drying technique presents different operational conditions, and thus, each study achieved a distinct drying time. Conventional drying methods for yacon roots can take up to 120 hours, as demonstrated by Castro *et al.* (2012). Studies by Bernstein and Noreña (2014), Campos *et al.* (2016), and Corrêa *et al.* (2021) highlight that extended processing times are associated with high energy consumption, which is undesirable from an industrial perspective. Moreover, longer drying durations can lead to changes in FOS content, as well as in the levels of antioxidants and phenols (Silveira *et al.*, 2024b). In this context, the application of drying pretreatments, such as blanching, osmotic dehydration, ethanol treatment, and ultrasound, has emerged as an effective strategy to improve process efficiency. Pretreatments can shorten drying time by facilitating moisture removal, reducing energy consumption, and simultaneously helping to preserve sensitive bioactive compounds such as FOS, antioxidants, and phenols, which might otherwise degrade during prolonged or more intense drying processes (Silveira *et al.*, 2024a). Building on this, the following sections will offer a more in-depth exploration of the pretreatment methods and drying techniques, followed by a discussion of their effects on yacon.

3.1 Pretreatments

Yacon roots are generally subjected to pretreatment before drying to accelerate the drying rate, denature enzymes (responsible for enzymatic browning), and maintain the nutritional value of the final product (Silveira *et al.*, 2024; Corrêa *et al.*, 2021). The main pretreatments applied to yacon roots are described below.

3.1.1 Blanching

Blanching is a pretreatment used to inactivate enzymes, commonly applied to foods, such as yacon, before processing. Some enzymes are responsible for browning during processing (Reis *et al.*, 2021; Macedo *et al.*, 2019). Enzymatic browning, resulting from cutting and handling yacon, promotes changes in important quality and acceptance parameters. This process is associated with the high phenolic compound content and the high activity of polyphenol oxidase (PPO) and peroxidases (POD), which also leads to a reduction in the total FOS content of yacon (Martins *et al.*, 2022). However, maintaining the color can be achieved through blanching, both chemical and thermal. Chemical blanching is based on the use of acids, antioxidants, and/or enzymes. In thermal blanching, heated water and/or steam is used, which may result in a loss of nutritional value due to nutrient leaching and compound degradation (Reis *et al.*, 2021).

Martins *et al.* (2022) used chemical blanching with a 2% citric acid solution, applied as a pretreatment before convective drying of yacon. This pretreatment was able to preserve the characteristics of the fresh product, resulting in better color parameters. The combination of blanching with techniques such as ethanol and ultrasound can improve the convective drying of yacon, producing higher quality dried products.

In the work of Campos *et al.* (2016), the addition of acids during the blanching of yacon had a significantly positive effect on the browning index of the dried samples. The combination of ascorbic acid with calcium chloride acted as a chelating agent, binding with metals such as iron and copper, catalyzing oxidation, and minimizing browning. The browning index represents the darkening that occurs during treatment and is reported as an important parameter in processes involving both enzymatic and non-enzymatic browning reactions (Campos *et al.*, 2016).

Khajehei *et al.* (2018) observed that yacon samples pretreated with diluted lemon juice exhibited better physical appearance after convective drying. Additionally, it was noted that the use of higher drying temperatures and pretreatment with lemon juice resulted in yacon chips with high antioxidant activity and higher total phenolic content.

Fante *et al.* (2013) discovered that blanching at 100 °C for 4 min was the most effective way to reduce the activity of polyphenol oxidase (PPO) and peroxidase (POD) enzymes while maintaining yacon inulin. The decrease in inulin content was linked to steam condensation on the surface of the slices, which could have contributed to inulin breakdown after chilling. Scher *et al.* (2015) investigated the effects of blanching on 1.75 mm yacon slices at temperatures ranging from 50 to 90 °C for 1 to 17 minutes. Lower temperatures (<60 °C) and shorter blanching durations (<3 min) reduced inulin losses caused by leaching into the blanching water. Therefore, blanching is an important pretreatment for protecting yacon quality during processing since it efficiently inactivates enzymes that would otherwise cause unwanted browning and quality deterioration. Blanching, whether chemical or thermal, minimizes color variance while also preserving beneficial components including inulin, FOS, and phenolics. Combining blanching with additional treatments, such as ultrasound, reduces FOS and inulin loss while increasing antioxidant retention. These tactics show that carefully selecting and adjusting blanching settings has a substantial impact on the nutritional and sensory properties of dried yacon, resulting in a product with higher commercial appeal and shelf life.

3.1.2 Osmotic dehydration (OD) and pulsed vacuum osmotic dehydration (PVOD)

Osmotic dehydration (OD) is the process of immersing food in a solution with high osmotic pressure, which provides a driving force for water removal by diffusion (Mendonça *et al.*, 2016). When used as a pretreatment for drying, it accelerates the drying rate and hence reduces drying time, resulting in reduced product exposure to high temperatures (Lopes *et al.*, 2024; Oliveira *et al.*, 2021). To improve mass transfer during OD, a method called vacuum pulse osmotic dehydration (PVOD) can be used. A brief vacuum pulse at the start of the OD process causes the pores in the plant tissue to enlarge, allowing the escape of gases trapped inside these pores. When the pressure is restored, the unobstructed pores allow for more effective water release and solute diffusion, improving the dehydration process (Corrêa *et al.*, 2021; Oliveira *et al.*, 2021).

In the study conducted by Mendonça *et al.* (2016), the use of different sweeteners (sorbitol, xylitol, and maltitol) as osmotic agents in yacon dehydration was evaluated. The research showed that xylitol at a concentration of 60 g/100 mL was the most effective for maximizing moisture loss and solid gain. The authors observed that the effective diffusion coefficient was highest at this xylitol concentration, with a value of 2.95×10^{-9} m^2/s, indicating greater mass transfer and enhanced osmotic dehydration efficiency. Regarding FOS concentration, the study did not provide specific measurements of this compound in the final products after osmotic dehydration. The research primarily focused on moisture loss, solid gain, and dehydration efficiency, without explicitly addressing effects on FOS or specific changes in color.

Oliveira *et al.* (2021) discovered that PVOD with sorbitol as an osmotic agent shortened the convective drying time of yacon slices by up to 43%. The reduced drying time resulted in roughly 38% FOS retention. Corrêa *et al.* (2021) also investigated the use of PVOD as a pretreatment in the convective drying of yacon slices and discovered that PVOD reduced drying time while retaining up to 60% FOS. Both investigations found that drying without PVOD resulted in increased FOS retention rates, which could be explained by the removal of the chemical blanching solution during immersion in the osmotic solution. This makes the slices vulnerable to enzymatic browning, which could have been responsible for FOS breakdown. Lopes *et al.* (2024) investigated the influence of PVOD on the drying of yacon slices in a vacuum microwave, as well as the impact on final product quality. Those authors discovered that the use of PVOD in the study resulted in much higher FOS retention and a significant reduction in drying time. In samples pretreatment with PVOD, fructan retention was approximately 95.74%, but in samples without PVOD, retention was up to 80.68%.

The studies by Oliveira *et al.* (2021), Corrêa *et al.* (2021), and particularly Lopes *et al.* (2024) emphasize the role of PVOD in retaining FOS during yacon dehydration, providing a more comprehensive perspective than that of dos Santos *et al.* (2024), who focused on osmotic dehydration efficiency with various sweeteners but did not quantify FOS preservation. In the work by Lopes *et al.* (2024), the combination of PVOD with vacuum microwave drying achieved significantly higher FOS retention (95.74%) compared to PVOD alone, highlighting how pulsed vacuum, when paired with microwave technology, not only enhances drying efficiency but also maximizes the preservation of sensitive bioactive compounds. These findings underscore PVOD effectiveness as an advanced strategy to optimize the functional quality and stability of dehydrated products, an aspect not explored by Santos *et al.* (2024).

3.1.3 Ethanol immersion

Ethanol immersion is a pretreatment that has been widely used due to ethanol being a low-cost and non-toxic solvent (Santos *et al.*, 2024). The addition of this solvent as a pretreatment can trigger the Marangoni effect. This effect promotes mass transfer at an interface between two fluids with different surface tensions. It can occur during drying, where ethanol vaporizes first, leaving water on the surface or the samples surface and resulting in a water/ethanol concentration gradient. This process generates a constant flow until the surface tension equilibrium is reached (Silveira *et al.*, 2024b).

The ethanol pretreatment induces structural changes in the food matrix, such as cell wall thinning and loss of turgor, which enhance mass transfer during drying (Guedes *et al.*, 2021). Silveira *et al.* (2024a) used ethanol pretreatment followed by convective drying of yacon slices at different temperatures (50 °C and 70 °C) and observed significant reduction of the drying time by up to 28% and saved energy by up to 22.72%, while preserving yacon antioxidant activity. However, the use of ethanol was responsible for reducing the FOS content due to the solubility of FOS in the solvent.

Silveira *et al.* (2024b) found that using ethanol immersion as a pretreatment for intermittent microwave drying of yacon effectively preserved bioactive substances such as fructans (FOS), phenolic compounds, and antioxidant activity. The ethanol pretreatment considerably reduced drying time and energy usage while limiting FOS breakdown. Under moderate temperature (52 °C), ethanol contributed to higher FOS retention than standard drying processes, indicating that this technology is suitable for products that require high nutrient retention.

The comparison of both studies (Silveira *et al.*, 2024a; Silveira *et al.*, 2024b) reveals that the combination of ethanol immersion with intermittent microwave drying was essential for the positive outcomes of the ethanol pretreatment. Silveira *et al.* (2024a) observed FOS degradation with convective drying combined with ethanol use, while Silveira *et al.* (2024b) demonstrated that intermittent microwave drying combined with ethanol use more effectively preserved FOS and other bioactive compounds. This effect is attributed to the volumetric heating provided by microwaves, which accelerates the drying process and reduces exposure time to high temperatures, with ethanol further enhancing the drying rate. Thus, this combination proves effective in preserving heat-sensitive compounds, such as FOS and other bioactives.

3.1.4 Ultrasound

Ultrasound (US) is a non-thermal technology with promising applications in the food industry, particularly for enzyme inactivation and enhancing mass transfer (Martins *et al.*, 2022). This kind of technology could be applied in a liquid medium as pretreatment for drying or in the drying itself (Corrêa *et al*., 2021). It inducing cavitation, generating microbubbles that collapse, producing mechanical action capable of disrupting cell walls. Additionally, it causes rapid cycles of compression and expansion in the food matrix, creating what is known as the sponge effect (dos Santos *et al.*, 2024). The application of US in a pretreatment results, in a further drying, on increased water diffusivity and reduced drying time. It potentially help maintain key quality attributes like color, antioxidant capacity, and bioactive compounds. This makes US a promising approach for improving drying processes in fruits and vegetables while preserving their nutritional and sensory qualities (dos Santos *et al.*, 2024).

In their study on ultrasound-assisted osmotic dehydration (OD) of yacon slices, Mendonça *et al.* (2016) observed that US increased OD efficiency but also caused depolymerization of FOS. It was due to the acoustic waves impact carbohydrate molecules, leading to a reduction in the molecular weight of FOS through free radical formation and polymer chain breakdown. Thus, although US enhances mass and solid transfer, it may also compromise the integrity of beneficial compounds like FOS.

Martins *et al.* (2022) explored US by combining it with ethanol and various blanching pretreatments to accelerate the convective drying of yacon. Ethanol had a more pronounced effect on reducing drying time than US alone, yet the combination of both showed a synergistic effect, further improving efficiency. The highest drying rate was observed in samples pretreated with US; however, water absorbed during this treatment appeared to limit the extent of drying time reduction. For color preservation, chemical blanching proved effective in maintaining the fresh appearance of yacon, whereas thermal blanching resulted in lower luminosity both before and after drying. This work did not observe the alteration of FOS content in the process.

Together, those studies illustrate the potential of US to enhance yacon processing and preserve visual attributes. Yet, Mendonça *et al.* (2016) highlighted a significant limitation: ultrasound can degrade bioactive compounds like FOS through depolymerization. This suggests that while US offers clear advantages for processing efficiency, it should be carefully calibrated to balance these benefits with the preservation of the product nutritional integrity, tailored to the specific goals of each application.

3.2 Drying Techniques Applied to Yacon

3.2.1 Sun Drying and Solar Drying

Sun drying and solar drying are food preservation techniques that rely on direct or indirect exposure to solar radiation. These methods have wide applications, including fruits, vegetables, grains, cereals, spices, and proteins, and are particularly valuable in rural areas and developing countries where electricity may be scarce or expensive (Pore *et al.*, 2020). In sun drying, food is directly exposed to sunlight, allowing heating through radiation (Malik & Kumar, 2024).

In solar drying, a collector converts solar energy into thermal energy, and the food is placed in a chamber without direct exposure to the sun. This system creates a clean and safe environment for drying products, maximizing the available solar energy and improving product quality (Malik & Kumar, 2024).

Future studies should focus on optimizing these methods, considering the use of pretreatments and combined technologies to improve the quality and stability of dried products, such as yacon.

3.2.2 Convective drying and far-infrared drying

The most reported method for drying yacon is convective drying. This technique relies on the transfer of heat from heated air to the material being dried, causing the moisture in the material to evaporate and be carried away by the air flow (Savas *et al.*, 2022). The main parameters that affect convective drying are air temperature, air velocity, and material thickness. Controlling these parameters is crucial to ensure process efficiency, as each factor significantly influences drying kinetics, energy efficiency, and quality attributes of the dried product obtained (Silveira *et al.*, 2024).

A study by Salinas *et al.* (2018) examined how drying conditions (temperature and air velocity) affect the physicochemical properties of yacon paste (FOS content). The study tested temperatures of 45 °C, 50 °C, 55 °C, and 60 °C, all with an air velocity of 2 m/s. Additionally, 60 °C was tested with air velocities of 3 m/s and 4 m/s. The best preservation of properties occurred at 55 °C and 2 m/s, offering an ideal balance between dehydration efficiency and FOS retention. Although 55 °C was not the lowest temperature used, the shorter drying time at this setting (230 minutes) resulted in better preservation of this heat-sensitive compound.

Baldeón *et al.* (2024) investigated the physicochemical properties of dehydrated yacon slices, analyzing color, texture, shrinkage, rehydration capacity, and microstructure, comparing convective drying (CD) and far-infrared drying (ID) methods at temperatures of 60 °C, 70 °C, and 80 °C, with an air velocity of 0.91 m/s in convective drying. The optimal condition was ID at 70 °C, which preserved the cellular microstructure and achieved an FOS retention of 38%. According to the authors, this preservation occurred because infrared rapidly generates heat on the material surface, which then propagates inward, promoting a more uniform and faster moisture removal than convective drying. This heating reduces the need for high surface temperatures, minimizing cellular collapse and preserving the product nutritional value.

Bernstein and Noreña (2013) evaluated different conditions for the convective drying of yacon slices: air temperatures of 50 °C and 60 °C, relative humidities of 20% and 30%, and an air velocity of 4 m/s. These conditions were applied in a pilot-scale drying unit, where 42 yacon slices (totaling 360 g) were dried until there was no weight variation for a period of 15 minutes. This setup allowed detailed monitoring of volume changes, structural properties, and thermodynamic characteristics throughout the drying process. The authors observed an approximate 89% reduction in volume and a rapid decrease in water activity and moisture content within the first 2.5 hours of drying. Thermodynamic analyses indicated a differential enthalpy between 12.76 and 48.02 kJ/mol and a differential entropy between 0.038 and 0.153 kJ/mol K, with stronger water-solid interactions at low moisture levels. The sorption isotherms, adjusted by the Chung–Pfost model, classified yacon as type III, characteristic of sugar-rich products.

Marques *et al.* (2022) evaluated the convective drying of yacon slices under controlled conditions (air velocity of 4 m/s, temperatures of 50 and 60 °C, and relative humidities of 20 and 30%). During the process, they monitored shrinkage in the diameter and height of the slices, as well as moisture loss. The diameter of the slices decreased to 60–70% of the initial value after 6 hours, regardless of the conditions, while the height showed a more significant reduction (5–30%), varying according to relative humidity. The authors identified anisotropic shrinkage, involving contractions in both the vertical and horizontal directions, which enabled them to predict the surface area and properties such as drying rate. Additionally, they were able to infer properties such as water activity and moisture differences between the surface and the center of the slice.

Marques *et al.* (2023) performed convective drying of yacon slices, with the study focusing on developing an extended and original van Meel model to predict shape changes in yacon slices during drying. To construct this model, the authors monitored sample shrinkage throughout the drying trials and conducted environmental scanning electron microscopy (ESEM) analyses. These analyses revealed a structural collapse in the radial direction. The authors attributed this phenomenon to an isovolumetric deformation that occurs during most of the drying process, where the reduction in sample volume corresponds to the volume of water removed. Based on this behavior, they proposed a van Meel model that incorporates the significant deformation observed in yacon during drying.

De Lisboa *et al.* (2018) investigated the effective diffusivity of yacon cylinders during convective drying, using three temperatures (50, 60, and 70 ºC) and three air velocities (1.0, 1.5, and 2.0 m/s). To model the process, the authors fitted the experimental data into different mathematical models, including the Approximation of Diffusion, Two Terms, Henderson & Pabis, and Page models, using non-linear regression analysis. It was observed that both temperature and air velocity significantly influence drying time, with effective diffusivity increasing proportionally with temperature, ranging from 1.18×10^{-9} to 2.15×10^{-9} m^2/s. Among the models evaluated, the Approximation of Diffusion provided the best fit to describe the drying kinetics of yacon.

Therefore, effectively drying yacon requires control of the operational drying conditions, as evidenced by the studies discussed in this section. Convective drying remains the most investigated technique, with process parameters such as air temperature, air velocity, and sample thickness being essential to determine process efficiency, final product quality, and FOS retention. Research by Salinas *et al.* (2018) and Baldeón *et al.* (2024) indicates that moderate conditions, like 55 °C at 2 m/s or infrared at 70 °C, provide a good balance between drying speed and the preservation of sensitive compounds, especially FOS, which are essential for the nutritional and functional value of yacon. Additionally, Bernstein and Noreña (2013) and Marques *et al.* (2022, 2023) highlighted the importance of understanding structural changes and shrinkage patterns during drying, revealing how anisotropic shrinkage and isovolumetric deformation influence the final texture and rehydration capacity of the product. De Lisboa *et al.* (2018) further contributed to these findings with detailed modeling of effective diffusivity at different temperatures and air velocities, offering a solid foundation for predicting and optimizing drying kinetics.

3.2.3 Heat Pump Drying

Heat pump dryers have been developed to dehydrate foods and biologically active products and have demonstrated greater efficiency compared to conventional drying methods (Loemba *et al.*, 2023). The efficiency of these dryers can be enhanced by integrating them with other heat sources, such as solar heating and microwave heating. These advanced systems are known as hybrid drying technologies (Qu *et al.*, 2022). Studies indicate that the combination of heat pump drying and microwave drying can optimize the dehydration of yacon. In a study conducted by Shi *et al.* (2015), the authors used adsorption isotherms and thermal transition analysis to investigate the interactions between water and biopolymers in yacon during this combined drying method. They found that the monolayer moisture content was 0.0795 g H_2O g^{-1} of dry solids, and the glass transition temperature ranged from 3.2°C to -73.3°C as moisture content increased. These results are important for optimizing the freezing and drying conditions of yacon, as well as for assessing its stability during storage at different moisture and temperature levels.

Another study evaluating the combination of heat pump drying and microwave drying was conducted by Shi *et al.* (2014), where a response surface methodology was used to analyze the impact of variables such as drying temperature, air velocity, moisture content, and microwave power. The results showed that drying temperature and air velocity were the most influential factors on drying rate and moisture removal efficiency. Optimizing these parameters allowed for achieving a high drying rate while minimizing undesirable changes in the product color. These findings reinforce the viability of this technique for industrial applications, offering a good balance between energy efficiency, stability, and preservation of yacon quality.

3.2.4 Microwave drying

Microwave drying is widely recognized for its high drying rate, resulting from the rapid temperature increase in the product due to the absorption of microwave energy, which is converted into heat through an ion-activated mechanism. This rapid heating causes water within the material to evaporate quickly, leading to lower specific energy consumption compared to traditional mechanical dryers (Paengkanya *et al.*, 2024). However, microwave drying also has disadvantages, such as uneven drying and scorching. To mitigate these issues, some pretreatments are often used in combination with microwave drying (Shinde & Ramaswamy, 2023). In a study conducted by Silveira *et al.* (2024), the use of microwaves combined with ethanol pretreatment proved particularly effective in maintaining the nutritional quality of yacon and optimizing the process, resulting in higher retention of fructooligosaccharides (64.1%), antioxidant capacity (73.9%), and total phenolic content (77.5%), as well as a significant reduction in drying time and energy consumption. Another study by Lopes *et al.* (2024) demonstrated that the combination of pulsed vacuum osmotic dehydration with microwave vacuum drying, especially under conditions of high power density and vacuum pressure, substantially reduced drying time and shrinkage of yacon slices, while increasing the retention of fructooligosaccharides by approximately 40%. Microwave drying of yacon, when integrated with pretreatments such as ethanol use and pulsed vacuum osmotic dehydration, shows promising results in preserving bioactive compounds, reducing drying time, and improving energy efficiency. These approaches could be valuable for the industrial production of yacon slices with high nutritional and sensory value.

3.2.5 Foam-Mat Drying

Foam-mat drying is a technique used to remove water from liquid or semi-liquid food products by converting them into foam and then drying it with hot air. This process involves using foaming agents and stabilizers to create a stable foam, which is spread into a thin layer and dried (Kumar *et al.*, 2023). The method is particularly suitable for heat-sensitive foods with high sugar content and high viscosity, which are often difficult to dry using other methods. Additionally, it offers an economical and feasible alternative to various other drying techniques in the production of food powders (Qadri *et al.*, 2020).

In a study conducted by Franco *et al.* (2017), the foam-mat drying of yacon juice was evaluated with different foam thicknesses (0.5 to 1.5 cm) and drying temperatures (50 to 70 °C), using egg albumin and an emulsifier as foaming agents. The results indicated that both the drying rate and effective diffusivity increased with the rise in temperature and foam thickness, proving more effective for foams formed with egg albumin. Another study on foam-mat drying of yacon investigated the physicochemical properties of the resulting powders. It was observed that the combination of a higher temperature (70 °C) and a thinner foam layer (0.5 cm) resulted in shorter drying times, lower moisture content, and reduced water activity. However, the solubility, density, and porosity of the particles were not significantly affected by the drying conditions (Franco *et al.*, 2016).

Franco *et al.* (2015) identified that during the foam-mat drying of yacon juice, diffusion was the primary mechanism driving internal moisture movement, while convective resistance limited the drying rate. Mathematical modeling using the finite element method was able to predict the process satisfactorily, and foam drying allowed for the production of high-quality yacon powder with potential for use in various food formulations. These results provide a solid foundation for future applications, and the mathematical modeling applied in the studies confirmed the predictive capability of the models used, offering a robust tool for process control and optimization.

3.2.6 Spray drying

Spray drying is widely used in the industry to transform liquids into powders. The process involves atomizing a liquid feed through a nozzle, followed by solvent evaporation in a controlled drying chamber. In this chamber, the dried particles are formed and collected. Among the advantages of this technique are greater product stability and lower transportation and storage costs. The basic principle of spray drying involves preparing an emulsion containing core and wall materials dissolved in water. Then, the moisture is evaporated, resulting in dry particles, either in powder or agglomerate form (Kandasamy & Naveen, 2022). In the study by Lago and Noreña (2016), yacon root juice was encapsulated by spray drying, using polydextrose and gum arabic as wall materials. The concentration of encapsulating agents and drying temperature directly influenced the retention of phenolic compounds and antioxidant activity. The best conditions were observed in the microparticles produced with polydextrose.

In the work of Arango-Torres *et al.* (2024), gum arabic and maltodextrin were used as wall materials for spray drying yacon. The encapsulated microparticles exhibited low hygroscopicity, high solubility (above 90%), and microbiological stability, ensured by low moisture content and water activity. Brites *et al.* (2016) studied the effect of temperature on the morphology of microparticles produced with gum arabic. The microparticles with gum arabic showed greater stability compared to those with polydextrose, reflecting a longer half-life for the phenolic compounds and demonstrating that the wall material significantly affects product stability.

The spray drying method used by Torres-Valenzuela *et al.* (2022) effectively encapsulated mango nectar sweetened with yacon syrup, using maltodextrin and Arabic gum as encapsulating agents. The best treatment identified was the formulation with 33.3% yacon syrup in the mango nectar, which achieved the highest sensory acceptance while providing the functional benefits of FOS present in yacon syrup.

In the study by Costa *et al.* (2024), microparticles were developed via spray drying to encapsulate *Lacticaseibacillus rhamnosus*, using a matrix composed of yacon flour, rich in FOS, combined with maltodextrin and gelatin as encapsulating agents. The optimal formulation, containing 11.11% maltodextrin, 2.22% gelatin, and 6.67% yacon flour, demonstrated an encapsulation efficiency of 69.92%, high thermal resistance (>64%), and strong probiotic viability under acidic pH conditions (>76%), which may suggest high bioavailability of bioactive compounds such as FOS.

Spray drying contributes to the economic and practical viability of using yacon in various sectors of the food industry, offering an efficient approach for producing ingredients that preserve nutritional benefits, promoting their use in high-value-added products, and expanding their possibilities in the market.

3.2.7 Freeze-Drying

Freeze-drying is a dehydration process that involves completely freezing the substance and then sublimating the water present in the material under vacuum. During sublimation, the ice crystals convert directly into vapor, resulting in a dry substance while maintaining its original characteristics. This method is widely used to preserve foods, medicines, and other heat-sensitive products (Ge *et al.*, 2024). A study conducted by Khajehei *et al.* (2018) demonstrated that freeze-drying effectively preserves the total phenolic content and antioxidant activity of yacon chips. This preservation is particularly enhanced when freeze-drying is combined with pretreatments, such as immersion in diluted lemon juice. The results highlight that the white cultivar of yacon exhibited higher total phenolic content and antioxidant activity after freeze-drying, especially when processed one week after harvest.

Lancetti *et al.* (2020) conducted a comparative study of different drying methods for the production of yacon flours intended for gluten-free products. Freeze-drying stood out for better preserving bioactive compounds and maintaining the color attributes of the flours. Although there was a slight loss of fructans during freeze-drying, the method was still effective in conserving reducing sugars, polyphenols, and antioxidant activity. Scheid *et al.* (2014) developed a freeze-dried yacon powder containing 7.4 g of fructooligosaccharides and evaluated the effects of consuming this product on glucose metabolism. Daily consumption of the freeze-dried yacon powder for 9 weeks was associated with a significant reduction in serum glucose levels in elderly individuals. This study highlights the potential of freeze-drying in the production of functional foods that can contribute to improved metabolic health, particularly in vulnerable populations.

Palavecino Prpich *et al.* (2023) investigate the use of yacon juice as a culture medium and cryoprotectant during the freeze-drying of industrially relevant bacterial strains, including *Latilactobacillus sakei* and *Staphylococcus vitulinus*. Yacon juice aided in bacterial preservation throughout the freeze-drying process, with post-lyophilization survival rates of 91.1% for *L. sakei* and 65.8% for *S. vitulinus*, indicating good stability. The cryoprotection provided by yacon juice is attributed to its FOS-rich composition, which acts as a cryoprotectant, helping maintain bacterial cell integrity during freeze-drying.

Although freeze-drying is considered the most expensive operation for producing dehydrated foods due to high energy consumption and the long dehydration time required, recent technological advancements and hybrid methods have been studied to improve the efficiency and cost-effectiveness of this process (Yao *et al.*, 2023). These advancements suggest that with the development of new technologies, freeze-drying could become more accessible, enabling the production of dehydrated foods with higher quality at a reduced cost.

4. Impacts of Drying Methods

As described in the previous sections, dehydration processes present an alternative for extending the shelf life of yacon, while also enabling new applications (Marques *et al.*, 2022; Reis *et al.*, 2021). Various dehydration techniques have already been applied to yacon, resulting in products such as flours (Rodrigues *et al.*, 2014), chips (Scher *et al.*, 2009), and powdered particulates (Bernstein & Noreña, 2014; Franco *et al.*, 2017). However, dehydration processes can lead to physical, chemical, and structural changes in yacon, as shown in Table 3.

Table 3 - Impact of dehydration methods on the nutritional and physicochemical properties of yacon (Organized by Drying Method).

Drying Method	**Applied Conditions**	**Considerations**	**References**
Convective, 50, 65 and 80 °C.	Pretreatment: blanching in water and steam;	The drying temperature in blanched samples did not affect FOS and reducing sugar content. Higher temperatures allowed for obtaining yacon flours with	(Campos *et al.*, 2016)

		better color and appearance parameters.	
Convective, 60, 70 and 80 °C.	Pretreatment: immersion in citric acid 1.25%;	No significant color differences were observed due to the pretreatment. Volatile compound loss was observed due to drying effects.	(Cuervo *et al*., 2018)
Convective, T = 50 °C.	Pretreatment: ultrasound and ethanol immersion;	Blanched samples showed improved color parameters. Pretreatments reduced drying time, leading to less exposure to high temperatures and better preservation of characteristics.	(Martins *et al*., 2022)
Convective, 70 °C	Pretreatment: immersion in $Na_2S_2O_5$ for enzyme inactivation; Incorporation of Lactobacillus casei LC-01.	LC-01 incorporation was evaluated under four different conditions. The product was assessed for the best survival rate of probiotics in simulated gastric conditions.	(Leone *et al*., 2017)
Convective,, T = 50, 60, and 70 °C; v = 1, 1.5, and 2 m/s.	Pretreatment: immersion in citric acid 3%;	Effective diffusivity increased with temperature. A drying temperature of 70 °C was recommended for shorter residence times.	(de Lisboa *et al*., 2018)
Convective, 50 and 60°C	Pretreatment: blanching;	The dried samples showed darkening even with prior blanching. Drying led to structural changes in the samples.	(Marques *et al*., 2020)
Convective drying	Pretreatment: ascorbic acid 15 mM and citric acid 75 mM; T = 50 °C.	The obtained yacon flour showed high levels of FOS and phenolic compounds.	(Rodrigues *et al*., 2014)
Convective drying	T = 45, 50, 55, and 60 °C; v = 2, 3, and 4 m/s.	Physicochemical changes were minimized in samples dehydrated at higher temperatures (55 and 60 °C).	(Salinas *et al*., 2018)
Convective drying	Pretreatment: steam blanching; T = 50, 60, and 70 °C.	Conversion of FOS to reducing sugars at 70 °C. In blanched and unblanched samples dried at 50, 60, and 70 °C for 300 min, inulin content decreased, while glucose and fructose increased.	(Scher *et al*., 2009)
Convective drying	T = 5 to 45 °C with 10 °C increments and v = 0.5 to 2 m/s with 0.5 m/s increments.	Drying temperature and air velocity had little effect on total color difference, shrinkage rate, and rehydration rate of dried yacon slices.	(Shi *et al*., 2013)
Convective drying and vacuum	Pretreatment: PVOD with sorbitol; T = 40, 50, 60, and 70 °C.	PVOD darkened the sample, and vacuum pulse drying positively influenced FOS retention.	(Lopes *et al*., 2016)

microwave drying		Microwave drying resulted in a higher-quality final product.	
Convective drying	Pretreatment: ethanol immersion; T = 50 and 70 °C.	Ethanol improved antioxidant activity preservation but caused FOS degradation.	(Silveira *et al*., 2024a)
Microwave drying	Pretreatment: ethanol immersion; T = 52 and 72 °C.	Drying at 52 °C with ethanol as a pretreatment resulted in dried samples with higher fructan retention, higher antioxidant activity, and minimal color variation.	(Silveira *et al*., 2024b)
Freeze-drying	T = 50 and 75 °C; v = 2 m/s; Freeze-drying (72 h, pressure of 64 μm Hg).	Shrinkage and structural collapse. Freeze-dried samples presented a lighter greenish and bluish color.	(Bernstein & Noreña, 2014)
Freeze-drying	Pretreatment: immersion in lemon juice for 10 min; T = 40, 50, and 60 °C.	Samples pre-treated with lemon juice and freeze-dried showed higher TPC and AA content. Convective drying at higher temperatures promoted better retention of TPC and AA.	(Khajehei *et al*., 2018)
Osmotic dehydration	T = 30 and 50 °C; Osmotic solution: sorbitol and glycerol (30, 50, and 70%).	Lower aw values were obtained with 70% glycerol at 50 °C. The addition of calcium lactate in the osmotic solution improved the cell wall structure.	(Brochier *et al*., 2015)
Osmotic dehydration	Osmotic solution: sorbitol and xylitol (20 – 60 °Brix). Application of US for 0 - 40 min.	US improved osmotic dehydration but resulted in fructan depolymerization. The highest fructan retention was observed with 60 °Brix DO for 267 min.	(Mendonça *et al*., 2016)
Foam-mat drying	Foam: emulsifier and egg albumin; T = 50, 60, and 70 °C.	Foams with albumin required less drying time since the fat molecules in the emulsifier are hydrophobic and resist mass transfer.	(Franco *et al*., 2017)
Vacuum convective drying	T = 65 °C; Pressure: 11.325 Pa.	Decreased luminosity and reflectance of the slices were observed, along with increased redness and yellowness. Changes in the hardness of the slices (softening followed by hardening) were noted.	(Reis *et al*., 2012)

FOS means fructooligosaccharides; AA antioxidant activity, TPC total phenolic compounds, PVOD vacuum pulse osmotic dehydration, US ultrasound, and DO osmotic dehydration.

Shrinkage is one of the most important physical changes that occur in food during drying. The loss of water, combined with the application of high processing temperatures, results in stress on the cellular structure, leading to changes in shape and volume reduction (Marques *et al.*, 2022; Silveira *et al.*, 2024). Marques *et al.* (2022) observed a 60 to 70% decrease in the diameter of yacon slices after 6 h of drying at 50-60 °C. Blanched yacon samples showed shrinkage and structural changes in a study by Bernstein and Noreña (2014). The authors found that blanched samples exhibited a less porous structure, indicating severe tissue shrinkage and structural collapse during the drying process.

Evaluating the sugar content of yacon dehydrated at 70 °C, Scher *et al.* (2009) observed the conversion of FOS into reducing sugars, in addition to a reduction in inulin content. The authors reported that although the tuber inulin content decreased, glucose and fructose levels increased in the dried product. Campos *et al.* (2016) found that drying temperature in both blanched and unblanched yacon samples did not influence the FOS and reducing sugar content. A drying temperature of 80 °C allowed the production of yacon flour with excellent physicochemical properties and color.

Various pretreatment methods have been explored to improve the quality of dried foods, such as the use of anti-browning agents, ethanol, ultrasound, chemical and thermal blanching, as well as osmotic dehydration. These methods aim to preserve desirable properties, such as antioxidant activity and color, while optimizing water removal and minimizing energy consumption (Silveira *et al.*, 2024).

5. Commercial and industrial applications of dried yacon

Yacon root has been widely studied in various drying processes for its use as FOS-rich flour in the preparation of sweets, breads, yogurt, and other products, as well as in the development of prebiotic functional foods (Campos *et al.*, 2016; Rocha *et al.*, 2018), yacon chip production (Khajehei *et al.*, 2018b), yacon as a probiotic carrier (Souza *et al.*, 2017), powdered beverages (Lago *et al.*, 2016), among other applications.

De Souza Leone *et al.* (2017) analyzed the adhesion of Lactobacillus casei, a bacterium with antimicrobial activity against pathogenic microorganisms, to dehydrated yacon to verify its viability as a probiotic food. The authors found that the probiotic effect of dried yacon was enhanced by the incorporation of Lactobacillus casei. The results showed that 75% of the cells present in the yacon produced with this bacterium survived the digestive system, colonizing the intestine and providing the benefits of probiotic food. Khajehei *et al.* (2018b) produced yacon chips through hot air convective drying and found that chips produced from the white cultivar had higher phenolic compound content and antioxidant activity than those from the red cultivar, demonstrating the influence of yacon genotype on bioactive compounds. Furthermore, the bioactivity of yacon chips was better preserved when pre-treated with lemon juice and higher drying temperatures were used, resulting in higher phenolic compound content and antioxidant activity.

Most of the dried yacon is used for producing FOS-rich flours, which can be utilized for the extraction and purification of FOS, the development of prebiotic functional foods, and as a source of nutritional enrichment (Campos *et al.*, 2016; Lancetti *et al.*, 2020). In their work, Habib *et al.* (2015) studied the influence of yacon flour on the liver and kidneys of diabetic rats, noting an increase in glutathione peroxidase and glutathione activity, along with a reduction in malondialdehyde activity due to inhibition of lipid peroxidation, superoxide dismutase, and catalase, thanks to the reduction of reactive oxygen species by direct free radical scavenging. They also found that rats supplemented with dried yacon flour showed improved kidney function. Grancieri *et al.* (2023) studied the influence of yacon flour consumption on rats with induced colorectal cancer. They found that the groups of rats that received 7.5% (25 mg/kg body weight) of the prebiotic FOS from the flour showed improved inflammation caused by colorectal cancer.

Machado *et al.* (2020) conducted a clinical trial to investigate the effect of yacon flour drinks on oxidative stress, concentrations of inflammatory markers, and fecal short-chain fatty acids in overweight patients. The authors concluded that short-term consumption of 25g of yacon flour for 6 weeks resulted in greater total antioxidant capacity, reduced oxidative stress, lower short-chain fatty acids, and no significant changes in most inflammatory variables. Derkanosova *et al.* (2022) applied dried yacon powder in bread as a supplement to wheat flour. The authors confirmed the positive effect of this material in enhancing alcoholic and lactic fermentation, but noted that there is an optimal dosage (3.5 to 7% of flour weight) to avoid dough darkening. Due to its hydrophobic properties, yacon improved the initial rheological properties of the dough.

Lancetti *et al.* (2020) applied 5% and 10% yacon flour in muffins as a substitute for corn starch. The resulting flours had high levels of reducing sugars, fructans, polyphenols, and antioxidant activity. The muffins were less firm, had more pores, and did not show changes in surface or crumb color. Simanca-Sotelo *et al.* (2021) produced and evaluated the acceptance of sweet biscuits made with blends of wheat and yacon flour. The biscuits had high levels of ether extract, fiber, ash, and carbohydrates, with a caloric value ranging from 375.32 to 386.04 kcal/g. Sensory acceptance tests showed higher scores for appearance, aroma, texture, and taste for the biscuits with a 70:30 wheat/yacon flour blend.

Rocha *et al.* (2018) produced a shake with yacon flour and studied the impact of its consumption on glycemic response and body weight. The study group consumed 350 mL of shake containing 21 g of yacon flour. The authors concluded that consuming this shake did not affect glycemic response, appetite, or food intake. Positive effects were only evident after chronic consumption, and they suggested further studies to evaluate long-term effects.

6. Future Research Suggestions and Perspectives for New Studies

The review of drying methods applied to yacon has revealed significant advancements and challenges that could be addressed in future research. Despite the progress made, specific areas still require further investigation to optimize processes and improve the quality of dehydrated products. One relevant research area involves investigating how different climatic and soil conditions in various regions affect the nutritional composition and functional properties of yacon. Different environments can significantly influence the content of bioactive compounds, such as fructooligosaccharides and antioxidants, which, in turn, impact the efficacy of drying methods and the quality of dehydrated products. Conducting comparative studies between yacon grown in different regions would help better understand these variations and adjust drying processes according to the specific characteristics of each region.

Another promising area for future research is the development of more robust and precise mathematical models that can predict yacon behavior during drying under different conditions. The application of advanced modeling techniques, such as artificial neural networks and genetic algorithms, could provide better insights into the mass and heat transfer phenomena involved in the process. Integrating experimental data with computational simulations could help optimize drying conditions, aiming for greater energy efficiency and improved quality of dehydrated products.

Furthermore, new technologies, such as the use of cold plasma and pulsed electric fields, could also be explored to investigate their potential to enhance drying kinetics and preserve the nutritional and sensory quality of yacon. Currently, most studies focus on the efficiency of the drying process and the preservation of bioactive compounds, but few evaluate the sensory quality and shelf life of dried yacon under long-term storage conditions. Future studies could investigate the long-term stability of bioactive compounds, such as fructooligosaccharides and phenolic compounds, under different storage conditions and packaging types. Exploring the applicability of edible coatings or smart packaging that prolong shelf life and preserve the sensory quality of dehydrated yacon is another research avenue that deserves attention.

There is growing interest in the development of functional foods from yacon, as exemplified by patent application BR 10 2024 010309 2 (ANNEX A), which describes a functional beverage made from yacon. Future research could focus on creating new products that combine dried yacon with other functional ingredients, aiming to maximize health benefits and meet market demands for innovative functional foods. Additionally, studying the bioaccessibility and bioavailability of bioactive compounds after drying and during human digestion could provide valuable insights into the nutritional value and health benefits of dehydrated yacon products.

Those research directions offer a broad field of exploration for the scientific and industrial community, promoting innovations in processing and applying yacon in various food products. Continued studies will contribute to consolidating yacon as a functional food with high added value and expanding market opportunities for products derived from this Andean tuberous root.

7. Conclusion

This review of drying of yacon revealed the use of several techniques and their advantages and disadvantages. Convective drying, while effective, can lead to structural collapse and loss of bioactive compounds if not carefully controlled. Freeze-drying preserves most nutritional qualities but is economically unfeasible for large-scale operations. Osmotic dehydration and microwave-assisted drying offer promising alternatives, especially when combined with pretreatments that enhance the retention of beneficial compounds. Future research should focus on developing more efficient and cost-effective drying methods, potentially through the integration of advanced technologies, such as cold plasma or pulsed electric fields. Additionally, further exploration of the long-term stability of dried yacon and its potential for the creation of innovative functional food products will be crucial for maximizing the market potential of this Andean root.

Acknowledgments

The authors gratefully acknowledge Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) and Fundação de Amparo à Pesquisa do Estado de Minas Gerais (FAPEMIG).

References

Ali, M. S., Elnaz, M., & Ladan, N. (2016). Prebiotic effect of Jerusalem artichoke (*Helianthus tuberosus*) fructans on the growth performance of *Bifidobacterium bifidum* and *Escherichia coli*. *Asian Pacific Journal of Tropical Disease*, *6*(5), 385–389. https://doi.org/10.1016/S2222-1808(15)61053-2

Arango-Torres, M. I., Cortés-Rodríguez, M., Largo-Ávila, E., Gallón-Bedoya, M., & Ortega-Toro, R. (2024). Yacon powder mix: Effects of the composition and the process of microencapsulation by spray drying. *Heliyon*, *10*(13), e33968. https://doi.org/10.1016/j.heliyon.2024.e33968

Baldeón, E. O., Salas-Valerio, W. F., Vidaurre-Ruiz, J. M., & Comettant-Rabanal, R. (2024). Convective drying kinetics of yacon (*Smallanthus Sonchifolius Poepp. & Endl.*) slabs and evaluation of the dryer PID temperature control system. *Chilean Journal of Agricultural & Animal Sciences*, *40*(2), 44–54. https://doi.org/10.29393/CHJAAS40-5CDER40005

Bernstein, A., & Noreña, C. P. Z. (2014). Study of thermodynamic, structural, and quality properties of yacon (*Smallanthus sonchifolius*) during drying. *Food and Bioprocess Technology*, *7*(1), 148–160. https://doi.org/10.1007/s11947-012-1027-y

Bisinella, R. Z. B., de Oliveira, C. S., Zappani, P. S. C., Schnitzler, E., & Masson, M. L. (2016). Thermal analysis as screening technique to assess spray-drying process of encapsulated “yacon” juice. *Journal of Thermal Analysis and Calorimetry*, *126*(3), 1841–1849. https://doi.org/10.1007/s10973-016-5696-z

Brites, M. L., Meira, S. M., Brandelli, A., & Noreña, C. Z. (2016). Characterization of powder from the permeate of yacon extract by ultrafiltration and dehydrated by spray drying. *Ciência e Agrotecnologia*, *40*(5), 585–595. https://doi.org/10.1590/1413-70542016405013916

Brito, V., Silva, É., & Cereda, M. (2015). Digestibilidade do amido *in vitro* e valor calórico dos grupos de farinhas de mandioca brasileiras. *Brazilian Journal of Food Technology*, *18*, 185–191. https://doi.org/10.1590/1981-6723.2714

Brochier, B., Marczak, L. D. F., & Noreña, C. P. Z. (2015). Osmotic dehydration of yacon using glycerol and sorbitol as solutes: Water effective diffusivity evaluation. *Food and Bioprocess Technology*, *8*(3), 623–636. https://doi.org/10.1007/s11947-014-1432-5

Caetano, B. F. R., Oliveira, T. T., Gonçalves, M. D., Lima, N. M. G., Guerra, M. C., & Seiva, F. R. F. (2016). Yacon (*Smallanthus sonchifolius*) as a food supplement: Health-promoting benefits of fructooligosaccharides. *Nutrients*, *8*(7), 436. https://doi.org/10.3390/nu8070436

Campos, D., Aguilar-Galvez, A., & Pedreschi, R. (2016). Stability of fructooligosaccharides, sugars and colour of yacon (*Smallanthus sonchifolius*) roots during blanching and drying. *International Journal of Food Science and Technology*, *51*(5), 1177–1185. https://doi.org/10.1111/ijfs.13074

Cao, Y., Zhao, G., Xu, S., & Guo, L. (2018). Phytochemical properties and nutrigenomic implications of yacon as a potential source of prebiotic: Current evidence and future directions. *Foods*, *7*(4), 59. https://doi.org/10.3390/foods7040059

Castro, A., Caballero, M., Herbas, A., & Carballo, S. (2012). Antioxidants in yacon products and effect of long term storage. *Food Science and Technology*, *32*(3), 432–435. https://doi.org/10.1590/S0101-20612012005000064

Chessum, K., Chen, T., Kam, R., & Yan, M. (2022). A comprehensive chemical and nutritional analysis of New Zealand yacon concentrate. *Foods*, *12*(1), 74. https://doi.org/10.3390/foods12010074

Choque Delgado, G. T., da Silva Cunha Tamashiro, W. M., Maróstica Junior, M. R., & Pastore, G. M. (2013). Yacon (*Smallanthus sonchifolius*): A functional food. *Plant Foods for Human Nutrition*, *68*, 222–228. https://doi.org/10.1007/s11130-013-0362-0

Corrêa, J. L. G., Lopes, F. J., de Mello Junior, R. E., de Jesus Junqueira, J. R., de Angelis Pereira, M. C., & Salvio, L. G. A. (2021). Dried yacon with high fructooligosaccharide content. *Journal of Food Process Engineering*, *44*(12). https://doi.org/10.1111/jfpe.13884

Costa, N. A., Amaral, E. P., Pereira, G. C., Silveira, L. R., Paiva, M. J. A., Leite Júnior, B. R. C., Stringheta, P. C., Paula, D. A., Martins, E. M. F., Martins, M. L., Vieira, É. N. R., Saldaña, M. D. A., & Ramos, A. M. (2024). Yacon flour (*Smallanthus sonchifolius*) as wall material for microencapsulation of *Lacticaseibacillus rhamnosus* GG: Characterization of microparticles and its use in pitaya jelly. *Food and Bioprocess Technology*. https://doi.org/10.1007/s11947-024-03526-6

Cuervo, S. P., Benitez, A., & Castellanos, S. M. (2018). Drying of yacon (*Smallanthus sonchifolius*) as a potential food product for international commercialization. *IOP Conference Series: Materials Science and Engineering*, *437*, 012005. https://doi.org/10.1088/1757-899X/437/1/012005

de Almeida Paula, H. A., Abranches, M. V., & de Luces Fortes Ferreira, C. L. (2015). Yacon (*Smallanthus sonchifolius*): A food with multiple functions. *Critical Reviews in Food Science and Nutrition*, *55*(1), 32–40.

de Lisboa, C. G. C., Gomes, J. P., de Figueiredo, R. M. F., Queiroz, A. J. M., Diogenes, A. M. G., & de Melo, J. C. S. (2018). Effective diffusivity in yacon potato cylinders during drying. *Revista Brasileira de Engenharia Agrícola e Ambiental*, *22*(8), 564–569. https://doi.org/10.1590/1807-1929/agriambi.v22n8p564-569

de Souza Leone, R., Brito, P. M., Santos, M. F., & Lopes, R. S. (2017). Evaluation of dried yacon (*Smallanthus sonchifolius*) as an efficient probiotic carrier of *Lactobacillus casei* LC-01. *LWT*, *75*, 220–226. https://doi.org/10.1016/j.lwt.2016.09.040

Derkanosova, N. M., Kosorukov, V. N., Raspopov, O. V., & Abdrakhmanova, A. S. (2022). Influence of yacon on the quality and safety of bread. *IOP Conference Series: Earth and Environmental Science*, *2022*, 012037.

Dos Santos, D. M., Roman Ross, N. C., Leonarski, E., Kuasnei, M., Quast, L. B., Bertan, L. C., & Quast, E. (2024). Osmotic dehydration of yacon potatoes (*Smallanthus sonchifolius*) using different sweeteners as osmotic agents. *Journal of Culinary Science & Technology*. https://doi.org/10.1080/15428052.2024.2339895

Drapal, M., & Fraser, P. (2019). Determination of carotenoids in sweet potato (*Ipomoea batatas L., Lam*) tubers: Implications for accurate provitamin A determination in staple sturdy tuber crops. *Phytochemistry, 167,* 112102. https://doi.org/10.1016/j.phytochem.2019.112102

Fante, L., Scher, C. F., Noreña, C. P. Z., & Rios, A. O. (2013). Study of enzyme inactivation using steam in yacon (*Smallanthus sonchifolius*) roots. *Journal of Food Processing and Preservation*, *37*, 16–24. https://doi.org/10.1111/j.1745-4549.2011.00609.x

Ferraro, V., Piccirillo, C., Tomlins, K., & Pintado, M. (2016). Cassava (*Manihot esculenta Crantz*) and yam (*Dioscorea spp.*) crops and their derived foodstuffs: Safety, security and nutritional value. *Critical Reviews in Food Science and Nutrition*, *56*, 2714–2727. https://doi.org/10.1080/10408398.2014.922045

Ferraz, A. P. C. R., Garcia, J. L., Costa, M. R., De Almeida, C. C. V., Gregolin, C. S., Alves, P. H. R., ... & Corrêa, C. R. (2020). Yacon (*Smallanthus sonchifolius*) use as an antioxidant in diabetes. In *Pathology* (pp. 379–386). Academic Press. https://doi.org/10.1016/B978-0-12-815972-9.00036-6

Franco, T. S., Perussello, C. A., Ellendersen, L. N., & Masson, M. L. (2017). Effect of process parameters on foam mat drying kinetics of yacon (*Smallanthus sonchifolius*) and thin-layer drying modeling of experimental data. *Journal of Food Process Engineering, 40*(1), e12264. https://doi.org/10.1111/jfpe.12264

Franco, T. S., Perussello, C. A., Ellendersen, L. N., & Masson, M. L. (2016). Effects of foam mat drying on physicochemical and microstructural properties of yacon juice powder. *LWT - Food Science and Technology, 66,* 503–513. https://doi.org/10.1016/j.lwt.2015.11.009

Franco, T. S., Perussello, C. A., Ellendersen, L. N., & Masson, M. L. (2015). Effect of process parameters on foam mat drying kinetics of yacon (*Smallanthus sonchifolius*) and thin-layer drying modeling of experimental data. *Journal of Food Process Engineering, 40*(1), e12264.

Gangta, R., Thakur, N. S., Hamid, Gautam, S., & Thakur, A. (2023). Optimization of pre-drying treatment and drying mode for reducing browning to produce shelf stable fructooligosaccharide rich yacon (ground apple) powder. *South African Journal of Botany, 157,* 96–105. https://doi.org/10.1016/j.sajb.2023.03.051

Ge, S., Han, J., Sun, Q., Zhou, Q., Ye, Z., Li, P., & Gu, Q. (2024). Research progress on improving the freeze-drying resistance of probiotics: A review. *Trends in Food Science & Technology, 147,* 104425. https://doi.org/10.1016/j.tifs.2024.104425

Gonzales, M., Rosario, R., & Walag, A. (2023). Proximate biochemical composition and antinutritional analyses of the selected parts of yacon (*Smallanthus sonchifolius*). *Asian Journal of Biological and Life Sciences*. https://doi.org/10.5530/ajbls.2023.12.47

Grancieri, M., de Souza, L. F., Ramos, R. O., & Costa, N. M. B. (2023). Yacon (*Smallanthus sonchifolius*) flour reduces inflammation and had no effects on oxidative stress and endotoxemia in Wistar rats with induced colorectal carcinogenesis. *Nutrients, 15*(14), 3281. https://doi.org/10.3390/nu15143281

Guedes, J. S., Santos, K. C., Castanha, N., Rojas, M. L., Matta Junior, M. D., Lima, D. C., & Augusto, P. E. D. (2021). Structural modification on potato tissue and starch using ethanol pretreatment and drying process. *Food Structure, 29,* 100202. https://doi.org/10.1016/j.foostr.2021.100202

Habib, N. C., Franco, P. C., & Gonzalez, R. J. (2015). Yacon roots (*Smallanthus sonchifolius*) improve oxidative stress in diabetic rats. *Pharmaceutical Biology, 53*(8), 1183–1193. https://doi.org/10.3109/13880209.2014.978719

Hashemi, S. M. B., & Gholamhosseinpour, A. (2020). Effect of ultrasonication treatment and fermentation by probiotic *Lactobacillus plantarum* strains on goat milk bioactivities. *International Journal of Food Science and Technology, 55,* 2642–2649.

Histifarina, D., Purnamasari, N. R., & Rahmat, R. (2023). Potential development and utilization of sweet potato flour as a raw material for the food industry. *IOP Conference Series: Earth and Environmental Science, 1230*(1), 012006. https://doi.org/10.1088/1755-1315/1230/1/012006

Jiménez, M., & Sammán, N. (2014). Chemical characterization and quantification of fructooligosaccharides, phenolic compounds and antiradical activity of Andean roots and tubers grown in Northwest Argentina. *Archivos Latinoamericanos de Nutrición, 64*(2), 131–138.

Kandasamy, S., & Naveen, R. (2022). A review on the encapsulation of bioactive components using spray-drying and freeze-drying techniques. *Journal of Food Process Engineering, 45*(8). https://doi.org/10.1111/jfpe.14059

Khajehei, F., Hartung, J., & Graeff-Hönninger, S. (2018). Total phenolic content and antioxidant activity of yacon (*Smallanthus sonchifolius Poepp. and Endl.*) chips: Effect of cultivar, pretreatment and drying. *Agriculture (Switzerland)*, *8*(12), 183. https://doi.org/10.3390/agriculture8120183

Kim, S. J., Jin, Y. I., Nam, J. H., Hong, S. Y., Sohn, W. B., Kwon, O. K., & Jeong, J. C. (2013). Comparison of nutrient composition of yacon germplasm. *Korean Journal of Plant Resources*, *26*(1), 9–18. https://doi.org/10.7732/kjpr.2013.26.1.009

Kumar, G., Kumar, N., Prabhakar, P. K., & Kishore, A. (2023). Foam mat drying: Recent advances on foam dynamics, mechanistic modeling and hybrid drying approach. *Critical Reviews in Food Science and Nutrition*, *63*(26), 8275–8291. https://doi.org/10.1080/10408398.2022.2053061

Lago, C. C., & Noreña, C. P. Z. (2016). Polydextrose as wall material for microencapsulation of yacon juice by spray drying. *Food and Bioprocess Technology*, *9*(12), 2103–2113. https://doi.org/10.1007/s11947-016-1797-8

Lago, C. C., & Noreña, C. P. Z. (2017). Thermodynamic and kinetics study of phenolics degradation and color of yacon (*Smallanthus sonchifolius*) microparticles under accelerated storage conditions. *Journal of Food Science and Technology*, *54*(13), 4197–4204. https://doi.org/10.1007/s13197-017-2887-y

Lancetti, R., Palavecino, P. M., Bustos, M. C., & León, A. E. (2020). Yacon (*Smallanthus sonchifolius*) flour obtention: Effect of process conditions on quality attributes and its incorporation in gluten-free muffins. *LWT*, *125*, 109217. https://doi.org/10.1016/j.lwt.2020.109217

Leidi, E. O., Herrmann, M., Fleck, C., Carvajal, L., & Schöberlein, L. (2018). Andean roots and tubers crops as sources of functional foods. *Journal of Functional Foods*, *51*, 86–93. https://doi.org/10.1016/j.jff.2018.10.013

Leone, R. de S., de Andrade, E. F., Ellendersen, L. N., Tais da Cunha, A., Chupel Martins, A. M., Granato, D., & Masson, M. L. (2017). Evaluation of dried yacon (*Smallanthus sonchifolius*) as an efficient probiotic carrier of *Lactobacillus casei* LC-01. *LWT*, *75*, 220–226. https://doi.org/10.1016/j.lwt.2016.08.027

Loemba, A. B. T., Kichonge, B., & Kivevele, T. (2023). Comprehensive assessment of heat pump dryers for drying agricultural products. *Energy Science & Engineering*, *11*(8), 2985–3014. https://doi.org/10.1002/ese3.1326

Lopes, F. J., Corrêa, J. L. G., Petri Júnior, I., Mello Júnior, R. E. de, Souza, A. U. de, Corona-Jiménez, E., & Pereira, M. C. de Â. (2024). Microwave-vacuum drying of pulsed vacuum osmotic dehydration-pretreated yacon as an alternative for preserving fructo-oligosaccharides. *Ciência e Agrotecnologia*, *48*. https://doi.org/10.1590/1413-7054202448015523

Macedo, L. L., Corrêa, J. L. G., da Silva Araújo, C., Vimercati, W. C., & Júnior, I. P. (2021). Convective drying with ethanol pretreatment of strawberry enriched with isomaltulose. *Food and Bioprocess Technology*, *14*, 2046–2061. https://doi.org/10.1007/s11947-021-02710-2

Macedo, L. L., da Silva Araújo, C., Vimercati, W. C., Saraiva, S. H., & Teixeira, L. J. Q. (2021). Influence of yacon syrup concentration and drying air temperature on properties of osmotically pre-dehydrated dried banana. *Heat and Mass Transfer*, *57*(3), 441–451. https://doi.org/10.1007/s00231-020-02966-y

Macedo, L. L., da Silva Araújo, C., Vimercati, W. C., Saraiva, S. H., & Teixeira, L. J. Q. (2019). Evaluation of different bleaching methods applied to yacon. *Journal of Food Process Engineering*, *42*(7). https://doi.org/10.1111/jfpe.13276

Machado, A. M., de Paula, T. O., Cardoso, L. D., Costa, N. M. B., Oliveira, D. S., & Peluzio, M. C. G. (2020). Effects of yacon flour associated with an energy-restricted diet on intestinal permeability, fecal short-chain fatty acids, oxidative stress, and inflammation markers in adults with obesity or overweight: A randomized, double-blind, placebocontrolled clinical trial. *Archives of Endocrinology and Metabolism*, *64*, 597–607. https://doi.org/10.20945/2359-3997000000277

Malik, A., & Kumar, M. (2024). Experimental ginger drying by a novel mixed-mode vertical solar dryer under partial and fully loaded conditions. *Innovative Food Science & Emerging Technologies*, *95*, 103736. https://doi.org/10.1016/j.ifset.2024.103736

Marques, B. C., Plana-Fattori, A., & Tadini, C. C. (2020). Data acquisition for modeling convective drying of yacón (*Smallanthus sonchifolius*) slices. In *11th International Conference on Simulation and Modelling in the Food and Bio-Industry, FOODSIM 2020*, 86–93.

Marques, B. C., Plana-Fattori, A., Flick, D., & Tadini, C. C. (2022). Convective drying of yacón (*Smallanthus sonchifolius*) slices: A simple physical model including shrinkage. *LWT*, *159*, 113151. https://doi.org/10.1016/j.lwt.2022.113151

Marques, B., Perré, P., Casalinho, J., Tadini, C. C., Plana-Fattori, A., & Almeida, G. (2023). Evidence of iso-volume deformation during convective drying of yacón: An extended van Meel model adapted to large volume reduction. *Journal of Food Engineering*, *341*, 111311. https://doi.org/10.1016/j.jfoodeng.2022.111311

Marques, C., Bortolan Toazza, C. E., Sari, R., Mitterer-Daltoé, M. L., Amaral, W., & Masson, M. L. (2021). Long-term storage of yacon (*Smallanthus sonchifolius*) juice: Phytochemical profile, in vitro prebiotic potential, and discriminant bioactive properties. *Food Bioscience*, *41*, 100970. https://doi.org/10.1016/j.fbio.2021.100970

Martins, A. F. L., Vieira, É. N. R., Leite Júnior, B. R. C., & Ramos, A. M. (2022). Use of ultrasound and ethanol to improve the drying of yacon potato (*Smallanthus sonchifolius*): Effect of chemical and thermal bleaching. *LWT - Food Science and Technology*, *162*, 113448. https://doi.org/10.1016/j.lwt.2022.113448

Mendonça, K. S., Corrêa, J. L. G., de Jesus Junqueira, J. R., Pereira, M. C. A., & Vilela, M. B. (2016). Optimization of osmotic dehydration of yacon slices. *Drying Technology*, *34*(4), 386–394. https://doi.org/10.1080/07373937.2015.1054511

Nishino, T., & Kiyohara, H. (2013). Effect of the removal of yacon root astringency on taste and function. *Journal of the Japanese Society for Food Science and Technology-Nippon Shokuhin Kagaku Kogaku Kaishi*, *60*, 133–137. https://doi.org/10.3136/nskkk.60.133

Oliveira, L. F., Corrêa, J. L. G., de Angelis Pereira, M. C., de Lemos Souza Ramos, A., & Vilela, M. B. (2016). Osmotic dehydration of yacon (*Smallanthus sonchifolius*): Optimization for fructan retention. *LWT*, *71*, 77–87. https://doi.org/10.1016/j.lwt.2016.03.028

Oliveira, L. F., Corrêa, J. L. G., Silveira, P. G., Vilela, M. B., & Junqueira, J. R. de J. (2021). Drying of ‘yacon’ pretreated by pulsed vacuum osmotic dehydration. *Revista Brasileira de Engenharia Agrícola e Ambiental*, *25*(8), 560–565. https://doi.org/10.1590/1807-1929/agriambi.v25n8p560-565

Oliveira, M. A., & Nishimoto, E. K. (2005). Evaluation of the development of yacon (Polymnia sonchifolia) plants and characterization of storage carbohydrates using HPLC. Brazilian Journal of Food Technology, 7(2), 215–220.

Paengkanya, S., Mitprayoon, L., & Nathakaranakule, A. (2024). Shiitake mushroom drying using belt-conveyor combined microwave-hot air and hot air techniques: Drying kinetics, energy consumption, and quality characteristics. *Drying Technology*, *42*(7), 1151–1164. https://doi.org/10.1080/07373937.2024.2311250

Palavecino Prpich, N., Godoy-Suárez, D., Ramos-Pulgar, R., Pradenas-Marchant, M., & Aranda, M. (2023). Utilization of yacon juice as a culture medium and cryoprotectant for industrially relevant bacterial strains. *Brazilian Journal of Food Technology*, *26*, e2023043.

Perussello, C. A., Kumar, C., de Castilhos, F., & Karim, M. A. (2014). Heat and mass transfer modeling of the osmo-convective drying of yacon roots (*Smallanthus sonchifolius*). *Applied Thermal Engineering*, *63*(1), 23–32. https://doi.org/10.1016/j.applthermaleng.2013.10.020

Perussello, C. A., Mariani, V. C., Masson, M. L., & de Castilhos, F. (2015). Propriedades termofísicas do yacon (*Smallanthus sonchifolius*): Determinação experimental e efeito do conteúdo de umidade. *Acta Scientiarum - Technology*, *37*(1), 167–173. https://doi.org/10.4025/actascitechnol.v37i1.20624

Pore, D. C., Patil, R. A., Patil, M. B., Nadaf, A. A., Kore, M. C., Husainy, A. S. N., & Parishwad, G. V. (2020). A glance on solar drying technology for dry fruit potential. *Journal of Alternative and Renewable Energy Sources*, *6*(2), 26–35. https://doi.org/10.46610/JOARES.2020.v06i02.004

Qadri, O. S., Srivastava, A. K., & Yousuf, B. (2020). Trends in foam mat drying of foods: Special emphasis on hybrid foam mat drying technology. *Critical Reviews in Food Science and Nutrition*, *60*(10), 1667–1676. https://doi.org/10.1080/10408398.2019.1588221

Qu, H., Masud, M. H., Islam, M., Khan, M. I. H., Ananno, A. A., & Karim, A. (2022). Sustainable food drying technologies based on renewable energy sources. *Critical Reviews in Food Science and Nutrition*, *62*(25), 6872–6886. https://doi.org/10.1080/10408398.2021.1907529

Reis, F. R., Lenzi, M. K., & Masson, M. L. (2012). Effect of vacuum drying conditions on the quality of yacon (*Smallanthus sonchifolius*) slices: Process optimization toward color quality. *Journal of Food Processing and Preservation*, *36*(1), 67–73. https://doi.org/10.1111/j.1745-4549.2011.00555.x

Reis, F. R., Marques, C., Moraes, A. C. S., & Masson, M. L. (2021). Effect of processing methods on yacon roots health-promoting compounds and related properties. *Trends in Food Science & Technology*, *113*(May), 346–354. https://doi.org/10.1016/j.tifs.2021.05.010

Rocha, D. M. U. P., Lopes, L. L., Franco, F. S., Nascimento, G. G., & Ribeiro, J. A. (2018). Acute consumption of yacon shake did not affect glycemic response in euglycemic, normal weight, healthy adults. *Journal of Functional Foods*, *44*, 58–64. https://doi.org/10.1016/j.jff.2018.03.002

Rodrigues, M. Z., Martins, E. F., Brandao, V. I., Madeira, R. O., Campos, A. N. D. R., & Ramos, A. M. (2013). Application of antioxidants to extend the shelf life of processed minimally yacon (*Smallanthus sonchifolius*). *International Journal of Postharvest Technology and Innovation*, *3*(1), 28–36. https://doi.org/10.1504/IJPTI.2013.051986

Rodrigues, O. R. L., Asquieri, E. R., & Orsi, D. C. (2014). Prevention of enzymatic browning of yacon flour by the combined use of anti-browning agents and the study of its chemical composition. *Food Science and Technology*, *34*(2), 275–280. https://doi.org/10.1590/fst.2014.0045

Salinas, J. G., Alvarado, J. A., Bergenståhl, B., & Tornberg, E. (2018). The influence of convection drying on the physicochemical properties of yacon (*Smallanthus sonchifolius*). *Heat and Mass Transfer*, *54*(10), 2951–2961. https://doi.org/10.1007/s00231-018-2334-2

Santos, A. A. L., Corrêa, J. L. G., Machado, G. G. L., Silveira, P. G., Cruz, M. S., & Nascimento, B. S. (2024). Acerola processing waste: Convective drying with ethanol as pretreatment. *Food Research International*, *190*, 114586. https://doi.org/10.1016/j.foodres.2024.114586

Santos, J. C. C., Corrêa, J. L. G., Furtado, M. L. B., Morais, L. C., Borges, S. V., Oliveira, C. R., Resende, J. V., & Oliveira, L. F. (2024). Influence of intensity ultrasound on rheological properties and bioactive compounds of araticum (*Annona crassiflora*) juice. *Ultrasonics Sonochemistry*, *105*, 106868. https://doi.org/10.1016/j.ultsonch.2024.106868

Savas, E. (2022). The modelling of convective drying variables' effects on the functional properties of sliced sweet potatoes. *Foods*, *11*(5), 741. https://doi.org/10.3390/foods11050741

Scheid, M. M. A., Genaro, P. S., Moreno, Y. M. F., & Pastore, G. M. (2014). Freeze-dried powdered yacon: Effects of FOS on serum glucose, lipids and intestinal transit in the elderly. *European Journal of Nutrition*, *53*(7), 1457–1464. https://doi.org/10.1007/s00394-013-064

Scher, C. F., Brandelli, A., & Noreña, C. Z. (2015). Dissolução de inulina do yacon durante o branqueamento em ´ agua quente. Ciencia E Agrotecnologia, 39, 523–529. https://doi.org/10.1590/S1413-70542015000500011

Scher, C. F., De Oliveira Rios, A., & Noreña, C. P. Z. (2009). Hot air drying of yacon (*Smallanthus sonchifolius*) and its effect on sugar concentrations. *International Journal of Food Science and Technology*, *44*(11), 2169–2175. https://doi.org/10.1111/j.1365-2621.2009.02056.x

Shi, Q., Zheng, Y., & Zhao, Y. (2013). Mathematical modeling on thin-layer heat pump drying of yacon (*Smallanthus sonchifolius*) slices. *Energy Conversion and Management*, *71*, 208–216. https://doi.org/10.1016/j.enconman.2013.03.032

Shi, Q., Zheng, Y., & Zhao, Y. (2014). Optimization of combined heat pump and microwave drying of yacon (*Smallanthus sonchifolius*) using response surface methodology. *Journal of Food Processing and Preservation*, *38*(5), 2090–2098. https://doi.org/10.1111/jfpp.12189

Shi, Q., Zheng, Y., & Zhao, Y. (2015). Thermal transition and state diagram of yacon dried by combined heat pump and microwave method. *Journal of Thermal Analysis and Calorimetry*, *119*(1), 727–735. https://doi.org/10.1007/s10973-014-4198-0

Shinde, B., & Ramaswamy, H. S. (2023). Microwave–osmotic–vacuum combination drying of mango cubes with maltodextrin moderated sucrose solution. *Drying Technology*, *41*(6), 1046–1059. https://doi.org/10.1080/07373937.2023.2201304

Silveira, P. G., Corrêa, J. L. G., Silva, C. R. de P., Macedo, L. L., Gonçalves, W. S., & Júnior, I. P. (2024). Innovative strategies in yacon drying: Ethanol pretreatment and intermittent microwave drying. *Journal of Food Science*. https://doi.org/10.1111/1750-3841.17254

Silveira, P. G., de P. Silva, C. R., Corrêa, J. L. G., Petri, I. J., & Borges, S. V. (2024). Process and quality parameters of convective dried yacon: Influence of ethanol treatment. *Food Research International*, *176*, 113863. https://doi.org/10.1016/j.foodres.2023.113863

Simanca-Sotelo, M., Gallego, C., Yepes-Medina, M., & Giraldo-Hernandez, M. (2021). Physico-chemical and sensory characterization of sweet biscuits made with yacon flour (*Smallanthus sonchifolius*). *NFS Journal*, *22*, 14–19. https://doi.org/10.1016/j.nfs.2021.01.002

Takenaka, M., Yoshida, S., & Uehara, M. (2003). Changes in phenolic compounds in yacon (*Smallanthus sonchifolius*) tubers during growth, storage, and processing. *Plant Foods for Human Nutrition*, *58*(3), 99–108.

Topolska, K., Radzki, R. P., Filipiak-Florkiewicz, A., Florkiewicz, A., Leszczyńska, T., & Cieślik, E. (2018). Fructan-enriched diet increases bone quality in female growing rats at calcium deficiency. *Plant Foods for Human Nutrition*, *73*, 172–179. https://doi.org/10.1007/s11130-018-0671-4

Torres-Valenzuela, L. S., Ortega-Sánches, M., García-Mendoza, J., García-Gil, N., Rendón-Villalobos, R., & Acevedo-Fani, A. (2022). Stabilization of mango-yacon functional drink using spray drying encapsulation. *Food Hydrocolloids*, *129*, 107680. https://doi.org/10.1016/j.foodhyd.2022.107680

Utami, N. W. A., Sone, T., Tanaka, M., Nakatsu, C. H., Saito, A., & Asano, K. (2013). Comparison of yacon (*Smallanthus sonchifolius*) tuber with commercialized fructo-oligosaccharides (FOS) in terms of physiology, fermentation products, and intestinal microbial communities in rats. *Bioscience of Microbiota, Food and Health*, *32*(4), 167–178. https://doi.org/10.12938/bmfh.32.167

Vasconcelos, C. M., de Oliveira, E. B., Rossi, S. N., Arantes, L. F., Puschmann, R., & Chaves, J. B. P. (2015). Evaluating strategies to control enzymatic browning of minimally processed yacon (*Smallanthus sonchifolius*). *Food and Bioprocess Technology*, *8*(9), 1982–1994. https://doi.org/10.1007/s11947-015-1558-0

Vasconcelos, C., Oliveira, E., Arantes, L., Rossi, S., Rocha, R., Puschmann, R., & Chaves, J. (2020). Antibrowning effect of the combination of ascorbic, citric, and tartaric acids on the quality of minimally processed yacon (*Smallanthus sonchifolius*). *Boletim do Centro de Pesquisa de Processamento de Alimentos*, *36*. https://doi.org/10.5380/BCEPPA.V36I2.62947

Yan, M. R., Welch, R., Rush, E. C., Xiang, X., & Wang, X. (2019). A sustainable wholesome foodstuff; health effects and potential dietotherapy applications of yacon. *Nutrients*, *11*(11), 2632. https://doi.org/10.3390/nu11112632

Yao, J., Chen, W., & Fan, K. (2023). Novel efficient physical technologies for enhancing freeze drying of fruits and vegetables: A review. *Foods*, *12*(23), 4321. https://doi.org/10.3390/foods12234321

Yuniastuti, A., & Iswari, R. (2019). Isolation and identification of inulin and FOS from *Dioscorea esculenta*. *KnE Social Sciences*. https://doi.org/10.18502/kss.v3i18.4696

Zhang, C., & Liu, Y. (2017). Sugaring-out-assisted aqueous two-phase extraction of fructooligosaccharides from yacon (*Smallanthus sonchifolius*). *Separation Science and Technology*, *52*, 1531–1536. https://doi.org/10.1080/01496395.2017.1293099

ARTICLE 2 - PROCESS AND QUALITY PARAMETERS OF CONVECTIVE DRIED YACON: INFLUENCE OF ETHANOL TREATMENT

Article published in the Journal Food Research International
ISSN: 1873-7145
DOI: 10.1016/j.foodres.2023.113863

P. G. Silveira[a*], C. R. de P. Silva[a], J. L. G. Corrêa[a], I. J. Petri [b] and S. V. Borges[a]
[a]Department of Food Science, Federal University of Lavras, Lavras, Brazil;
[b]Department of Engineering, Federal University of Lavras, Lavras, Brazil.

Abstract

Yacon is a highly perishable tuberous root, rich in fructooligosaccharides (FOS). Convective drying preceded by ethanol treatment (ET) is an alternative for increasing shelf life in a shorter process. The aim of this study was to investigate the impact of ET and temperature (50°C and 70°C) on quality parameters (fructan retention, total phenolic content, antioxidant capacity, shrinkage, color and microstructural parameters) and process parameters (drying time, drying kinetics, and energy consumption) in the convective drying of yacon slices. The ET induced structural alterations in the tissues and cells that aids in the reduction of drying time up to 28.00%. ET resulted in an increase in effective diffusivity and leaded to noteworthy reduction in energy consumption (up to 22.72%). The quality parameters such as color, shrinkage, and total phenolic content showed no significant differences among the treatments. The use of ethanol promoted highest preservation of antioxidant activity; however, it caused degradation of FOS. The ethanol pretreated drying at 50°C was the better condition for lower consumption and preservation of quality parameters as total phenolic content, antioxidant capacity and fructan retention, but the samples dried at 50°C were the ones with the highest fructan retention (55.11 ± 2.19 %).

Keywords: Marangoni effect. Energy efficiency. Fructooligosaccharides. Phenolic compounds. Prebiotic.

1. Introduction

Yacon roots (*Smallanthus sonchifolius*) belong to the botanical family Asteraceae. It is a perennial herbaceous species native to Andean region. Its tuberous roots are described as succulent and slightly sweet, and they are consumed fresh or in salads as a dietary and traditional food (Corrêa *et al.*, 2021). Yacon has been attracting increasing attention due to its beneficial health properties and potential applications in the food industry (Verediano *et al.*, 2021). It is described as a functional food with a low glycemic index, antioxidant potential, rich in phenolic compounds, and high amounts of fructooligosaccharides (Paredes *et al.*, 2018).

Recent studies showed that yacon extracts have prebiotic effects, increasing the abundance of beneficial bacteria such as *Lactobacillus* and *Bifidobacterium* (Martino *et al.*, 2020). Researchs indicate that daily consumption of yacon roots, rich in fructooligosaccharides (FOS), may be promising in mitigating liver damage caused by high-fructose diets, serving as a potential nutritional strategy in treating liver diseases (Alemán *et al.*, 2022). Furthermore, studies on the impregnation of yacon FOS in foods, such as apple slices, highlight the ability of its componentsto improve functional properties of dehydrated foods (Mejía Águila *et al.*, 2021). The incorporation of yacon flour into meat products, such as sheep mortadella, has shown to be a promising alternative in producing healthy meat products (do Santos Junior *et al.*, 2020). Additionally, the use of yacon flour in sweet biscuit production has demonstrated suitable physicochemical characteristics and sensory acceptance, suggesting its applicability as a functional ingredient in the baking industry (Simanca-Sotelo *et al.*, 2021). Those studies complement the investigation into the benefits of yacon, expanding the understanding of its properties and potential applications in the food industry. However, challenges such as perishability, color instability after processing, and intrinsic characteristics such as high moisture content have been the focus of studies to enhance the industrial application of yacon (Martins *et al.*, 2022). Therefore, yacon requires applying preservation techniques (Limbaga; Esguerra; Castillo-Israel, 2020). Convective drying with heated air is widely used as a preservation technique, a simple moisture removal process affected by various factors such as temperature and air velocity (Macedo *et al.*, 2021a). Food drying prevents harmful microbial and physicochemical reactions, extends the shelf life of dried products, and reduces weight and volume leading to lower packaging, storage, and transportation costs (Macedo *et al.*, 2023).

Traditional drying methods require long processing time and large amounts of energy, which is undesirable from an industrial perspective and may compromise product quality (Bitencourt *et al.*, 2022). Some alternatives for improving the quality of a convective dried food is the use of pretreatments as ultrasound, vacuum, osmotic dehydration, high hydrostatic pressure, pulsed electric fields, carbonic maceration ethanol, and microwave (Corrêa *et al.*, 2017; Macedo *et al.*, 2022).

Ethanol is a low-cost and non-toxic solvent and the immersion in ethanol used as a pretreatment in food drying, could aids in moisture removal due to changes in the cell wall that enhance drying, such as changes in vapor pressure and the Marangoni effect (Macedo *et al.*, 2021b). There is a growing interest in using ethanol treatment to improve drying processes, and some beneficial effects with the use of this solvent have been reported in studies with food materials such as bananas (Corrêa *et al.*, 2012), strawberry (Macedo *et al.*, 2021a), and potato (Guedes *et al.*, 2021). Guedes *et al.* (2021) found that ethanol treatment can significantly reduce drying time for starchy foods like potatoes, without negatively impacting the quality of the final product. Rojas and Augusto (2018) further supported those findings, demonstrating that ethanol treatment can improve the drying and rehydration processes of vegetables like pumpkin. Junqueira *et al.* (2021) noted that while ethanol treatment can reduce drying time and preserve nutritional characteristics in taioba leaves, it may also lead to a decrease in total phenolic compounds and antioxidant activity. Those studies collectively suggest that while ethanol can be beneficial in the drying industry and food products, its use may have some limitations, particularly in the preservation of certain nutritional components.

This study aimed to evaluate the influence of an emerging technology, specifically the utilization of ethanol as a pretreatment in yacon drying, encompassing the assessment of physicochemical, bioactive, microstructural, and antioxidant parameters. Furthermore, the investigation sought to understand the effects of those elements on the drying process parameters, such as drying time, drying kinetics, and energy consumption.

2. Materials and methods

2.1 Material

The yacon roots were obtained from the local market in Lavras, Minas Gerais state, Brazil, and were stored under refrigeration (4±1°C) for up to seven days (Oliveira and Nashimoto, 2005). The fresh roots had an average moisture content of 8.06±0.64 (d.b.), fructooligosaccharides (FOS) content of 67.84±1.86 (g $100g^{-1}_{sample_{d.b.}}$), and water activity ($a_w$) of 0.985±0.010.

The roots were washed with tap water and sanitized in a chlorine solution at a ratio of 100:1 (v v^{-1}) for 15 min. Then, they were rinsed with distilled water to remove excess sodium hypochlorite, and excess water was removed using absorbent paper. Finally, the roots were cut into parallelepiped shapes with a square base of 2 cm per side and a thickness of 0.4 cm using a mold. They were immediately immersed in a 1% citric acid solution for 3 min for enzymatic inactivation (Corrêa *et al.*, 2021).

2.2 Experimental design

The experiments were conducted in a completely randomized design arranged in a full 2×2 factorial scheme, using drying temperatures of 50 and 70ºC, with and without ethanol treatment, as shown in Table 1. The ethanol treatment is described as follows. The data underwent scrutiny through analysis of variance (ANOVA). Treatment comparisons were conducted using the Tukey test, while individual comparisons between each treatment and the control sample (fresh sample) were performed employing the Dunnett test. Statistical significance was predetermined at $p < 0.05$.

Table 1 - Two-level factorial experimental design used.

Code	**Ethanol treatment**	**Temperature (°C)**
50	No	50
50 ET	Yes	50
70	No	70
70 ET	Yes	70

ET - Ethanol treatment.

The statistical analyses were performed at a significance level of 5% using the Statistica software (Stat Soft Inc., Tulsa, OK, USA).

2.3 Ethanol treatment

The ethanol treatment of yacon slices was performed by immersing the samples in 99% ethanol (v v^{-1}) at a ratio of 1:5 (w v^{-1}) for 2 min at 25°C (Macedo *et al.*, 2021a).

2.4 Convective drying

The samples with and without ethanol treatment was dried in a convective dryer (Eco Engenharia Educacional, MD018 model, Brazil) with a parallel flow in an air velocity of 1 m.s^{-1} at 50°C and 70°C. For each drying process, 68.0 ±0.5 g of sample was used.

The weight of the samples was measured every 5 min during the first hour of drying to evaluate the moisture content evolution over time. Subsequently, the weights were measured every 10 min using an analytical balance (Marte Cientifica, model AD33000, Brazil) with a precision of ± 0.01 g attached to the sample holder. Drying was stopped when the samples reached the equilibrium moisture content at each temperature.

The moisture ratio (MR) and drying rate (DR) were determined according to Equations (1) and (2), respectively.

$$MR = \frac{X_t - X_e}{X_0 - X_e} \tag{1}$$

$$DR = \frac{X_t - X_{t+\Delta t}}{\Delta t} \tag{2}$$

Where X_0, X_t, X_e, $X_{t+\Delta t}$, and Δt represent, on a dry basis, the initial moisture content, moisture at time t (min), equilibrium moisture content, moisture at time t+Δt, and time difference (min), respectively.

The drying curves were fitted to the Fick model (Equation 3) to describe the drying kinetics of yacon slices based on a solution considering a semi-infinite plate with unidirectional diffusion limited by the smallest dimension (Crank, 1975).

$$MR = \left[\frac{8}{\pi^2}\sum_{i=0}^{\infty}\frac{1}{(2i+1)^2}\exp\left(-(2i+1)^2\pi^2 D_{eff}\frac{t}{4L^2}\right)\right] \tag{3}$$

Where D_{eff} represents the effective diffusivity (m².s^{-1}), t is the time (s), i is the number of series terms, L is the length corresponding to half of the thickness (m), and MR is the dimensionless moisture content.

2.5 Energy consumption (Et)

The E$_t$ consumed by the equipment used in the drying tests of yacon slices at different air temperatures was calculated according to Equation (5) (Corrêa *et al.*, 2021).

$$E_t = A.\upsilon_a.\rho_a.t.C_a.\Delta T \tag{4}$$

Where E_t is the total energy consumption (kWh), A is the area of the cross-section of the container in which the sample is placed (m^2), υ_a is the air velocity (m s^{-1}), ρ_a is the air density (kg m^{-3}), t is the time when the equipment is turned on (hr), C_a é the specific heat of the air (kJ kg^{-1} K^{-1}), and ΔT is the temperature difference (K). The specific density and heat of the air are temperature functions, and the values were obtained from thermodynamic tables (Smith *et al.*, 2019).

The energy consumption required to remove 1 kg of water was calculated according to Equation (5).

$$EC = \frac{E_t}{m_f - m_0} \tag{5}$$

Where EC is the energy consumption per kg of water; m_f and m_0 are the sample mass (kg) at the end and beginning of drying, respectively.

2.6 Qualitative analyses

Fresh and dried samples were characterized for moisture content, water activity, shrinkage, color, the content of total phenolic compounds, and antioxidant capacity fructooligosaccharides (FOS) and the dried slices were evaluated through their structure.

2.6.1 Moisture content and water activity (aw)

The a_w measures water availability in food and is a key factor in food quality and safety. High a_w makes the food susceptible to microbial proliferation. Therefore, reducing a_w is essential to prevent microbial growth and ensure product quality. It was determined using a digital hygrometer (Aqualab series 3TE, Decagon, Pullman, USA) at 25°C (Macedo *et al.*, 2022).

The moisture content was determined by the gravimetric method established by method 934.06 of AOAC, wherein the samples were placed in an oven at 70°C, under vacuum (AOAC, 2010).

2.6.2 Shrinkage (Sh)

Sample shrinkage was determined based on the displacement method using toluene for volume calculations, according to Equation (6) (Gamboa-Santos *et al.*, 2014).

$$Sh\,(\%) = \left(1 - \frac{V}{V_0}\right).100 \tag{6}$$

Where V and V_0 are the volume (m^3) of the dried and fresh samples, respectively.

2.6.3 Color

The instrumental measurements of color parameters were performed on the fresh and dried samples using a portable colorimeter (model LS173, Shenzhen Linshang Technology Co., Ltd., Shenzhen, Guangdong, China). The results were expressed using the CIELab color scale. The total color difference (ΔE) and the chroma (C_{ab}) was calculated using Equation (7) and (8), respectively:

$$\Delta E = \sqrt{(L^* - L_0^*)^2 + (a^* - a_0^*)^2 + (b^* - b_0^*)^2} \quad (7)$$

$$C_{ab} = \sqrt{a^{*2} + b^{*2}} \quad (8)$$

Where L^*, a^*, and b^* are chromatic scales where L^* represents lightness, a^* represents shades ranging from red to green, and b^* represents shades ranging from yellow to blue.

2.6.4 Total phenolic content (tpc) and antioxidant capacity (ac)

The samples (fresh and dried) were prepared by extracting 1.0 g of sample in 100 mL of 50.00% ethanol at 25°C for 120 min. The extraction was conducted in a water bath (model 501-DE, Vargem Grande Paulista, São Paulo, Brazil) with temperature and agitation control. After extraction, the samples were centrifuged for 15 min at 3500×g, and the supernatant was collected to determine phenolic compounds and antioxidant capacity (AC). The total phenolic content (TPC) was determined according to the method proposed by Huang *et al.* (2005) with some modifications. 250.00 μL of the sample, 250.00 μL of Folin-Ciocalteu reagent (1:3), and 2 mL of distilled water were homogenized, and after 5 min, 250.00 μL of 10.00% sodium carbonate solution was added. Finally, the mixture was kept in the dark for 1 hour at room temperature for absorbance readings. Gallic acid was used as a standard to generate a calibration curve, and TPC was expressed as mg of gallic acid equivalent/100 g of the extract on a dry weight basis (mg GAE (100 $g^{-1}_{sample_{d.b.}}$).

Antioxidant analysis with the DPPH free radical was performed according to Stojakowska *et al.* (2013) with some modifications. 75.00 μL of sample and 2925 μL of DPPH solution were added to a cuvette. The samples were left in the dark for 30 min. A calibration curve was generated using Trolox as a standard, and the results were expressed as Trolox equivalents (TE) per gram of extract (μM TE $g^{-1}_{sample_{d.b.}}$).

Readings were performed on a Shimadzu® UV/Visible spectrophotometer (model SPD-10A) using a wavelength of 750.00 nm for TPC quantification and 515 nm for AC determination.

2.6.5 Fructan retention – FR

The FOS content was quantified following the AOAC 997.08 method (AOAC, 2010) using the Fructan HK Assay Procedure commercial kit (Magazyme International Ireland, Ltd., Bray, Ireland). FR is calculated using Equation (9).

$$FR(\%) = \frac{F_d}{F_f}.100 \tag{9}$$

Where F_d is the concentration of FOS in the dried sample and F_f is the concentration of FOS in the fresh sample.

2.6.6 Yacon structure

Scanning Electron Microscopy (SEM) was used to observe the structure of fresh and dried (treated and non-treated) yacon slices. The internal structure of yacon slices was observed, i.e., the surfaces correspondent to the slice thickness. For this, rectangular cuts were made in the samples, using a scalpel. After cutting, the obtained pieces were fixed overnight in 2.50% glutaraldehyde and cacodylate buffer (pH 7.20). It is important to note that this procedure ensure that structural changes will not occur during the dehydration step Subsequently, the samples were removed from the solution and washed three times with cacodylate buffer. Then, the samples were dehydrated in a graded acetone series (20.00%, 40.00%, 60.00%, 70.00%, and 90.00%) and finally absolute acetone three times for 1 hour. After the last immersion (using absolute acetone) the samples were transferred to stubs, which contained a double-sided carbon tape to hold the samples. The metallization process deposited a thin layer of gold in the stubs, which were placed in a scanning electron microscope (TESCAN CLARA UHR-SEM, TESCAN Ltd., Kohoutovice, CZE) operating at 20kV (Guedes *et al.*, 2021). The samples were then evaluated in the microscope using an Earhart-Thornley Detector (ETD) for secondary electrons and the magnification of 2000× and 8400 ×.

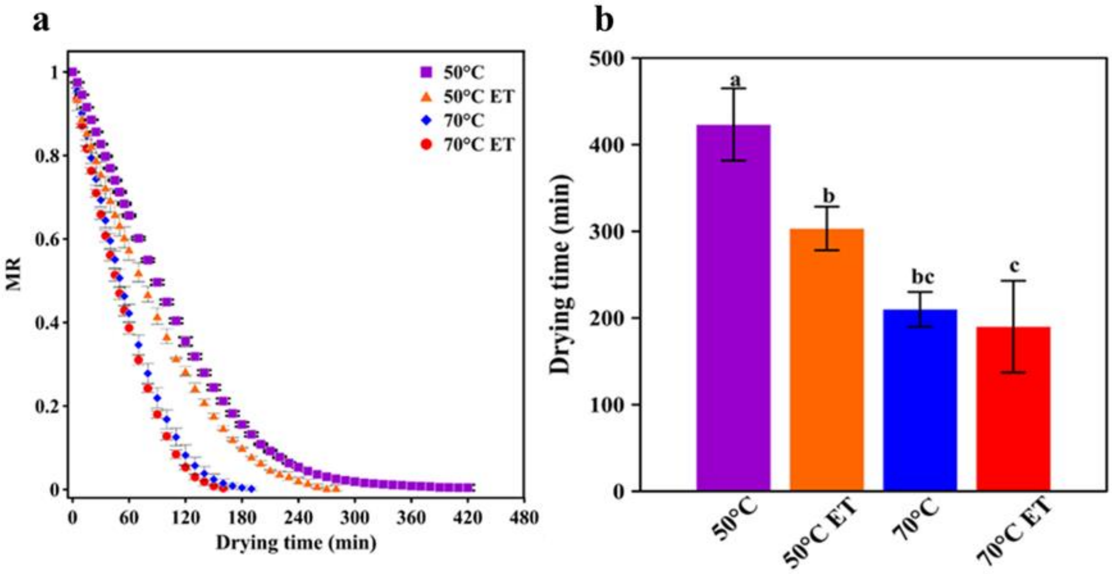
The wall thickness was measured by image analysis using the free software Image J$^{®}$ 1.45 s, which provides the sample thickness by converting the pixels in the image into real dimensions, from a known scale (Junqueira *et al.*, 2018). For each sample, the wall thickness at five different points was determined using software ImageJ®.

3 RESULTS AND DISCUSSION

3.1 Drying

The drying kinetics and drying time are shown in Figure 1. During the drying process, the sample moisture content was reduced until its equilibrium condition at each condition. Significant differences in drying time were observed for the studied treatments (Figure 1b). Treatment 50°C exhibited the longest drying time while the shortest one was obtained in the treatment 70°C ET. Moreover, no statistically significant differences in drying time were observed between treatments 50°C ET and 70°C and between 70°C and 70°C ET. Using ethanol as pretreatment caused a time reduction of 28.00% and 10.53% at 50 and 70ºC, respectively. This effect has been reported previously in studies that used ethanol as a pretreatment, such as Corrêa *et al.* (2012), who studied the use of ethanol as a pretreatment in the drying of bananas, Macedo *et al.* (2023) in the drying of strawberries, Guedes *et al.* (2021) in the drying of potatoes, Macedo *et al.* (2021a) in the drying of red and white dragon, Junqueira *et al.* (2021) in the drying of taioba leaves. According to Guedes *et al.* (2021), the use of ethanol as a pretreatment can cause structural changes that enhance subsequent drying, as ethanol disrupts cell wall components, increasing permeability and mass transfer.Those effects can be evidenced by Figure 2, which shows SEM images of yacon slices, fresh and after drying.

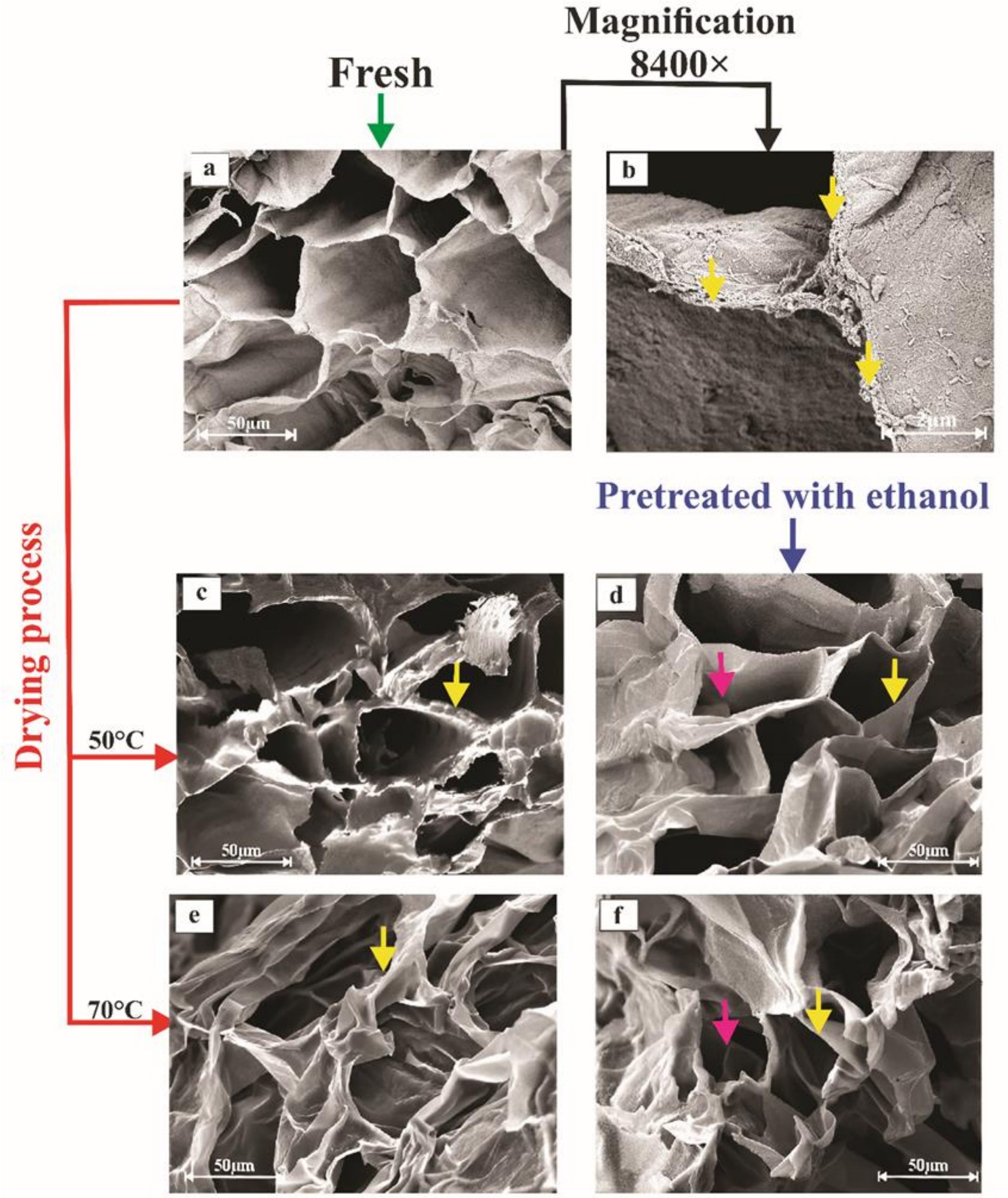
Figure 1 - Drying kinetics (a), drying time (b).



Caption: Mean ± standard deviation, n = 3. ET - Ethanol treatment. Equal letters indicate no significant difference by the Tukey test ($p < 0.05$) between pretreated and no treated samples.

Fresh yacon slices (Figure 2a) exhibit a tissue composed of elongated and polyhedral turgid cells, with a clearly defined cell wall, as evidenced in Figure 2b. It is possible to observe that, after treatment with ethanol, cells lose turgor, altering their initial shape and becoming more distorted and compacted compared to fresh samples, at 50°C and 70°C (region indicated by the pink arrow in Figure 2d and f). The region indicated by the yellow arrows in Figure 2 highlights the region for measuring the thickness of cell walls in treated samples (Fig 2d and f) and untreated ones (Fig 2b and c).

Figure 2 - Yacon microscopic tissues.



Caption: Fresh (a), Magnification 8400 x in the region of the cell wall of the fresh yacon slice (b), 50°C (c) and 50°C ET (d), 70°C (e) and 70°C ET.

The measurements of the thickness are presented in Table 2. It is shown that slices treated with ethanol presents a significant reduction in cell wall thickness ($p < 0.05$), ranging from 0.33 to 0.36 ± 0.01 µm. It makes easier the flow of moisture in the cell wall. According to Guedes *et al.* (2021), ethanol extracts some components from the cell wall and membrane, reducing their thickness. However, compounds like cellulose, hemicellulose and lignin are not removed. This maintains walls thinner, preventing collapse, preserving the cell organelles such as vacuole. Similar results were obtained by Santos *et al.* (2021), Saavedra *et al.* (2023) and

Guedes *et al.* (2021) in the ethanol pretreated drying of carrot, pineapple and potatoes, respectively. According to Pratyusha (2022), the absence of cell collapse with ethanol treatment indicates preservation of the cell organelle structure, such as the vacuole. The vacuole is responsible for storing high concentrations of phenolic compounds in plant cells. Khoddami *et al.* (2013) suggested that ethanol immersion proves ineffective in extracting phenolic compounds resident in the vacuole. Thus, ethanol treatment could maintain the total phenolic content and antioxidant activity in yacon slices.

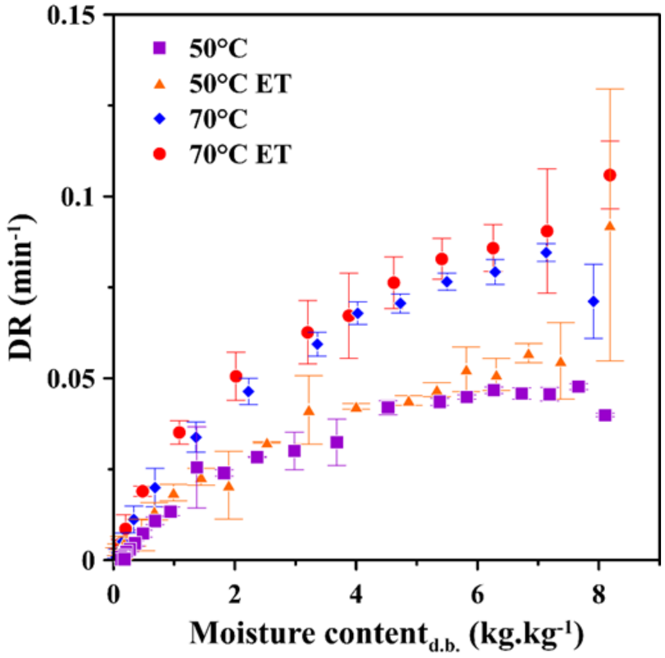
Table 2 - Wall thickness at different drying conditions

Code	**Thickness (µm)**
Fresh	1.178 ± 0.001^a
50°C	0.791 ± 0.050^b
50°C ET	0.333 ± 0.010^d
70°C	0.716 ± 0.010^c
70°C ET	0.360 ± 0.010^d

Mean ± standard deviation, n = 3. ET - Ethanol treatment. Equal letters indicate no significant difference by the Tukey test ($p < 0.05$) between pretreated and no treated samples.

Figure 2c and 2e represent the trials without ethanol treatment at 50°C and 70°C, respectively. It is evident that the rise in drying temperature led to the loss of cell turgidity and structure alteration, potentially enhancing mass transfer during the drying process. As a result, the resistance to moisture removal is reduced with temperature It is also related to an increase in the water molecules mobility (Santos *et al.*, 2021). Moreover, the external resistance is also reduced with the temperature, due to the increase in its driving force (Junqueira *et al.*, 2021): The mixture of ethanol with water presents lower vapor pressure concerning the one of water (Saavedra *et al.*, 2023). The temperature decreased the drying time by 50.00% for experiments at 50 and 70ºC without pretreatment and 36.00% for the same temperatures with ethanol treatment. The increase in the temperature tends to enhance heat transfer and accelerate the evaporation process. The higher the temperature, the higher the drying rate (Figure 3) (Hadjout Krimat *et al.*, 2023). Similar results were found by Salinas *et al.* (2018), Corrêa *et al.* (2021) and Oliveira *et al.* (2021) in studies involving convective drying of yacon under different temperatures.

Figure 3 - Drying rate with and without pretreatment.



Caption: ET - ethanol treatment.

In all the studied cases, the maximum DR was achieved at the beginning of the process when MR presented its maximum values. Besides, the drying rate increased with temperature, with a higher reduction in moisture content (MR), as can be observed at 70°C and 70°C ET (Figure 2). The DR tends to decrease with the processing time, with a short period of near-constant DR, where the evaporation rate of water from the sample surface was similar to the diffusion within the material towards the surface. At both temperatures, the DR of treated samples was higher than that of non-treated due to increased water mobility within the pores, reducing internal resistance to moisture transport. The Table 3 presents the effective diffusivity (D_{eff}) and fitting parameters obtained using the Fick model. The Fick model was satisfactorily fitted to the drying kinetics of yacon. Good fits of the Fick model applied to the convective drying of yacon have also been reported by Corrêa *et al.* (2021) and Oliveira *et al.* (2021). There was an increase in D_{eff} due to ethanol treatment in the 50°C and 50°C ET treatments; however, the same was not observed between the 70°C and 70°C ET treatments, where there was no significant difference. The D_{eff} increased with the use of the ethanol treatment and with temperature as pointed by Junqueira *et al.* (2023) and Macedo *et al.* (2023). Both dependencies have the same reasons discussed in the drying time. As stated by Guedes *et al.* (2021), the reduction in drying time and the subsequent increase in effective diffusivity during ethanol treatment can be attributed to a synergetic effect involving structural changes and the Marangoni effect.

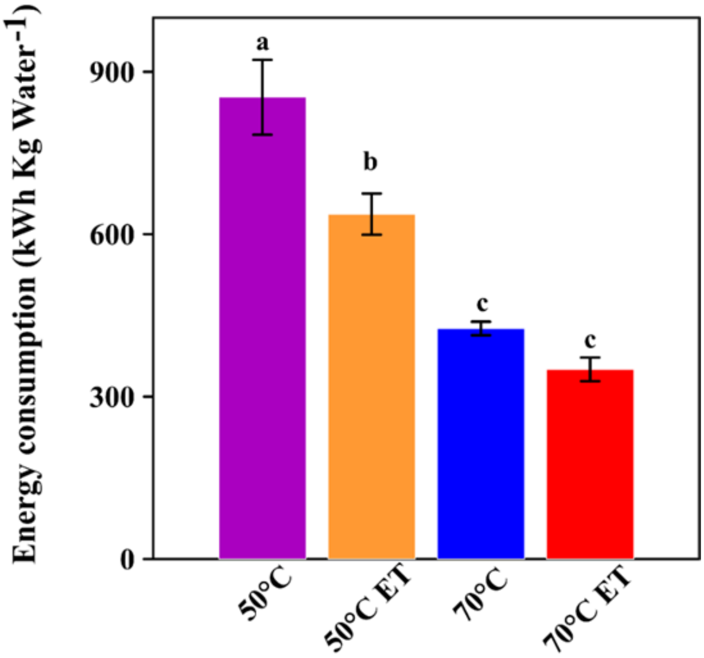
Table 3 - Effective diffusivities of water (*Deff*) and statistical parameters for the drying kinetics of yacon.

Code	D_{eff} (× 10^{-10}, m^2s^{-1})	R^2
50°C	1.920 ± 0.01^c	0.915
50°C ET	2.400 ± 0.01^b	0.917
70°C	2.990 ± 0.01^a	0.919
70°C ET	3.300 ± 0.01^a	0.916

Mean ± standard deviation, n = 3. ET - Ethanol treatment. Equal letters indicate no significant difference by the Tukey test ($p < 0.05$) between pretreated and no treated samples.

The energy consumption is presented in Figure 4. It was observed that the increase in temperature led to a reduction in consumption, regardless of the use of pretreatment. The consumption was reduced by up to 58.92% with the temperature increase from 50 to 70°C in pretreated samples. The increase in temperature results in greater excitation of water molecules within the material, increasing vapor pressure and, consequently, water diffusivity (Rodríguez-Ramos *et al.*, 2021). Therefore, it is observed that the energy consumption at 70°C was lower than that at 50°C, as also reported by Corrêa *et al.* (2021). Ethanol as a pretreatment reduced energy consumption by up to 22.72% (Figure 4).

Figure 4 - Energy consumption at different drying conditions.



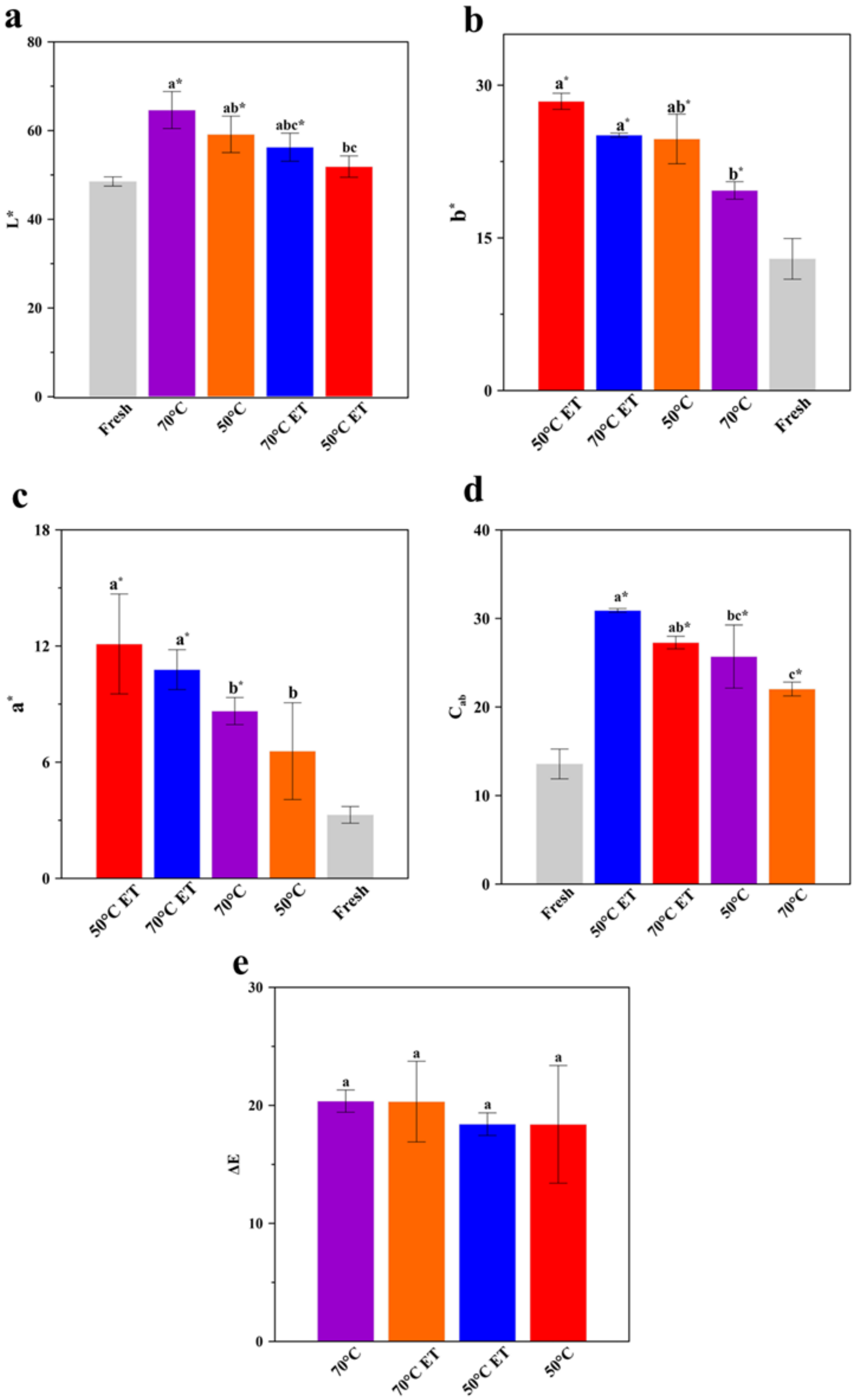
Caption: Mean ± standard deviation, n = 3. ET - Ethanol treatment. Equal letters indicate no significant difference by the Tukey test ($p < 0.05$) between pretreated and no treated samples.

3.2 Quality analyses

The dried yacon slices exhibited a_w= 0.360 ± 0.010, values below 0.6, considered the lower limit for microbial growth (Macedo *et al.*, 2023). The dried product presented a high degree of shrinkage (Sh), it ranged from 84.16 ± 1.88% to 87.68 ± 0.45%, with no significant differences among the treatments. This substantial shrinkage is a common feature in drying processes and usually influences texture and chewability (Macedo *et al.*, 2021a). Similar behavior was obtained by Corrêa *et al.* (2012) in the drying of bananas. On the other hand, Braga *et al.* (2010) obtained greater shrinkage coefficients using ethanol in pineapple drying. This means that the influence of ethanol treatment in Sh is dependent on the food material. For all dried samples, it was observed that shrinkage was anisotropic due to the uneven decrease in linear dimensions in different directions within the microstructure of the food, resulting in yacon distortion. The reduction in the volume of the material is due to water removal during drying, especially in materials such as yacon, where water represents a significant portion of its composition. Similar results were reported by Corrêa *et al.* (2021). Other studies discussed shrinkage during convective drying of yacon. For example, Bernstein and Noreña (2014) investigated the effect of convective drying on yacon thermodynamic and structural properties. They reported a collapse and severe shrinkage in the tissue of the slices. Additionally, they observed stomata opening in the surface layer caused by prolonged drying time.

The colorimetric parameters of dried and fresh yacon are shown in Figure 5. It was observed that the color parameters of yacon were significantly affected by temperature and ethanol treatment ($p \leq 0.05$). After drying, the samples showed a significant increase in the L^* parameter (Figure5a), proportional to the temperature increment. This effect was also described by Corrêa *et al.* (2021), where the authors highlighted higher values of L^* and ΔE at the highest drying temperature (70°C). In a study conducted by Salinas *et al.* (2018), where yacon was evaluated at different drying temperatures (45°C, 50°C, and 55°C), an increase in the red (a^*) and yellow (b^*) tones were observed in samples with higher temperature, resulting in a strong orange coloration. During convective drying, yacon tends to exhibit dark pigments due to the degradation of compounds present in the root through oxidation, Maillard reactions and caramelization (Corrêa *et al.*, 2021).

Figure 5 - Colorimetric parameters of fresh and dried yacon.



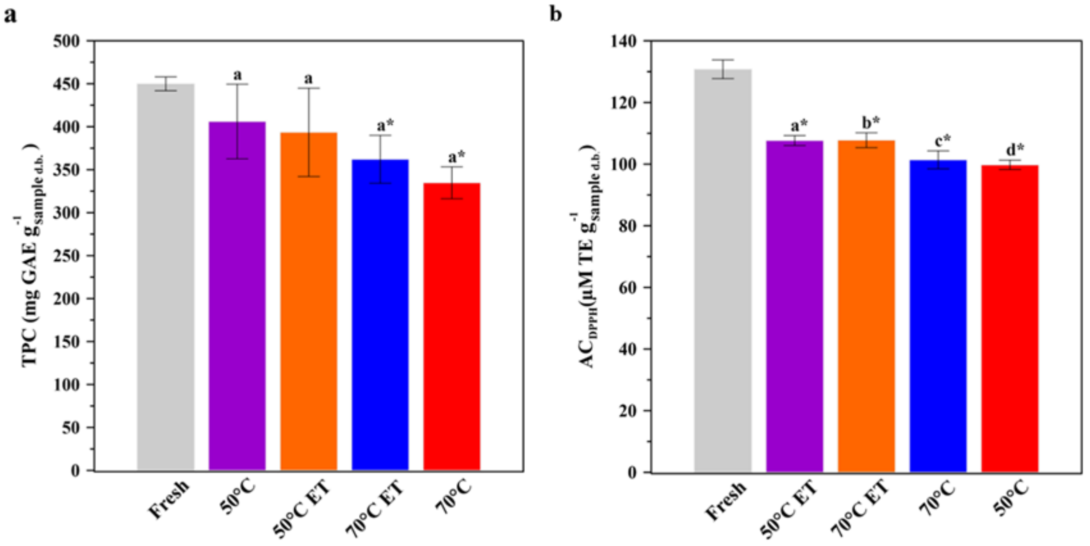
Caption: Mean ± standard deviation, n = 3. ET - Ethanol treatment. Equal letters indicate no significant difference by the Tukey test ($p < 0.05$) between pretreated and no treated samples. The asterisk indicates a significant difference between each treatment and the fresh sample by the Dunnett test ($p < 0.05$).

The ethanol pretreated samples showed a significant increase in the b^*(Figure 5b), a^* (Figure 5c) and C_{ab} (Figure 5d) parameter, while the L^* parameter was reduced after drying.

This may have occurred because ethanol treatment could increase the vulnerability of the samples to oxidation caused by contact with the external air. Additionally, immersion in ethanol can also remove air from the tissues, alter the composition of cell walls, and increase the surface contact of the samples, enabling the action of oxidative agents (Macedo *et al.*, 2022). In all treatments, no significant difference was observed in the ΔE parameter (Figure 5e), which minimizes the effects of temperature and ethanol treatment on the color parameters of yacon. Corrêa *et al.* (2021) also reported a few significant differences in the color parameters of yacon after convective drying.

The values of TPC and AC are presented in Figure 6. The TPC results showed no significant differences among the dried samples. The treatments dried at 50°C did not statistically differ from the fresh yacon sample, indicating that the degradation of phenolic compounds was minimized at this temperature. The treatments dried at 70°C showed lower retention of phenolic compounds, and there was a significant difference compared to the fresh yacon ($p < 0.05$). The TPC in the 70°C ET treatment was reduced by 19.52%, and in the 70°C treatment, it was reduced by 25.60%. The reduction in TPC values with increasing drying temperature in yacon roots was also reported by Castro *et al.* (2012). Studies have shown that convective drying at moderate temperatures can lead to higher retention of phenolic compounds, while very high temperatures can result in a significant loss of those compounds (Barros *et al.*, 2020).

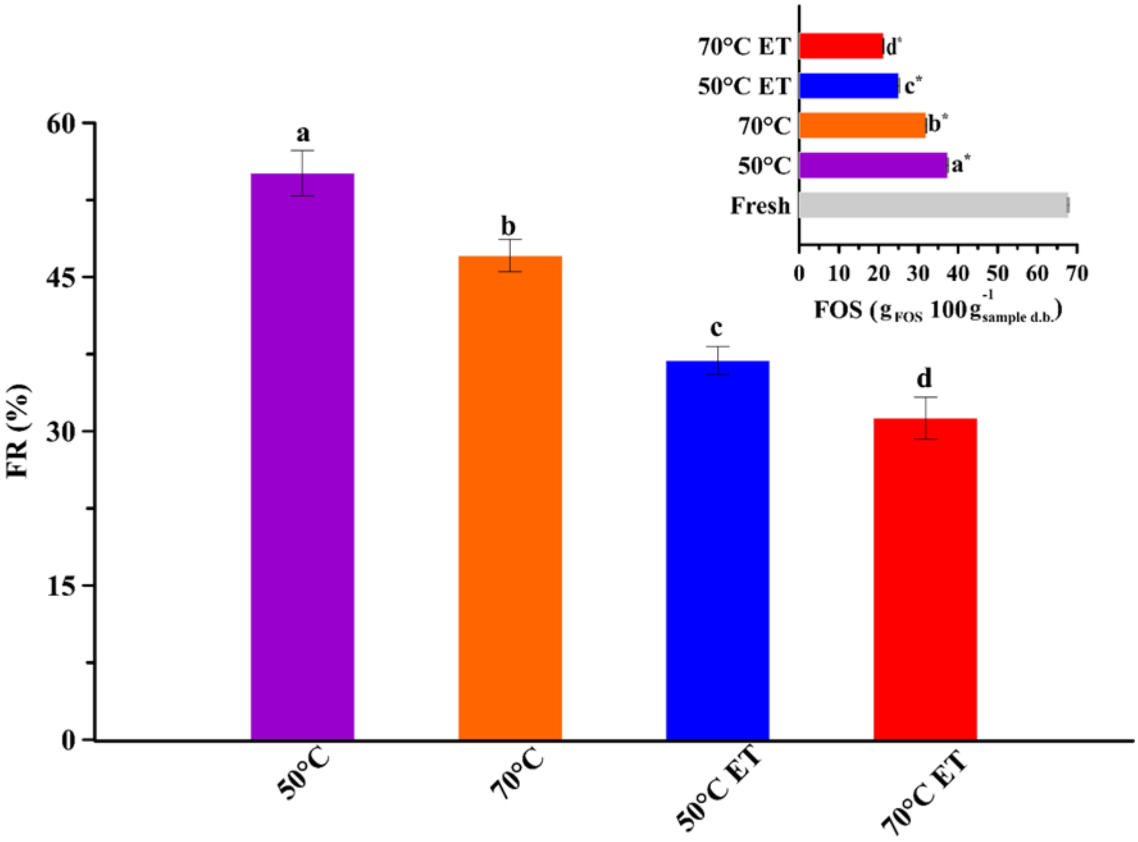
Figure 6 - Total phenolics content and antioxidant capacity.



Caption: Mean ± standard deviation, n = 3. ET - Ethanol treatment. Equal letters indicate no significant difference by the Tukey test ($p < 0.05$) between pretreated and no treated samples. The asterisk indicates a significant difference between each treatment and the fresh sample by the Dunnett test ($p < 0.05$).

The AC of the fresh sample was 130.77 ± 3.02 (µM TE $g^{-1}_{sample_{d.b.}}$). Campos *et al.* (2012) reported a similar value of AC for yacon roots quantified by the assay DPPH (135.10 ± 0.10 µM TE $g^{-1}_{sample_{d.b.}}$). There was a significant reduction in the AC values for the dried samples. This can be justified by the drying process, which can degrade bioactive compounds due to temperature and exposure time to air (Castro; Mayorga; Moreno, 2018). The ethanol pretreated samples presented higher activity, indicating a beneficial effect of the pretreatment. This effect may be related to the preservation of cellular structure after immersing the samples in ethanol, as reported by Khoddami *et al.* (2013). Araújo *et al.* (2022) in an ethanol pretreated drying study observed that this preservation could also be related to the drying time obtained due to the use of ethanol. The retention of fructooligosaccharides (FOS) on a dry basis is shown in Figure 7. The fresh yacon exhibited a FOS content of 67.84 ± 1.86 (g_{FOS} $100g^{-1}_{sample_{d.b.}}$), as reported by Oliveira *et al.* (2021). According to the results, all dried samples showed significant differences among themselves and compared to the fresh yacon. It was also observed that the pretreated samples resulted in lower percentages of FOS in the final product compared to the non-treated samples. The interaction between ethanol and FOS can reduce the content of those compounds, resulting in their extraction or decomposition during processing. Additionally, the immersion of the samples in ethanol can cause the loss of FOS due to its solubility in the solvent (Piazzi Fuhr *et al.*, 2023). The period of ethanol immersion was adopted based on other works to reduce drying time with consequent improvement in some processes and quality parameters. Although the immersion period was short, the solubilization of the FOS in ethanol was relevant.

Figure **7** - Retention of fructans (FR).



Caption: Mean ± standard deviation, n = 3. ET - Ethanol treatment. Equal letters indicate no significant difference by the Tukey test ($p < 0.05$) between pretreated and no treated samples.

3.2 Conclusions

The study investigated the effects of temperature and ethanol treatments on convective drying of yacon slices. The ethanol treatment presented as advantages a significant reduction in drying time was up to 28.00% and higher energy saving (22.72%); ΔE parameter was not significantly affected, as well shrinkage; Ethanol treatment at 50°C exhibited high concentrations of phenolic compounds and demonstrated high antioxidant capacity. As drawbacks, the ethanol treatment at high temperatures was not so significant as at lower temperatures and induced reduction in the levels of total phenolic compounds and antioxidant capacity, indicating a possible degradation of bioactive components at higher temperatures. Despite the pointed relevant advantages of the ethanol pretreated, the drying at 50°C without treatment was considered the best condition due to its highest retention of FOS. For future research, a more detailed analysis of changes in sensory properties, such as texture and consumer perception is recommended.

References

Alemán, M. N., Sánchez, S. S., & Honoré, S. M. (2022). Daily Intake of Smallanthus sonchifolius (Yacon) Roots Reduces the Progression of Non-alcoholic Fatty Liver in Rats Fed a High Fructose Diet. Plant Foods for Human Nutrition, 77(4), 521–528. https://doi.org/10.1007/s11130-022-01009-7

AOAC. (2010) *Oficial methods of analysis* (18th ed). AOAC Internacional Association of Oficial Analytical Chemists, 2010.

Araújo, C. da S., Corrêa, J.L.G., Dev, S., Macedo, L.L., Vimercati, W.C., Rodrigues de Oliveira, C., Pio, L.A.S. (2022). Influence of pretreatment with ethanol and drying temperature on physicochemical and antioxidant properties of white and red pulp pitayas dried in foam mat. *Drying Technology*, 40, 484–493. https://doi.org/10.1080/07373937.2020.1809446

Barros, V.M., Moreira, J. de J. da S., Leite Neta, M.T.S., Nunes, T.P., Vasvary, E.H.S.C., Narain, N., Wartha, E.R.S. de A. (2020). Reduction of antinutrients and maintenance of bioactive compounds in flour from agro-industrial residue of acerola (*Malpighia emarginata* D.C.). *Research, Society and Development*, 9, e980998054. https://doi.org/10.33448/rsd-v9i9.8054

Bernstein, A., Noreña, C.P.Z. (2014). Study of Thermodynamic, Structural, and Quality Properties of Yacon (*Smallanthus sonchifolius*) During Drying. *Food Bioprocess Technology*, 7, 148–160. https://doi.org/10.1007/s11947-012-1027-y

Bitencourt, B.S., Corrêa, J.L.G., Carvalho, G.R., Augusto, P.E.D. (2022). Valorization of Pineapple Pomace for Food or Feed: Effects of Pretreatment with Ethanol on Convective Drying and Quality Properties. *Waste Biomass Valorization*, 13, 2253–2266. https://doi.org/10.1007/s12649-021-01659-9

Braga, A.M.P., Silva, M.A., Pedroso, M.P., Augusto, F., Barata, L.E.S. (2010). Volatile Composition Changes of Pineapple during Drying in Modified and Controlled Atmosphere. *International Journal of Food Engineering,* 6. https://doi.org/10.2202/1556-3758.1835

Campos, D., Betalleluz-Pallardel, I., Chirinos, R., Aguilar-Galvez, A., Noratto, G., Pedreschi, R. (2012). Prebiotic effects of yacon (*Smallanthus sonchifolius* Poepp. & Endl), a source of fructooligosaccharides and phenolic compounds with antioxidant activity. *Food Chemistry*, 135, 1592–1599. https://doi.org/10.1016/j.foodchem.2012.05.088

Castro, A., Caballero, M., Herbas, A., Carballo, S. (2012). Antioxidants in yacon products and effect of long term storage. *Food Science and Technology*, 32, 432–435. https://doi.org/10.1590/S0101-20612012005000064

Castro, A.M., Mayorga, E.Y., Moreno, F.L. (2018). Mathematical modelling of convective drying of fruits: *A review. Journal Food Engineering*, 223, 152–167. https://doi.org/10.1016/j.jfoodeng.2017.12.012

Corrêa, J.L.G., Braga, A.M.P., Hochheim, M., Silva, M.A. (2012). The Influence of Ethanol on the Convective Drying of Unripe, Ripe, and Overripe Bananas. *Drying Technology*, 30, 817–826. https://doi.org/10.1080/07373937.2012.667469

Corrêa, J.L.G., Lopes, F.J., Mello Junior, R.E., Jesus Junqueira, J.R., Angelis Pereira, M.C., Salvio, L.G.A. (2021). Dried yacon with high fructooligosaccharide content. *Journal Food Processing Engineering*, 44. https://doi.org/10.1111/jfpe.13884

Corrêa, J.L.G., Rasia, M.C., Mulet, A., Cárcel, J.A. (2017). Influence of ultrasound application on both the osmotic pretreatment and subsequent convective drying of pineapple (*Ananas comosus*). *Innovative Food Science & Emerging Technologies*, 41, 284–291. https://doi.org/10.1016/j.ifset.2017.04.002

Crank, J., 1975. *The Mathematics of Diffusion*, 2nd ed. Oxford University Press, London.

do Santos Junior, A. C., Oliveira, R. F. de, Henry, F. da C., Maia Junior, J. de A., Moulin, M. M., Della Lucia, S. M., Quirino, C. R., Martins, M. L. L., & Rampe, M. C. C. (2020). Physicochemical composition, lipid oxidation, and microbiological quality of ram mortadella supplemented with Smallanthus sonchifolius meal. Food Science & Nutrition, 8(11), 5953–5961. https://doi.org/10.1002/fsn3.1880

Gamboa-Santos, J., Montilla, A., Cárcel, J.A., Villamiel, M., Garcia-Perez, J. V. (2014). Air-borne ultrasound application in the convective drying of strawberry. *Journal Food Engineering*, 128, 132–139. https://doi.org/10.1016/j.jfoodeng.2013.12.021

Guedes, J.S., Santos, K.C., Castanha, N., Rojas, M.L., Matta Junior, M.D., Lima, D.C., Augusto, P.E.D. (2021). Structural modification on potato tissue and starch using ethanol pretreatment and drying process. *Food Structure,* 29, 100202. https://doi.org/10.1016/j.foostr.2021.100202

Hadjout-Krimat, L., Belbahi, A., Dahmoune, F., Hentabli, M., Boudria, A., Achat, S., Remini, H., Oukhmanou-Bensidhoum, S., Spigno, G., Madani, K. (2023). Study of microwave and convective drying kinetics of pea pods (*Pisum sativum* L.): A new modeling approach using support vector regression methods optimized by dragonfly algorithm techniques. *Jounal Food Process Engineering*, 46. https://doi.org/10.1111/jfpe.14232

Huang, D., Ou, B., Prior, R.L. (2005). The Chemistry behind Antioxidant Capacity Assays. *Journal Agriculture Food Chemistry*, 53, 1841–1856. https://doi.org/10.1021/jf030723c

Limbaga, J.C., Esguerra, E.B., Castillo-Israel, K.A.T. (2020). Enzymatic browning and chemical composition of whole yacon [*Smallanthus sonchifolius* (Poepp.) H. Rob.] tubers as affected by blanching. *Food Research*, 4, 1554–1562. https://doi.org/10.26656/fr.2017.4(5).107

Junqueira, J. R. de J., Corrêa, J. L. G., Resende, N. S., Balbinoti, T. C. V., Gatti, I. P., & Mendonça, K. S. de. (2021). Ethanol pretreatment in taioba leaves during vacuum drying. Ciência e Agrotecnologia, 45. https://doi.org/10.1590/1413-7054202145020421

Junqueira, J. R.J., Corrêa, J. L. G., de Mendonça, K. S., de Mello Júnior, R. E., & de Souza, A. U. (2018). Pulsed Vacuum Osmotic Dehydration of Beetroot, Carrot and Eggplant Slices: Effect of Vacuum Pressure on the Quality Parameters. Food and Bioprocess Technology, 11(10), 1863–1875. https://doi.org/10.1007/s11947-018-2147-9

Khoddami, A., Wilkes, M. A., & Roberts, T. H. (2013). Techniques for analysis of plant phenolic compounds. Molecules, 18(2), 2328–2375. https://doi.org/10.3390/molecules18022328

Macedo, L.L., Corrêa, J.L.G., Araújo, C. da S., Vimercati, W.C., Pio, L.A.S. (2021a). Process optimization and ethanol use for obtaining white and red dragon fruit powder by foam mat drying. *Journal Food Science*, 86, 426–433. https://doi.org/10.1111/1750-3841.15585

Macedo, L.L., Corrêa, J.L.G., da Silva Araújo, C., Cardoso, W.S. (2023). Use of Ethanol to Improve Convective Drying and Quality Preservation of Fresh and Sucrose and Coconut Sugar-impregnated Strawberries. *Food Bioprocess Technology*. https://doi.org/10.1007/s11947-023-03066-5

Macedo, L.L., Corrêa, J.L.G., da Silva Araújo, C., Vimercati, W.C., Júnior, I.P. (2021b). Convective Drying with Ethanol Pretreatment of Strawberry Enriched with Isomaltulose. *Food Bioprocess Technology*, 14, 2046–2061. https://doi.org/10.1007/s11947-021-02710-2

Macedo, L.L., Corrêa, J.L.G., Petri Júnior, I., Araújo, C. da S., Vimercati, W.C. (2022). Intermittent microwave drying and heated air drying of fresh and isomaltulose (Palatinose) impregnated strawberry. *LWT*, 155, 112918. https://doi.org/10.1016/j.lwt.2021.112918

Martino, H. S. D., Kolba, N., & Tako, E. (2020). Yacon (Smallanthus sonchifolius) flour soluble extract improve intestinal bacterial populations, brush border membrane functionality and morphology in vivo (Gallus gallus). Food Research International, 137, 109705. https://doi.org/10.1016/j.foodres.2020.109705

Martins, A. F. L., Vieira, É. N. R., Leite Júnior, B. R. C. de, & Ramos, A. M. (2022). Use of ultrasound and ethanol to improve the drying of yacon potato (Smallanthus sonchifolius): Effect of chemical and thermal bleaching. LWT, 162, 113448. https://doi.org/10.1016/j.lwt.2022.113448

Mejía-Águila, R. A., Aguilar-Galvez, A., Chirinos, R., Pedreschi, R., & Campos, D. (2021). Vacuum impregnation of apple slices with Yacon (Smallanthus sonchifolius Poepp. & Endl) fructooligosaccharides to enhance the functional properties of the fruit snack. International Journal of Food Science & Technology, 56(1), 392–401. https://doi.org/10.1111/ijfs.14654

Oliveira, L.F., Corrêa, J.L.G., Silveira, P.G., Vilela, M.B., Junqueira, J.R. de J. (2021). Drying of ‘yacon’ pretreated by pulsed vacuum osmotic dehydration. *Revista Brasileira de Engenharia Agrícola e Ambiental*,25, 560–565. https://doi.org/10.1590/1807-1929/agriambi.v25n8p560-565

Oliveira, M.A., Nishimoto, E.K. (2005). Carbohydrate characterization and quantification for yacon (Polymnia sonchifolia) stored under ambient and refrigerated conditions. Revista Raízes e Amidos Tropicais, 1, 30-39.

Paredes, L.L.R., Smiderle, F.R., Santana-Filho, A.P., Kimura, A., Iacomini, M., Sassaki, G.L. (2018). Yacon fructans (*Smallanthus sonchifolius*) extraction, characterization and activation of macrophages to phagocyte yeast cells. *International Journal Biology Macromolecules*, 108, 1074–1081. https://doi.org/10.1016/j.ijbiomac.2017.11.034

Piazzi Fuhr, A.C.F., Vieira, Y., Kuhn, R.C., Salau, N.P.G. (2023). Selective adsorption processes for fructooligosaccharides separation by activated carbon and zeolites through machine learning. *Chemical Engineering Research and Design*, 190, 379–394. https://doi.org/10.1016/j.cherd.2022.12.041

Pratyusha, S. (2022). Phenolic Compounds in the Plant Development and Defense: An Overview. Plant stress physiology, 7, 1-18. https://10.5772/intechopen.102873

Rodríguez-Ramos, F., Leiva-Portilla, D., Rodríguez-Núñez, K., Pacheco, P., Briones-Labarca, V. (2021). Mathematical modeling and quality parameters of Salicornia fruticosa dried by convective drying. *Journal Food Science Technology,* 58, 474–483. https://doi.org/10.1007/s13197-020-04556-6

Rojas, M. L., & Augusto, P. E. D. (2018). Ethanol pretreatment improves vegetable drying and rehydration: Kinetics, mechanisms and impact on viscoelastic properties. Journal of Food Engineering, 233, 17–27. https://doi.org/10.1016/j.jfoodeng.2018.03.028

Salinas, J.G., Alvarado, J.A., Bergenståhl, B., Tornberg, E. (2018). The influence of convection drying on the physicochemical properties of yacón (*Smallanthus sonchifolius*). *Heat and Mass Transfer*, 54, 2951–2961. https://doi.org/10.1007/s00231-018-2334-2

Santos, K. C., Guedes, J. S., Rojas, M. L., Carvalho, G. R., & Augusto, P. E. D. (2021). Enhancing carrot convective drying by combining ethanol and ultrasound as pretreatments: Effect on product structure, quality, energy consumption, drying and rehydration kinetics. Ultrasonics Sonochemistry, 70(June 2020), 105304. https://doi.org/10.1016/j.ultsonch.2020.105304

Saavedra, J., de Oliveira Gomes, B., Augusto, P. E. D., Rojas, M. L., & Miano, A. C. (2023). Structure–process interaction in mass transfer processes: Application of ethanol and ultrasound in a vascular structure. Journal of Food Process Engineering, 46(6), 1–13. https://doi.org/10.1111/jfpe.14187

Simanca-Sotelo, M., De Paula, C., Domínguez-Anaya, Y., Pastrana-Puche, Y., & Álvarez-Badel, B. (2021). Physico-chemical and sensory characterization of sweet biscuits made with Yacon flour (Smallanthus sonchifolius). NFS Journal, 22, 14–19. https://doi.org/10.1016/j.nfs.2020.12.001

Smith, J.M., Van Ness, H.C., Abbott, M.M., Swihart, M.T. (2019). *Introduction to Chemical Engineering Thermodynamics*, 8th ed. LTC, Rio de Janeiro, Brazil.

Stojakowska, A., Michalska, K., Malarz, J., Beharav, A., Kisiel, W. (2013). Root tubers of Lactuca tuberosa as a source of antioxidant phenolic compounds and new furofuran lignans. *Food Chemistry*, 138, 1250–1255. https://doi.org/10.1016/j.foodchem.2012.11.062

Verediano, T. A., Viana, M. L., das G.V. Tostes, M., & Costa, N. M. B. (2021). The Potential Prebiotic Effects of Yacon (Smallanthus sonchifolius) in Colorectal Cancer. Current Nutrition & Food Science, 17(2), 167–175. https://doi.org/10.2174/1573401316999200605160433

ARTICLE 3 - INNOVATIVE STRATEGIES IN YACON DRYING: ETHANOL PRETREATMENT AND INTERMITTENT MICROWAVE DRYING

Article published in the Journal of Food Science
ISSN: 1750-3841
DOI: 10.1111/1750-3841.17254

Silveira[a*], P. G., Corrêa[a], J. L. G., Silva[a],C. R. de P., Macedo[a], L. L., Gonçalves[a], W. S. and Petri Júnior [b] I.
[a]Department of Food Science, Federal University of Lavras, Lavras, Brazil.
[b]Department of Engineering, Federal University of Lavras, Lavras, Brazil.

Abstract

The yacon roots are rich in fructooligosaccharides (FOS) and highly perishable. Drying is crucial for food quality and extending shelf life. However, preserving thermosensitive compounds, such as fructooligosaccharides (FOS), poses a challenge in conventional drying methods. In this regard, microwave drying and ethanol pretreatment have emerged as a promising solution for maintaining nutrients and reducing drying time. The objective of this study was to assess how ethanol pretreatment and sample temperature affect quality and process parameters during intermittent microwave drying of yacon. Drying at 52°C treated with ethanol was the one that stood out for presenting the highest fructan retention (64.1%), low drying time, lower energy consumption (364.00 ± 5.03 kWh kg water^{-1}), higher retention of antioxidant capacity (73.9%) and total phenolic content (77.5%), and slight variation in color parameters. Therefore, microwave drying with a controlled temperature of yacon pretreated with ethanol effectively reduces drying time and energy consumption by maintaining quality parameters.

Keywords: Antioxidant capacity; fructan retention; Marangoni effect; phenolic compounds; shrinkage.

1. Introduction

Yacon roots (*Smallanthus sonchifolius*) are widely consumed due to their high concentrations of fructooligosaccharides (FOS). FOS are considered prebiotics and soluble fibers with anti-obesity properties, inhibiting adipogenesis and improving visceral adipose tissue function (Honoré *et al.*, 2018). The roots of yacon have an extremely short shelf life due to their high water activity. In addition, FOS hydrolysis occurs quickly after harvest (Mendonça *et al.*, 2017). Therefore, the use of technologies to increase shelf life and to maintain nutritional properties is of utmost importance (Brochier *et al.*, 2015). Processing techniques, such as drying, are essential for preserving and retaining its biological activity.

Drying is a unit operation widely used to increase the shelf life of perishable foods. Even though heated air drying is still the most used (Chandramohan, 2020), other technologies have been employed for better energy utilization and food quality maintenance. Microwave is among such technologies (Souza *et al.*, 2022). The use of microwave energy for drying provides volumetric heating, resulting in high drying rates, low energy consumption, and preservation of heat-sensitive compounds (Macedo *et al.*, 2022).

Microwave usage is a widely adopted technology, but it may present some challenges, such as overheating of food matrices. In an effort to address these drawbacks, some authors have explored the effects of intermittent microwave heating systems, along with the investigation of various pretreatments (Borah *et al.*, 2023; Qin *et al.*, 2022).

Ethanol immersion is among the pretreatments for drying. It stands out for being cost-effective, non-toxic, and easy to apply (Corrêa *et al.*, 2012). It is linked to maintaining the nutritional value of dried products (Macedo *et al.*, 2022; Araújo *et al.*, 2022), reducing energy expenditure (Junqueira *et al.*, 2022), and decreasing drying time (Guedes *et al.*, 2021). However, there is no publications of the combined effect of intermittent microwave drying with ethanol as a pretreatment for yacon.

This study hypothesized that the use of Intermittent Microwave Drying (IMWD) and ethanol as a pretreatment could contribute to better preservation ofthe nutritional value of yacon slices. Additionally, it suggests that a reduced environmental impact may be achieved by lowering energy consumption during the drying process of yacon slices.

Given the above, this study aimed to evaluate the pretreatment with ethanol on the IMWD drying of yacon, focused on obtaining dried yacon with high FOS retention. Process parameters (drying kinetics, drying time, and energy consumption) and quality parameters (total phenolic content, antioxidant capacity, water activity, shrinkage, and color) were evaluated to achieve it.

2. Material and Methods

2.1. Material preparation and experimental design

The yacon tubers (*Smallanthus sonchifolius*) were purchased in the local market (Lavras, Minas Gerais state, Brazil) and selected by color, integrity, and maturation stage. The fresh yacon presented an average moisture content of 8.63 ± 1.62% (d. b.), FOS content of 67.84 ± 1.86 (g (100 g sample)$^{-1}$), and water activity (a_w) of 0.985 ± 0.001. These values are close to those observed in the literature (Oliveira *et al.*, 2021; Corrêa *et al.*, 2021).

The roots were washed with tap water, peeled, and cut into rectangular parallelepiped samples measuring 20 x 20 x 4 mm using a mold and stainless-steel knife. The samples were immersed in a 1% citric acid solution (w/v) for 3 min to prevent enzymatic browning (Silveira *et al.*, 2024).

The experimental conditions according to the use of ethanol pretreatment and inner sample temperature in the microwave drying are described in Table 1. Such conditions were executed in triplicate.

Table 1 - Experimental conditions according to the ethanol pretreatment (ET) and temperature (T).

Code	**ET**	**T (°C)**
52°C	No	52
52°C ET	Yes	52
72°C	No	72
72°C ET	Yes	72

The experiments were conducted in a completely randomized design, arranged in a 2×2 factorial scheme (Table 1). Each experiment was performed in triplicate, and the average values were reported. The data were submitted for analysis of variance (ANOVA). In the case of significant effects, the means were compared by the Tukey test. Each treatment was compared individually with the fresh sample by the Dunnett test. A multivariate analysis was conducted using the principal component analysis (PCA) on the drying time, water activity, shrinkage, colorimetric parameters, total phenolic content, FOS, and antioxidant capacity by DPPH method responses to analyze their particular interrelationships influenced by ethanol pretreatment. Statistical analyses were performed using the probability level of 5% and the Statistica software (Statsoft, Tulsa, USA).

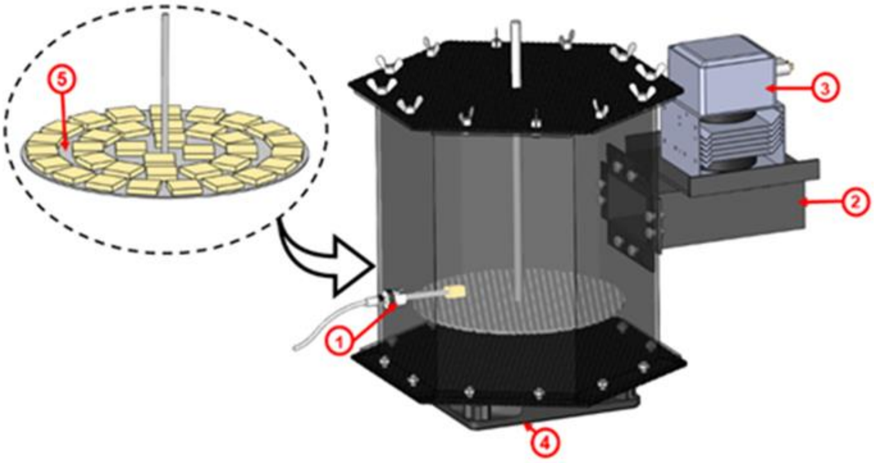
2.2. Ethanol Pretreatment (ET)

The ET was performed by immersion of the sample in 99.8% ethanol (v v^{-1}), in the proportion of 1:5 (w v^{-1}), for 2 min, at 25°C (Macedo *et al.*, 2022).

2.3. Intermittent microwave drying (IMWD)

The yacon slices were subjected to IMWD at a microwave power of 505.6 W. In each batch, 67.96 ± 0.42 g of fresh (untreated) or pretreated yacon were dried, corresponding to 27 samples (placed in monolayers). The mass of each sample was measured in an analytical balance (Ohaus Adventurer, ARC 120, USA) every five minutes until the mass variation was lower than 1% (Gomes *et al.*, 2021). The drying time was considered in this condition. The dryer used was a hexagonal microwave cavity measuring 12 cm on each side and 24.5 cm in height (see Figure 1). The cavity featured a WR340 waveguide measuring 12 cm in length, centered on one of the walls, a 2M319J magnetron, and perforated lids to allow for the passage of drying air through the cavity, following the method described in Costa *et al.* (2021). In addition, a blower was attached to the base of the cavity to promote continuous air flow at a velocity of 0.5 m s^{-1} at room temperature (22.57 ± 1.81°C) after passing through a bed of silica gel.

Figure 1 - Hexagonal microwave dryer.



Caption: (1) k-type thermocouple, (2) Waveguide, (3) Magnetron, (4) Fan, (5) Holder detail filled with samples.

The samples were placed in a circular holder with a diameter of 18.5 cm, which was positioned vertically 3.0 cm from the bottom of the cavity. The holder was then coupled to an analytical balance (Ohaus Adventurer, ARC 120, USA) to monitor the sample mass during drying.

The temperature of the samples was continuously measured using a K-type thermocouple inserted in yacon slices. The microwave magnetron was automatically turned on and off by a system developed using a NI-USB6009 card and LabView software to maintain a set-point temperature of 52°C and 72°C (Costa *et al.*, 2021). Sample temperatures varied within a narrow range, as commonly occurs in intermittent microwave drying (Macedo *et al.*, 2022), in which the sample temperatures were close to set-point values (Table 2).

Table 2 - Sample temperature (T) and percentage of time with magnetron turned on (On).

Code	**T (°C)**	**On (%)**
52°C	52.00 ± 3.30^b	30.76 ± 0.07^b
52°C ET	53.54 ± 4.9^b	22.81 ± 0.07^c
72°C	71.32 ± 3.21^a	33.19 ± 0.49^a
72°C ET	72.41 ± 4.72^a	33.16 ± 0.61^a

Mean ± standard deviation, n = 3. Equal lowercase letters indicate no significant difference among treatments by the Tukey test ($p < 0.05$). ET - ethanol treatment.

The magnetron was automatized in an on/off system. It was turned on initially, causing the material to heat up quickly, and as soon as it reached the rated temperature, the magnetron was turned off (Macedo *et al.*, 2022). The slices were cooled due to air circulation at room temperature (22.57 ± 1.81°C) and water evaporation. The magnetron was reconnected when the sample was below the set-point temperature. As a result, most of the time, the magnetron remained switched off, mainly in the experiments at 52°C ET, where the magnetron remained switched off for 77.18% of the time (Table 2). In this scenario, the on/off system allowed for high energy savings due to the time the magnetron remains off.

The moisture ratio (MR) was calculated during drying, according to Equation (1) (Macedo *et al.*, 2023).

$$MR = \frac{X_t - X_e}{X_0 - X_e} \quad (1)$$

X_0, X_t, and X_e represent the dry basis moisture (kg water kg $\text{sample}_{\text{d.b}}^{-1}$) at the initial, time t, and the equilibrium stage, respectively. The equilibrium moisture content was 0.126 ± 0.025 (kg water kg $\text{sample}_{\text{d.b}}^{-1}$) and was obtained under conditions of infinite drying time.

The drying rate (DR) was determined according to the moisture content (dry basis) according to Equation (2) (Macedo *et al.*, 2022).

$$DR = \frac{X_t - X_{t+\Delta t}}{\Delta t} \tag{2}$$

Where, the drying rate (kg water kg dried solid^{-1} min^{-1}) is denoted as DR, the time (min) is represented by t, the time difference (min) is indicated as Δt and the the moisture content (kg of water kg of dried sample^{-1}) is represented by X_t and $X_{t+\Delta t}$ at t and $t + \Delta t$, respectively.

2.5. Energy consumption (EC)

The EC by the equipment utilized in the drying experiments of yacon slices at various air temperatures was calculated according to Equation (3) (Corrêa *et al.*, 2021),

$$E_t = V \times I \times t \tag{3}$$

E_t is the total energy consumption (kWh), V is the voltage (V), I is the current (A), and t is the time when the equipment is turned on (h).

The energy consumption required to remove 1 kg of water was calculated according to Equation (4).

$$EC = \frac{E_t}{m_f - m_0} \tag{4}$$

EC is the energy consumption per kg of water, E_t is the total energy consumption (kWh) of each drying, and m_f and m_0 are the sample mass (kg) at the end and beginning of drying, respectively.

2.6. Quality analysis

The samples underwent characterization regarding their moisture content, water activity, shrinkage, color, total phenolic content, antioxidant capacity, and FOS retention.

2.6.1. Moisture content and Water activity (a_w)

The gravimetric method established by the AOAC 934.06 methodology (AOAC, 2010) determined the moisture content, wherein the samples were placed in an oven at 70°C under vacuum.

Water activity in the samples was measured at 25°C using an electronic hygrometer (Aqualab, series 3 TE, Washington, USA).

2.6.2. Shrinkage

The shrinkage was assessed using the toluene displacement method (Macedo *et al.*, 2021; Silveira *et al.*, 2024) and computed using Equation (5):

$$Shrinkage\ (\%) = \left(1 - \frac{V}{V_0}\right) \times 100 \quad (5)$$

V and V_0 represent the volumes (m^{-3}) of dried and fresh samples, respectively.

2.6.3. Color

The colorimetric parameters of the samples were obtained with the aid of a digital colorimeter (model LS173, Shenzhen Linshang Technology Co., Ltd., Shenzhen, Guangdong, China), with D65 illuminator and 10° viewing angle, using CIELab color scale. Three randomly slices of dried yacon obtained after each drying process had their color parameter measured at different positions on each slice. Subsequently, the average of all color parameters was calculated. The L^* parameter represents the luminosity, ranging from 0 (black) to 100 (white). The total color difference (ΔE) of the samples in the fresh sample, whose parameter is represented by subindex “0”, was calculated according to Equation (6); moreover, the color variables were used to calculate the chroma (C_{ab}) (Equation 7) (Macedo *et al.*, 2023).

$$\Delta E = \sqrt{(L^* - L_0^*)^2 + (a^* - a_0^*)^2 + (b^* - b_0^*)^2} \quad (6)$$

$$C_{ab} = \sqrt{a^{*2} + b^{*2}} \quad (7)$$

L^* indicates the lightness, a^* indicates red-green, b^* indicates yellow-blue, and C_{ab} indicates chromaticity or color saturation.

2.6.4. Total phenolic content (TPC)

The TPC was determined according to the Folin-Ciocalteu method. The extract was prepared using 1 g of sample and 100 mL of a solution containing distilled water and ethanol

(1:1) at 25°C for 2 hours. The mixture was centrifuged at 3520 rpm for 15 min. 0.5 mL of Folin-Ciocalteu reagent (a mixture of phosphomolybdic and phosphotungstate) and 1.5 mL of sodium carbonate at 20% were placed in amber flasks. The reaction mixture consisted of 0.25 mL of extract, 200 mL of distilled water, 0.25 mL of Folin-Ciocalteu reagent, and 0.25 mL of 10% sodium carbonate, placed in amber flasks. The amber flasks were stirred, left in the dark for 1 hour, and then absorbance was measured at 765 nm. The gallic acid was used as a standard to create the calibration curve (concentration range from 0 to 520 mg mL^{-1}, $R^2 = 0.99$). All analyses were performed in triplicate (Macedo *et al.*, 2022).

2.6.5. Antioxidant capacity

The same extract prepared to analyze total phenolic content was used for antioxidant capacity analysis (Macedo *et al.*, 2022). Antioxidant capacity was quantified by the method of 2,2-diphenyl-2-picrilhydrazil (DPPH).

2.6.6. Fructan retention (FR)

The fructan content (FOS) was determined enzymatically using the Fructan HK Assay Prodedure commercial kit from Magazyme International Ireland, Ltd., Bray, Ireland in accordance with the AOAC 997.08 methodology (AOAC, 2010)· Fructan retention is given by Equation 8.

$$F_R = \frac{F_d}{F_f} \times 100 \tag{8}$$

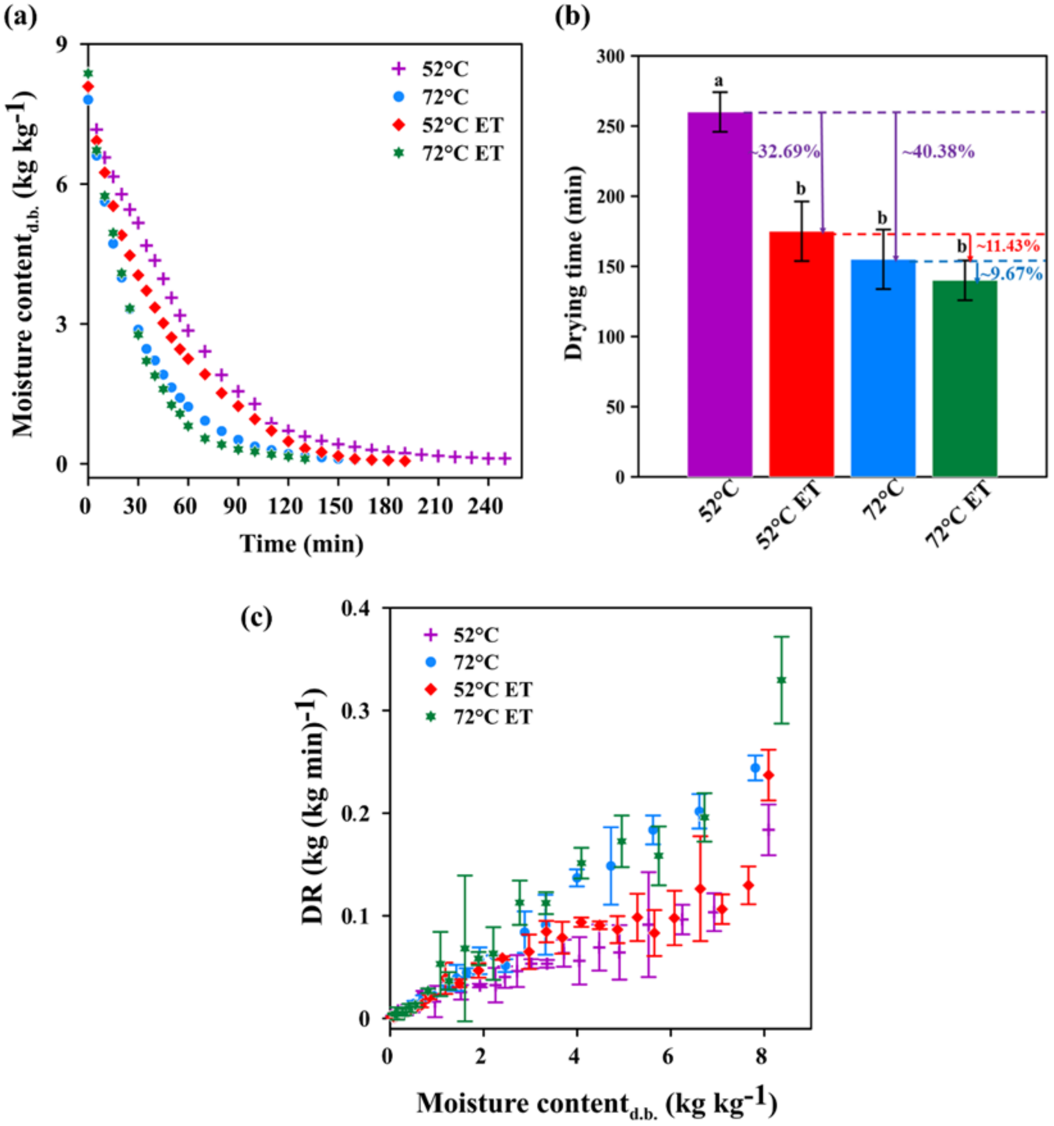
F_R is the fructan retention, F_d is the fructan concentration in the dried sample, and F_f is the fructan concentration in the fresh sample.

3. Results and discussion

3.1. Drying

The reduction of moisture content according to the time is shown in Figure 2. The moisture content decreased exponentially (Figure 2a), corroborating the literature (Guedes *et al.*, 2021; Oliveira *et al.*, 2021; Silveira *et al.*, 2024). In the initial minutes of drying, a noticeable decrease in moisture content can be seen. (Figure 2a). This is because the root had a high moisture content of at the start of the process, wich made a lot of unbound water readily removable (Macedo *et al.*, 2022). Furthermore, IMWD promotes the volumetric heating of samples generated by the agitation of water molecules (dipolar rotation) due to the electromagnetic field. Thus, a high gradient of water vapor pressure is formed between the interior and surface of the material, accelerating the mass transfer (Junqueira *et al.*, 2017). The intermittent method (on/off mode) reduces the risk of overheating the sample, which would cause yacon chemicals to degrade or even burn (Dehghannya *et al.*, 2018).

Figure 2 - Moisture content kinetics, drying time and drying rate.



Caption: Moisture content kinetics (a), drying time of samples at 52 °C and 72 °C, with (ET) and without ethanol pretreatment (b), and drying rate (c). Equal lowercase letters indicate no significant difference between non- and osmotically pretreated samples by the Tukey test ($p < 0.05$).

The drying time (DT) ranged from 140 to 260 min (Figure 2b). According to Figure 2b, significant differences ($p<0.05$) can be observed between the 52°C and 52°C ET treatments, highlighting a 34.62% reduction in drying time. This drying time reduction was attributed to using ET as a pretreatment. ET can induce structural changes and physical mechanisms that enhance subsequent drying. This may occur due to increased steam pressure of the sample and the Marangoni effect (Guedes *et al.*, 2021). The main structural change observed with ET, as reported by Silveira *et al.* (2024), is the reduction in cell wall thickness, directly impacting lower resistance to mass transfer. According to Guedes *et al.* (2021), several physical mechanisms can directly affect drying time, including increased sample vapor pressure and the Marangoni effect. The increase in vapor pressure refers to the rise in pressure exerted by vapor within the sample, given that ethanol diffuses into the sample, forming an aqueous ethanol solution. It is known that aqueous ethanol solutions exhibit lower intermolecular forces and higher vapor pressure than pure water, which could potentially reduce the drying time of the sample (Corrêa *et al.*, 2012).

Furthermore, ethanol has a lower boiling point than water, thus evaporating faster during drying, leaving more water than ethanol on the surface and promoting a gradient of surface tension (Bitencourt *et al.*, 2022). As the ethanol concentration is reduced on the sample surface during drying, this region reaches a higher surface tension concerning the adjacent layers. This gradient in tension displaces fluid from internal layers of food. This results in a continuous flow within the inner layers of the food to the surface, which happens until a balance of surface tension is reached; this phenomenon is called the Marangoni effect. Macedo *et al.* (2021) and Guedes *et al.* (2021) described in their studies that using ethanol as a pretreatment impacted the reduction in DT and hygroscopicity, minimization of the loss of bioactive compounds, low impact on the molecular profile of samples, and increased shelf life of dried products. Silveira *et al.* (2024) and Macedo *et al.* (2021) reported a reduction in drying time due to the use of ET as a pretreatment in different food matrices.

It is also noticeable that the 72°C and 72°C ET treatments did not show significant differences between them ($p<0.05$) (Figure 2), a result that could be attributed to ethanol evaporating faster at the temperature of 72°C. It corroborates the study of Silveira *et al.* (2024).

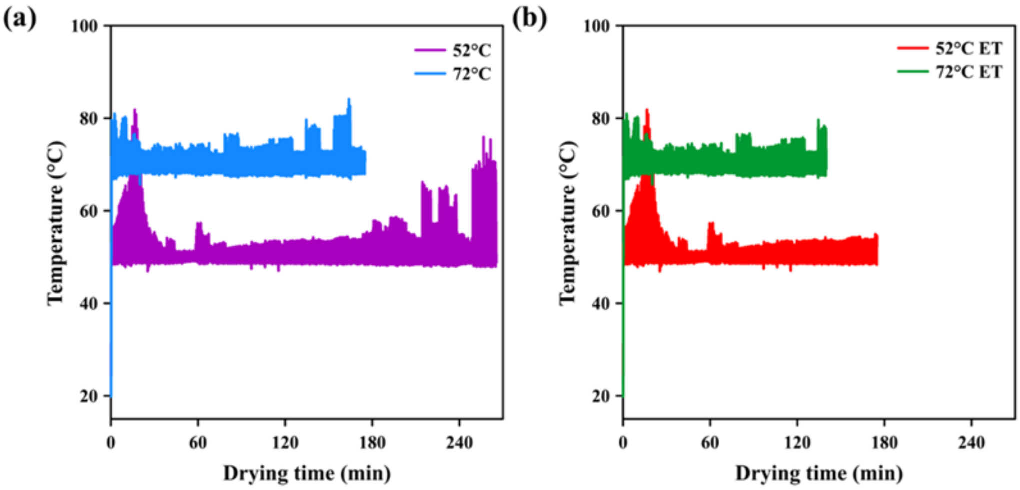
The treatments predominantly exhibited periods of decreasing drying rate, implying a dominance of diffusive processes (Figure 2c). Furthermore, the slices submitted to drying at 52°C showed lower drying rates (Figure 2c) than ET slices at the same temperature (52°C ET). The same behavior was observed at 72ºC. The variation in drying rates can be attributed to the use of ET and the increase in temperature. ET leads to decreased mass transfer resistance and higher drying rates (Silveira *et al.*, 2024). The temperature increase reduces internal resistance to moisture removal, as it is associated with enhanced mobility of water molecules. External resistance decreases with temperature due to increased driving force (Junqueira *et al.*, 2021).

Temperature also had a significant influence on DT (Figure 2b). The slices dried at 72°C showed a reduction in DT equal to 40.38 and 20%, respectively, compared to those dried at 52°C. The increase in DT promotes higher mobility of the water molecule inside the food and increases the water pressure gradient between the phases, decreasing the resistance to water transport (Bitencourt *et al.*, 2022). It is important to note that at 72ºC, the ET was not so relevant as at 52ºC because the driving force of temperature is higher than the Marangoni, making this second one less relevant at higher temperatures.

3.1.1. Sample temperature

Temperature data during the drying of yacon slices are presented in Figure 3. It is noted that in the first 30 minutes of drying, temperature spikes occur. These spikes may have occurred due to the high content of free water present in the yacon at the beginning of drying, causing greater agitation of water molecules by microwaves, thus resulting in rapid heating of the sample. Similar results were observed by Macedo *et al.* (2022) during intermittent microwave drying of strawberry cubes.

Figure 3 – Drying temperature.



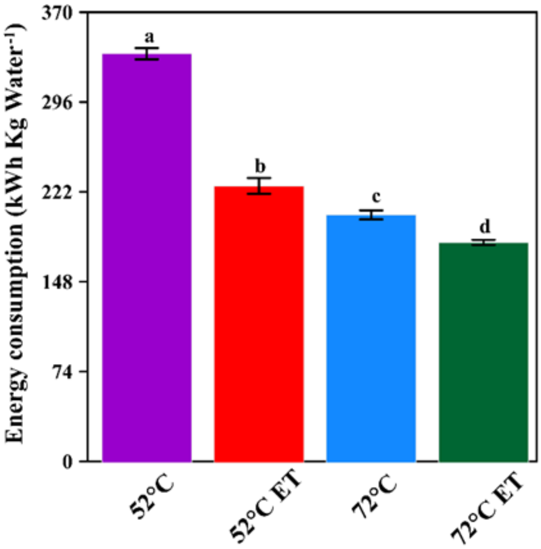
Caption: Temperature of 52°C and 72°C IMWD (a) and Temperature of 52°C ET and 72°C ET IMWD (b)

The temperature variation during IMWD can be attributed to the on/off system. The peaks and valleys observed in Figure 3 a and b reflect, respectively, the heating of the samples and the tempering points. Therefore, they indicate when the microwave is on or off. Furthermore, it is possible to observe that towards the end of the drying process, the presence of temperature peaks tends to be higher. These peaks may have occurred due to the shrinkage of the sample during IMWD, making the thermocouple more susceptible to interactions with the electromagnetic field (Kalinke *et al.*, 2022; Lapshinov, 2021).

3.1.2. Energy consumption (EC)

Drying is a process characterized by high energy demands. These energy requirements can be linked to adverse environmental impacts; hence, using technologies with lower energy consumption is paramount. In this context, conducting an analysis (Figure 4) of Energy Consumption (E_c) provides crucial insights into IMWD.

Figure 4 - Energy consumption (EC) at different drying conditions.



Caption: Mean ± standard deviation, n = 3. Equal lowercase letters indicate no significant difference among treatments by the Tukey test ($p < 0.05$). ET - ethanol treatment.

In Figure 4, it was determined that a range of 195 to 364 kWh per kilogram of water removed is needed to achieve constant mass in the drying trials. These values align with previously observed results in other investigations conducted by Mendonça *et al.* (2017), Corrêa *et al.* (2021) and Macedo *et al.* (2021) in the drying of yacon and strawberries, respectively.Figure 4 highlights that the highest E_c was at 52°C without pretreatment due to its prolonged DT (Figure 2). Subsequently, this scenario was followed by the experiment at 52°C with pretreatment. Ethanol treatment (ET) stood out for its efficiency in enhancing energy savings (34.41%). As shown in Figure 2, samples subjected to ethanol immersion (52°C ET and 72°C ET) recorded the lowest DT. The 72°C treatments exhibited lower energy consumption, primarily due to their shorter drying time. This reduction in DT is associated with a decrease in mass transfer resistance and an increase in driving force caused by the elevated internal temperature. This observation follows Macedo *et al.* (2022), who assessed strawberry microwave drying pretreated with ethanol. Therefore, both the ET and the temperature increase benefitted energy saving.

3.2. Quality properties

3.2.1. Water activity (a_w)

The a_w of the dried yacon slices was 0.364±0.005, lower than 0.6, the minimum value required to prevent microbial growth and chemical reactions in biological materials (Pereira *et al.*, 2016). This result indicates the drying process effectiveness in lowering water activity while preserving product quality and safety.

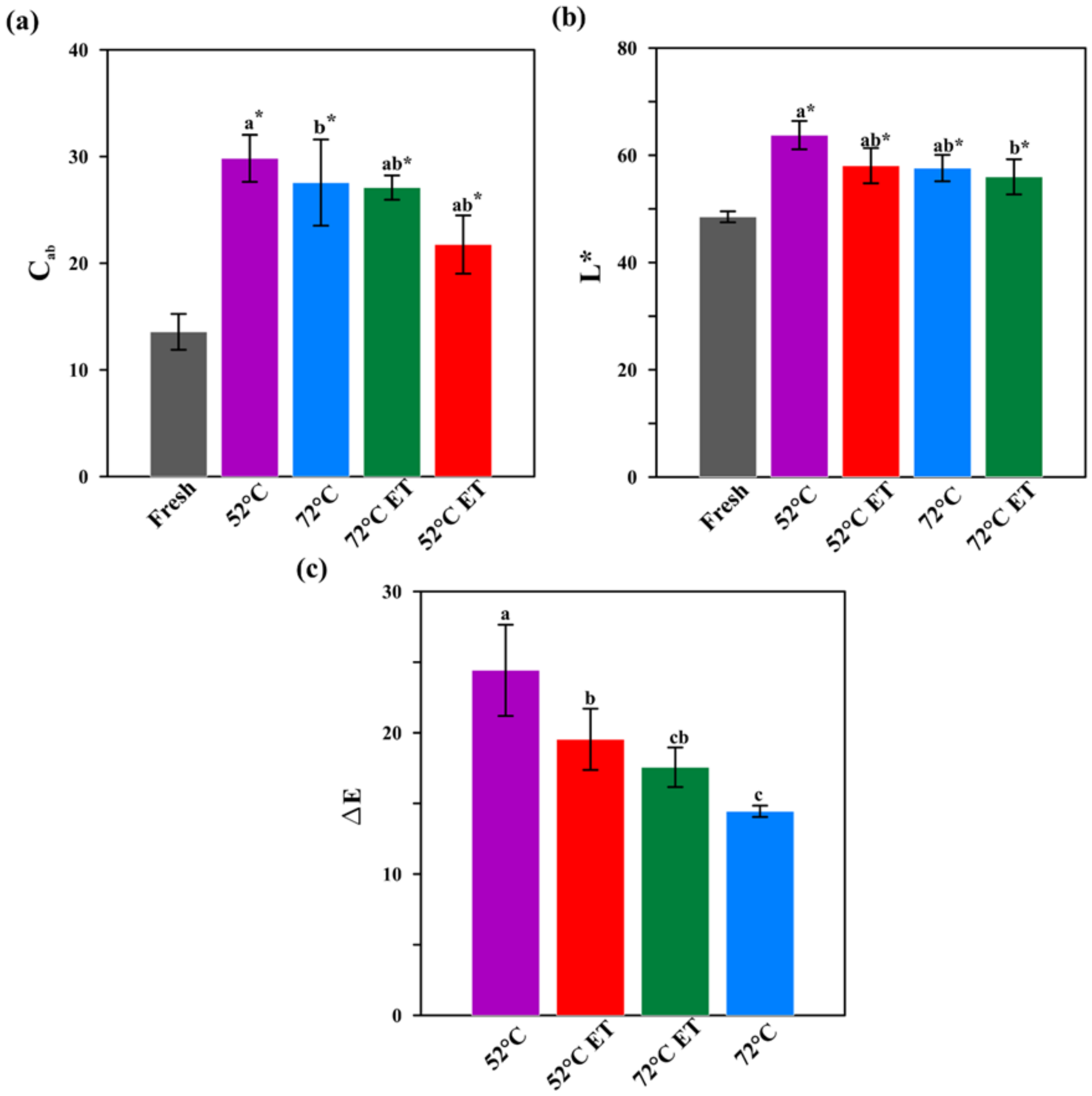
3.2.2. Shrinkage

Shrinkage is a physical phenomenon that occurs in most drying processes of biological products. It ranged from 84.16 ± 1.88 to 87.68 ± 0.45%, with no significant differences between the treatments. The reduction in the volume is caused by the removal of moisture, particularly in materials such as yacon, where moisture makes up a large amount of composition. Bernstein and Noreña (2014) reported that dried yacon at 50 and 75°C shrank by approximately 89%. Corrêa *et al.* (2021) reported that yacon shrank about 84.87%. All dried samples showed anisotropic shrinkage due to deformations in the food microstructure, which distorted the yacon.

3.2.3. Color

The color of the food is one of the most important quality parameters, as it determines the acceptance of processed food products. The color is usually altered in a drying process. Such alteration is related to the process variables. Figure 5 shows the colorimetric properties of fresh and dried yacon.

Figure 5 - Colorimetric parameters of fresh and dried yacon.



Caption: Values are mean ± standard deviation, n = 3. Mean ± standard deviation, n = 3. Equal lowercase letters indicate no significant difference between non- and pretreated samples by the Tukey test ($p < 0.05$). The asterisk indicates a significant difference between each treatment and the fresh sample by the Dunnett test ($p < 0.05$). ET - ethanol treatment.

The fresh yacon had the following color parameters: L^* = 48.52 ± 1.03, C_{ab} = 13.57 ± 1.68, a^* = 3.28 ± 0.44, and b^* = 12.94 ± 2.05. The color properties of yacon were significantly altered, with an increase in both L^* and C_{ab} values observed in all treatments. Oliveira *et al.* (2021) reported similar results during convective drying of yacon, with an increase in L^*, C_{ab}, and ΔE, suggesting that the final product had a lighter color.

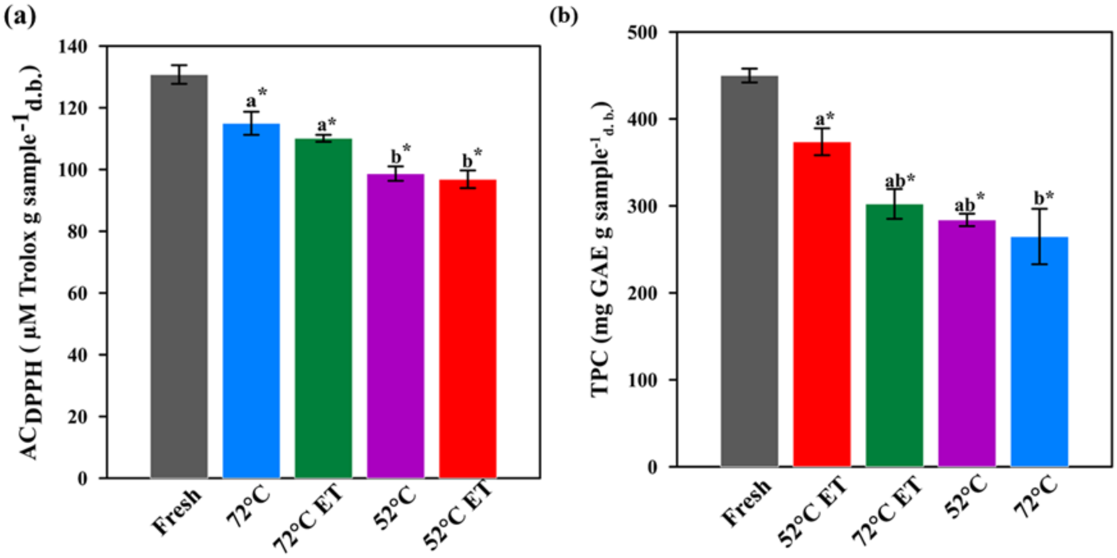
A reduction in the L^*, C_{ab}, and ΔE parameters was observed in ET samples after comparing the treated and untreated samples. The decrease in L^* values may suggest that ethanol immersion can remove some of the citric acid added to the sample, activating polyphenol oxidase (PPO) and promoting sample browning (Rojas *et al.*, 2020). Furthermore, the ET reduced the C_{ab} and ΔE values, suggesting an increase in the saturation of the yellow color and a darkening of the sample compared to the dried samples without pretreatment. Similar results were observed by Macedo *et al.* (2021) in the drying of strawberries and by Araujo *et al.* (2022) in the drying of red dragon fruit (pitaya).

It should be noted that color variation is a complex phenomenon that depends on multiple factors, such as moisture content, pigment content (loss or concentration), the presence of occluded gases, and exposure to heat and light (Corrêa *et al.*, 2021). The color difference between the dried samples and the fresh yacon was significant based on the measured parameters.

3.2.4. Total phenolic content (TPC) and Antioxidant capacity (AC)

The TPC and AC for the several tested conditions are presented in Figure 6. Fresh yacon was shown to be a rich source of antioxidant compounds (Figure 6ab). These compounds contribute to yacon being classified as a prebiotic food with several preventive and therapeutic health benefits, with positive effects on several diseases, such as diabetes (Mendonça *et al.*, 2015).

Figure 6 - Total phenolic content and antioxidant.



Caption: Mean ± standard deviation, n = 3. Equal lowercase letters indicate no significant difference between non- and pretreated samples by the Tukey test ($p < 0.05$). The asterisk indicates a significant difference between each treatment and the fresh sample by the Dunnett test ($p < 0.05$). ET - ethanol treatment

Fresh yacon presented AC of 130.32 ± 3.02 (µM Trolox/g sample$_{d.b.}$). The AC obtained was within the range reported for fresh yacon in previous studies such as Campos *et al.* (2012) (135.7 ± 4.5 µM Trolox g sample^{-1} $_{d.b}$) and Castro-Muñoz *et al.* (2016) (136.0 ± 6.1 µM Trolox g sample^{-1} $_{d.b}$). Regarding TPC, the value obtained was 449.88 ± 7.95 (µg GAE g sample^{-1} $_{d.b.}$), which was also in the range reported by Ueda *et al.* (2019) (452 ± 1.9 µg GAE g sample^{-1} $_{d.b}$).

Microwave drying significantly decreased the AC and TPC of the samples (Figures 6a and 6b). When comparing the dried samples at 72°C with those at 52°C, a significant difference was observed ($p < 0.05$) in AC and TPC analysis. This difference is closely related to the DT. The longer the exposure to heat, the greater the degradation of the compounds since these compounds are thermosensitive and, therefore, easily degraded when heated (Macedo *et al.*, 2021). Ueda *et al.* (2019) and Campos *et al.* (2012) observed the same phenomenon.

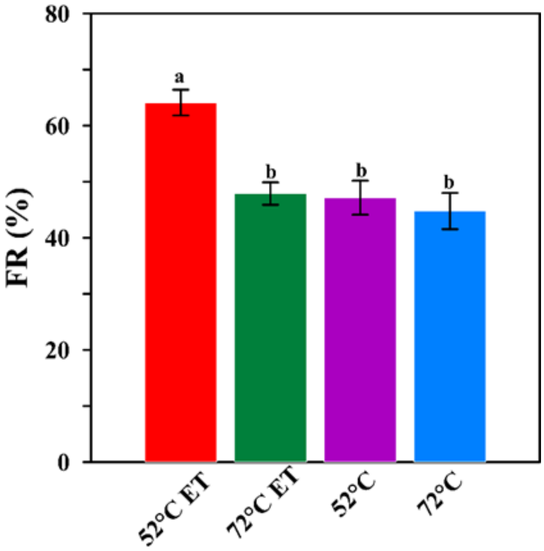
When comparing untreated samples (52 and 72°C) with pretreated samples (52 and 72°C ET), a 4.65% reduction in AC values was found. The samples dried at 52 and 72°C showed retention rates of phenolic compounds equal to 63.10 and 53.93%. The pretreated samples showed higher retention rates, 77.50% (52°C ET) and 67.18% (72°C ET). The reduction of AC after drying pretreated samples may be related to different phenomena. First, pretreatment can increase the exposure of compounds to the oxidizing effect of drying air. Immersion in ethanol can remove air from tissues and alter the cell walls of the porous structure, and due to the large surface area and fine geometry of yacon samples (Rojas *et al.*, 2018) can further expose the internal constituents. Secondly, a slight surface browning was observed during the drying of the pretreated samples. This may indicate that immersion in ethanol can remove part of the citric acids previously added to the sample, allowing the activity of polyphenol oxidase (PPO) since there is a direct relationship between the activity of this enzyme and the browning reaction with the decrease in the phenolic content of yacon (Rojas *et al.*, 2020).

The increase in TPC with ethanol may be associated with a decrease in drying time, preserving bioactive and antioxidant compounds due to the decrease in the exposure time of the product to air at high temperatures (Araújo *et al.*, 2022). Thus, ethanol had a beneficial effect on the preservation of TPC (Figure 6b).

3.2.5. Fructan Retention (FR)

Figure 7 shows the FR for the various treatments. FOS is a thermosensitive compound, so it was expected that by increasing the temperature, there would be greater degradation. However, it was observed that there were no significant differences between the dried samples at 52°C, 72°C, and 72°C ET. This can be justified by the DT being reduced in treatments at 72°C and 72°C ET, thus enabling a concentration of FOS similar to the dried product at 52°C (Corrêa *et al.*, 2021). The FR of 52°C ET treatment significantly differed from the other treatments due to its shorter DT, decreased by 34.62% because of the ET. In addition, the operating temperature was milder, allowing a greater preservation of the compound. Oliveira *et al.* (2021), Corrêa *et al.* (2021), and Oliveira *et al.* (2016) observed that the time of exposure to heat directly influences the values of FR. The longer the DT, the shorter the FR. Thus, the use of ET showed positive effects by reducing the DT and allowing greater maintenance of the fructan in the final product.

Figure 7 - Fructan retention (FR) in different treatments.

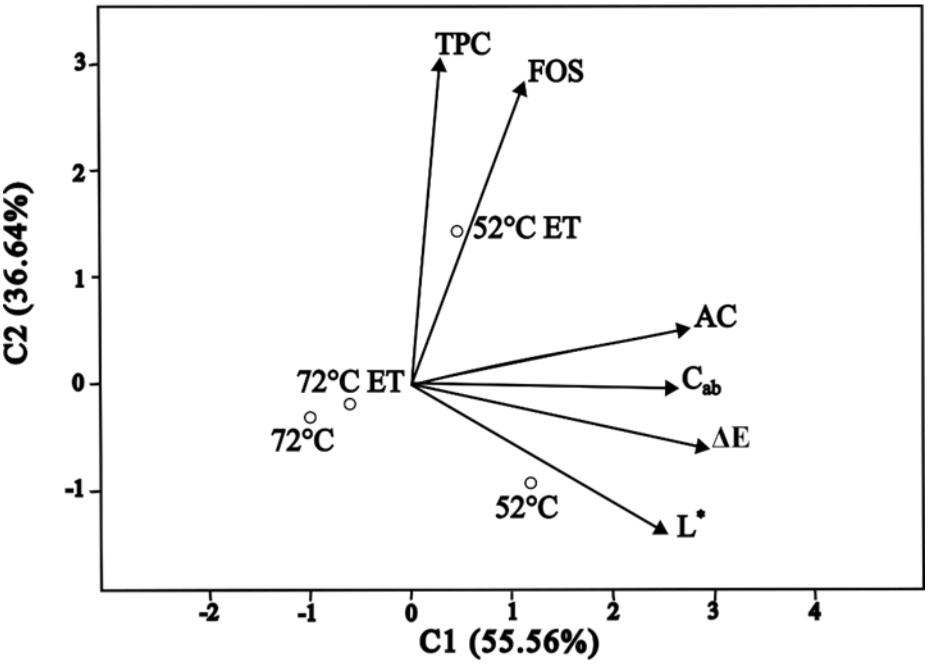


Caption: Mean ± standard deviation, n = 3. Equal lowercase letters indicate no significant difference between non- and pretreated samples by the Tukey test ($p < 0.05$). ET - ethanol treatment

3.3. Principal component analysis (PCA)

The principal component analysis (PCA) was used to investigate the influence of both studied factors (temperature and pretreatment) on DT, a_w, shrinkage, color parameters, FOS, TPC, and AC, as shown in Figure 8.

Figure 8 - Principal component analysis.



The first (C1) and second (C2) axles were responsible for 55.56% and 35.64% of the variance, respectively, representing 91.2% of the total explained variance. As seen in the scores plot (Figure 8), the samples dried at 72°C and 72°C ET were on the negative side of the C1 axis, while the dried samples at 52°C and 52°C ET were on the positive side of the C1 axis, evidencing the differences between the properties of drying temperatures after drying process.

The shrinkage, TPC, AC, and FOS responses were observed to be positively correlated (Figure 8). It can be observed that the highest values of these responses were associated with the 52°C ET treatment. As expected, high values of phenolic compounds and antioxidants were obtained when the DT was short, indicating that longer DT resulted in greater degradation of these compounds.

Generally, the IMWD yacon pretreated with ethanol were associated with lower DT and higher values of C_{ab} (color attribute), ΔE (color difference), AC, and FOS. However, temperature showed a significant effect on the degradation of these compounds, highlighting that in a microwave drying of yacon, the combination of milder temperatures (52°C) and the use of ethanol is an excellent alternative to produce dried yacon slices with maximum levels of bioactive compounds and antioxidants.

4. Conclusions

The effects of ethanol treatments and temperature on the intermittent microwave drying of yacon slices were evaluated. Ethanol treatment exhibited advantages such as a significant reduction in drying time, up to 34.62%, and greater energy savings, up to 32.41%. Parameters such as ΔE, shrinkage, AC, TPC, and FR showed similar trends with the reduction in drying time, as lower drying time correlated with lower ΔE and higher values of AC, TPC, and FR. Therefore, ethanol directly influenced yacon slices with improved nutritional attributes. Using a milder temperature (52°C) also contributed to this outcome. These findings suggest the potential applicability of such optimized drying conditions for the industrial production of yacon slices with enhanced nutritional and sensory qualities. Additionally, investigating the effects of ethanol immersion time and drying parameters on the quality attributes of yacon slices can provide further insights into process optimization and product development.

References

AOAC (2010). *Official methods of analysis. AOAC internacional association of official analytical chemists*, 18th ed. Oxford University Press: USA.

Araújo, C. da S.; Corrêa, J. L. G.; Dev, S.; Macedo, L. L.; Vimercati, W. C.; Oliveira, C. R. de; Pio, L. A. S. (2022). Influence of pretreatment with ethanol and drying temperature on physicochemical and antioxidant properties of white and red pulp pitayas dried in foam mat. *Drying Technol*ogy, *40*, 484-493. DOI: 10.1080/07373937.2020.1809446.

Bernstein, A.; Noreña, C. P. Z. (2014).Study of thermodynamic, structural, and quality properties of yacon (Smallanthus sonchifolius) during drying. *Food Bioprocess Technology*, *7*, 148–160. DOI: 10.1007/s11947-012-1027-y.

Bitencourt, B. S.; Corrêa, J. L. G.; Carvalho, G. R.; Augusto, P. E. D. (2022) Valorization of pineapple pomace for food or feed: effects of pretreatment with ethanol on convective drying and quality properties. *Waste Biomass Valor*ization, *13*, 2253–2266. DOI: 10.1007/s12649-021-01659-9.

Borah, M. S., Bhagya Raj, G. V. S., Tiwari, A., & Dash, K. K. (2023). Effect of intermittent microwave convective drying on quality characteristics of persimmon fruit. Journal of Agriculture and Food Research, 14(July), 100816. https://doi.org/10.1016/j.jafr.2023.100816

Brochier, B.; Marczak, L. D. F.; Noreña, C. P. Z. (2015). Osmotic dehydration of yacon using glycerol and sorbitol as solutes: Water effective diffusivity evaluation. *Food Bioprocess Technoogy*. *8*, 623–636. DOI: 10.1007/s11947-014-1432-5.

Campos, D.; Betalleluz-Pallardel, I.; Chirinos, R.; Aguilar-Galvez, A.; Noratto, G. (2012). Prebiotic effects of yacon (*Smallanthus sonchifolius* Poepp. & Endl), a source of fructooligosaccharides and phenolic compounds with antioxidant activity. *Food Chemistry* , *135*, 1592–1599. DOI: 10.1016/j.foodchem.2012.05.088.

Castro-Muñoz, R.; Yáñez-Fernández, J.; Fíla, V. (2016). Phenolic compounds recovered from agro-food by-products using membrane technologies: An overview *Food Chemistry*, *213*, 753-762. DOI: 10.1016/j.foodchem.2016.07.030.

Chandramohan, V. P. (2020). Convective drying of food materials: An overview with fundamental aspect, recent developments, and summary. *Heat Transfer*, *49*, 1281-1313. DOI: 10.1002/htj.21662.

Corrêa, J. L. G.; Braga, A. M. P.; Hochheim, M.; Silva, M. A. (2012) The influence of ethanol on the convective drying of unripe, ripe, and overripe bananas. *Drying Technology*, *30*, 817-826. DOI: 10.1080/07373937.2012.667469.

Corrêa, J. L. G.; Lopes, F. J.; de Mello Junior, R. E.; Junqueira, J. R. de J.; Pereira, M. C. de A.; Salvio, L. G. A. (2021). Dried yacon with high fructooligosaccharide content. *J. Food Procesing Engineering*, *44*. DOI: 10.1111/jfpe.13884.

Costa, F. O.; Alvarenga, T. F.; Mesquita, T. V. C.; Petri Júnior, I. (2021) Hybrid drying of pulped arabica coffee cherry beans (*Coffea arabica* L. cv. Catuai) using a hexagonal microwave drieder designed by numerical simulations. *Journal Food Processing Eng*ineering, *44*. DOI: 10.1111/jfpe.13666.

Dai, J.-W.; Xiao, H.-W.; Zhang, L.-H.; Chu, M.-Y.; Qin, W.; Wu, Z.-J.; Han, D.-D.; Li, Y.-L.; Liu, Y.-W.; Yin, P.-F (2019). Drying characteristics and modeling of apple slices during microwave intermittent drying. *Journal. Food Processing Engineering*, *42*. DOI: 10.1111/jfpe.13212.

Dehghannya, J.; Hosseinlar, S. H.; Heshmati, M. K. (2018) Multi-stage continuous and intermittent microwave drying of quince fruit coupled with osmotic dehydration and low temperature hot air drying. *Innov. Food Science Emerging Technol*ogy, *45*, 132-151. DOI: 10.1016/j.ifset.2017.10.007.

Gomes, B. de O., Santos, K. C., Carvalho, G. R., Bitencourt, B. S., Guedes, J. S., & Augusto, P. E. D. (2022). c(Eugenia pyriformis Cambess) drying: Ethanol as pretreatment, convective drying kinetics and bioactive compounds. Journal of Food Processing and Preservation, 46(2), 1–11. https://doi.org/10.1111/jfpp.16284

Guedes, J. S.; Santos, K. C.; Castanha, N.; Rojas, M. L.; Matta Junior, M. D.; Lima, D. C.; Augusto, P. E. D. (2021). Structural modification on potato tissue and starch using ethanol pretreatment and drying process. *Food Structure*, *29*. DOI: 10.1016/j.foostr.2021.100202.

Honoré, S. M.; Grande, M. V.; Rojas, J. G.; Sánchez, S. S. (2018). *Smallanthus sonchifolius* (Yacon) flour improves visceral adiposity and metabolic parameters in high-fat-diet-fed rats. *Journal Obesity*, 1-15. DOI: 10.1155/2018/5341384.

Junqueira, J. R. de J.; Corrêa, J. L. G.; Petri Junior, I.; Gatti, I. P.; Mendonça, K. S. de. (2022). Microwave drying of sweet potato: Drying kinetics and energetic analysis. *Aust. Journal Crop Sci*ence, *16*, 1185-1192. DOI: 10.21475/ajcs.22.16.10.p3673.

Junqueira, J. R. de J., Corrêa, J. L. G., Resende, N. S., Balbinoti, T. C. V., Gatti, I. P., & de Mendonça, K. S. (2021). Ethanol pretreatment in taioba leaves during vacuum drying. Ciencia e Agrotecnologia, 45. https://doi.org/10.1590/1413-7054202145020421

Junqueira, J. R. J.; Corrêa, J. L. G.; Ernesto, D. B. (2017). Microwave, convective, and intermittent microwave-convective drying of pulsed vacuum osmodehydrated pumpkin slices. *Journal Food Processing Preserv*ation, *41*. DOI: 10.1111/jfpp.13252.

Kalinke, I., Kubbutat, P., Taghian Dinani, S., Ambros, S., Ozcelik, M., & Kulozik, U. (2022). Critical assessment of methods for measurement of temperature profiles and heat load history in microwave heating processes—A review. Comprehensive Reviews in Food Science and Food Safety, 21(3), 2118–2148. https://doi.org/10.1111/1541-4337.12940

Lapshinov, B. A. (2021). Temperature Measurement Methods in Microwave Heating Technologies. Measurement Techniques, 64(6), 453–462. https://doi.org/10.1007/s11018-021-01954-w

Macedo, L. L.; Corrêa, J. G.; Araújo, C. da S.; Cardoso, W. S. (2023). Use of ethanol to improve convective drying and quality preservation of fresh and sucrose and coconut sugar-impregnated strawberries. *Food Bioprocess Technol*ogy DOI: 10.1007/s11947-023-03066-5.

Macedo, L. L.; Corrêa, J. L. G.; Araújo, C. da S.; Vimercati, W. C.; Petri Júnior, I. (2021). Convective drying with ethanol pretreatment of strawberry enriched with isomaltulose. *Food Bioprocess Technol*ogy, *14*, 2046–2061. DOI: 10.1007/s11947-021-02710-2.

Macedo, L. L.; Corrêa, J. L. G.; Petri Júnior, I.; Araújo, C. da S.; Vimercati, W. C. (2022). Intermittent microwave drying and heated air drying of fresh and isomaltulose (Palatinose) impregnated strawberry. *LWT*, *155*. DOI: 10.1016/j.lwt.2021.112918.

Mendonça, K.; Corrêa, J.; Junqueira, J.; Angelis-Pereira, M.; Cirillo, M.(2017). Mass transfer kinetics of the osmotic dehydration of yacon slices with polyols. *Journal Food Processing Preserv*ation, *41*, 1–8. DOI: 10.1111/jfpp.12983.

Oliveira, L. F.; Corrêa, J. L. G.; Pereira, M. C. de A.; Ramos, A. L. S.; Vilela, M. B. (2016). Osmotic dehydration of yacon (Smallanthus sonchifolius): Optimization for fructan retention. *LWT*, *71*, 77–87. DOI: 10.1016/j.lwt.2016.03.028.

Oliveira, L. F.; Corrêa, J. L. G.; Silveira, P. G.; Vilela, M. B.; Junqueira, J. R. de J.(2021). Drying of ‘yacon’ pretreated by pulsed vacuum osmotic dehydration. *Revista Brasileira Engenharia Agricola e Ambiental*, *25*, 560–565. DOI: 10.1590/1807-1929/agriambi.v25n8p560-565.

Pereira, J. A. R.; Teixeira, M. C.; Saczk, A. A.; Barcelos, M. de F. P.; Oliveira, M. F. de; Abreu, W. C. de. (2016). Total antioxidant activity of yacon tubers cultivated in Brazil. *Food Science Technology*, *40*. DOI: 10.1590/1413-70542016405009416.

Qin, Y., Duan, Z., Zhou, S., & Wei, Z. (2022). Effect of intermittent microwave drying on nutritional quality and drying characteristics of persimmon slices. Food Science and Technology (Brazil), 42, 1–8. https://doi.org/10.1590/fst.37422

Rojas, M. L.; Augusto, P. E. D. (2018) Ethanol and ultrasound pretreatments to improve infrared drying of potato slices. *Innovative Food Science Emerging Technology*, *49*, 65–75. DOI: 10.1016/j.ifset.2018.08.005.

Rojas, M. L.; Silveira, I.; Augusto, P. E. D. (2020). Ultrasound and ethanol pretreatments to improve convective drying: Drying, rehydration and carotenoid content of pumpkin. *Food Bioproducts Processing*, *119*, 20–30. DOI: 10.1016/J.FBP.2019.10.008.

Silveira, P. G., de P. Silva, C. R., Corrêa, J. L. G., Petri, I. J., & Borges, S. V. (2024). Process and quality parameters of convective dried yacon: Influence of ethanol treatment. Food Research International, 176(October 2023), 113863. https://doi.org/10.1016/j.foodres.2023.113863

Smith, J. M.; Van Ness, H. C.; Abbott, M. M.; Swihart, M. T. (2019). *Introduction to chemical engineering thermodynamics*, 8th ed. LTC: Rio de Janeiro.

Souza, A. U. de; Corrêa, J. L. G.; Tanikawa, D. H.; Abrahão, F. R.; Junqueira, J. R. de J.; Jiménez, E. C (2022). Hybrid microwave-hot air drying of the osmotically treated carrots. *LWT*, *156*. DOI: 10.1016/j.lwt.2021.113046.

Ueda, Y.; Matsuda, Y.; Murata, T.; Hoshi, Y.; Kabata, K.; Ono, M.; Kinoshita, H.; Igoshi, K.; Yasuda, S. (2019). Increased phenolic content and antioxidant capacity of the heated leaves of yacon (*Smallanthus sonchifolius*). *Bioscience Biotechnology Biochemistry*, *83*, 2288–2297. DOI: 10.1080/09168451.2019.1644151.

3 GENERAL CONCLUSION

This study successfully achieved its proposed objectives, demonstrating that drying is an effective method for extending the shelf life of yacon slices while preserving their nutritional value. Ethanol pretreatment proved to be highly beneficial, reducing drying time by up to 34.62% and contributing to a lower carbon footprint. Among the tested methods, intermittent microwave drying combined with ethanol pretreatment resulted in superior fructooligosaccharide (FOS) retention (~60% at 52°C) compared to convective drying with ethanol at 50°C (~35%). This improvement can be attributed to the reduced drying time, as convective drying required approximately 300 minutes, whereas intermittent microwave drying was completed in just 160 minutes. The prolonged exposure of samples to hot air in convective drying likely led to greater degradation of bioactive compounds.

Furthermore, this research provides valuable insights into optimizing drying conditions for yacon. The results indicate that ethanol pretreatment, in conjunction with intermittent microwave drying at moderate temperatures, offers an efficient and sustainable strategy for preserving the nutritional and functional properties of dried yacon. This combination aligns with sustainable development goals by enhancing food preservation techniques while minimizing energy consumption and environmental impact.

Future research should explore the long-term stability of bioactive compounds in dried yacon under different storage conditions, as well as investigate the potential of advanced drying technologies, such as cold plasma and pulsed electric fields, to further enhance product quality. Additionally, integrating computational modeling techniques, such as artificial neural networks and genetic algorithms, could provide deeper insights into the mass and heat transfer phenomena governing the drying process, optimizing both energy efficiency and product quality.

In conclusion, this study underscores the potential of ethanol pretreatment and intermittent microwave drying as a promising approach to improve the efficiency, sustainability, and nutritional retention in yacon drying. These findings contribute to advancing food processing strategies, ensuring better preservation of bioactive compounds, and opening new opportunities for the development of functional food products derived from this Andean root.

ANNEX

ANNEX A - Functional beverage of yacon and *Lippia dulcis*.

Patent deposit number: BR 10 2024 010309 2

P. G. Silveira[a*], C. R. de P. Silva[a], J. L. G. Corrêa[a], I. J. Petri [b] and R. A. Rocha[a]
[a]Department of Food Science, Federal University of Lavras, Lavras, Brazil;
[b]Department of Engineering, Federal University of Lavras, Lavras, Brazil.

Abstract

The invention presents a functional beverage obtained from the processing of yacon roots, sweetened with *Lippia dulcis* essential oil, within the technical field of food science and technology. The invention highlighted in this patent is a functional beverage that not only offers a distinctive flavor but also provides significant health benefits. This beverage is formulated from the strategic combination of yacon roots, recognized for their prebiotic properties, and *Lippia dulcis* essential oil, notable for the presence of hernandulcin, a bisabolane sesquiterpene that is 1000 to 1500 times sweeter than sucrose. Yacon, rich in fructooligosaccharides, promotes the growth of beneficial gut bacteria, while *Lippia dulcis* contributes hernandulcin and verbascosides, known for their antidiabetic properties. During production, yacon roots undergo a washing and blanching process and are subsequently processed to obtain the extract. The essential oil of *Lippia dulcis* is extracted using the Clevenger method. The strategic combination of these ingredients in specific proportions results in a synergistic beverage, enhancing antidiabetic effects and promoting gut health. The synergy between yacon fructooligosaccharides and *Lippia dulcis* verbascosides provides a more effective antidiabetic action than products using only one of these components. The use of natural and sustainable ingredients, such as yacon roots and *Lippia dulcis* essential oil, contributes to the economic feasibility of the production process. Furthermore, the growing demand for food products that combine sensory pleasure and nutritional value positions this functional beverage as an appealing choice for health-conscious consumers seeking wellness benefits.

Field of the Invention

[001] The present invention relates to an innovative functional beverage obtained from the processing of yacon roots and sweetened with *Lippia dulcis* essential oil. This unique beverage offers health benefits and can be applied within the technical field of food science and technology. The scope of application includes the development of new food products as well as food processing, encompassing areas such as nutrition, food biotechnology, and public health.

Background of the Invention

[002] The development of functional foods in the current landscape reflects a growing awareness of the link between diet and health, driving innovation in the food industry to meet the increasing demands of consumers seeking convenient and nutritious options.

[003] Yacon (Smallanthus sonchifolius) is a root that has been extensively studied due to its functional properties. The bioactive compounds present in yacon include fructooligosaccharides (FOS), which are prebiotic fibers that support gut health and offer potential health benefits. Yacon also contains phenolic compounds such as chlorogenic acid and caffeic acid, known for their antioxidant properties.

[004] Yacon is particularly rich in fructooligosaccharides, especially inulin, which is a specific type of this carbohydrate. Inulin is a non-digestible carbohydrate that acts as dietary fiber and a prebiotic, promoting gut health by stimulating the growth of beneficial bacteria in the colon.

[005] Its potential as a functional food ingredient, alternative sweetener, and source of phytochemicals makes yacon a valuable addition to the food industry for the creation of innovative, health-promoting products.

[006] Compared to other foods such as Manuka honey, yacon has a lower glycemic index. This characteristic is beneficial for the development of products, particularly for the creation of foods targeting individuals seeking to manage blood sugar levels and overall glycemic response.

[007] Yacon has a high moisture content and contains enzymes like polyphenol oxidase, making it susceptible to enzymatic browning, a process that can affect its appearance and sensory quality. Additionally, its low pH creates a favorable environment for microbial growth, raising preservation concerns. Therefore, processing techniques can be applied to maintain yacon quality and extend its shelf life.

[008] Several yacon processing alternatives have been employed, including the production of various derived products such as syrup, powder, and herbal tea. These different processing methods have been explored to validate the health claims associated with yacon, with special attention to its bioactive components, such as fructooligosaccharides.

[009] Yacon derivatives, including flours and extracts, have increasingly been used in food technology as fiber sources, showing relatively satisfactory results in physicochemical and sensory analyses. Among the products manufactured with these derivatives are cooked ham, light yogurt, sweets with different gelling agents, cakes with added yacon flour, and sliced bread.

[010] Another species with physicochemical and nutraceutical properties similar to yacon is tupinambur (*Helianthus tuberosus*), also known as Jerusalem artichoke, sunroot, or earth apple. Like yacon, tupinambur is known for its edible tuberous roots and for containing various bioactive compounds beneficial to health.

[011] *Lippia dulcis,* also known as Aztec sweet herb, is a plant from the Verbenaceae family that has traditionally been used in Mexican medicine for its medicinal properties. *Lippia dulcis* has been employed in the treatment of diseases as an anti-inflammatory, antitussive, antipyretic, expectorant, emollient, and diuretic agent.

[012] *Lippia dulcis* is widely recognized for its sweetening potential, attributed to hernandulcin. Hernandulcin is a sesquiterpene lactone responsible for the sweet taste of *Lippia dulcis,* making it a natural alternative sweetener. Verbascoside is another major compound present in this species. It is a phenylethanoid glycoside found in *Lippia dulcis* that contributes to its medicinal properties, including antioxidant and anti-inflammatory effects.

[013] The presence of hernandulcin and verbascoside in *Lippia dulcis* highlights its functional versatility as a natural sweetener and a source of bioactive compounds with potential health benefits, making it a promising option for applications in food, pharmaceuticals, and other industries.

[014] The essential oil extracted from *Lippia dulcis* has been the subject of numerous studies focusing on its chemical composition, seasonal variations, and potential health benefits. Studies have identified the chemical profile of *Lippia dulcis* essential oil, revealing the presence of several components, such as oxygenated bisabolane-type sesquiterpenes, including epi-α-bisabolol and hernandulcin. These components contribute to the oil aromatic and potentially therapeutic properties.

[015] *Lippia dulcis* essential oil has a sweet, herbal aroma with subtle mint and lemon notes, making it an interesting addition for flavoring foods and beverages.

[016] The essential oil of *Lippia dulcis* also exhibits antifungal activity, which can be particularly useful in preventing fungal growth in foods, extending their shelf life, and maintaining quality.

[017] Peppermint essential oil is widely used in the food industry. However, while peppermint essential oil offers refreshing and mentholated notes, *Lippia dulcis* oil has a sweeter and more herbal profile, making it an excellent option for use in desserts and sweetened beverages.

[018] The technology described in patent BR 20 2020 002434 0 U2 outlines a method for producing yacon juice flavored with fruits or spices. While the document BR 20 2020 002434 0 U2 focuses on the production of yacon juice flavored with liquid or powdered ingredients, the present invention differs from both previously mentioned technologies by using *Lippia dulcis* essential oil to impart greater sweetness to the juice and provide even greater nutritional value to the beverage. This enhancement is due to glycosides present in the oil, capable of inhibiting the α-glucosidase enzyme, thus aiding in reducing glycemic spikes.

[019] Document BR 10 2018 007265 0 A2 describes a bioactive compound obtained by mixing yacon syrup with a concentrated carotenoid extract, which has sweetening properties. This compound is used to sweeten foods such as yogurts and juices. The manufacturing process involves specific steps to prepare both the yacon syrup and the concentrated carotenoid extract. While BR 10 2018 007265 0 A2 focuses on the development of a sweetening bioactive compound based on yacon syrup and carotenoid extracts, the present invention does not involve the use of carotenoids or concentrated extracts. The nutritional value in our invention is derived from a medicinal plant with antidiabetic properties, making the yacon juice a powerful beverage for the treatment and management of diseases such as diabetes.

[020] Document PI 1106621-0 B1 describes a prebiotic food product made from yacon roots containing fructooligosaccharides and inulin, which can be consumed directly or added to various preparations. The manufacturing process involves sanitization, peeling, blending with ascorbic and citric acids, and vacuum concentration until reaching 40°-50° Brix. Unlike the method described in PI 1106621-0 B1, the present invention does not involve the vacuum concentration of yacon juice. Additionally, *Lippia dulcis* essential oil is used to impart greater sweetness and a high antidiabetic potential to the beverage.

[021] The current state of the art does not offer an effective solution that combines the benefits of yacon, known for its prebiotic and glycemic control properties, with the therapeutic qualities of *Lippia dulcis* essential oil. Therefore, the development of a pioneering functional beverage obtained from the processing of yacon roots and enriched with *Lippia dulcis* essential

oil represents a significant advancement, as the integration of these ingredients results in a unique synergy, enhancing the positive effects of both. Unlike existing alternatives, our formulation not only provides an exceptional nutrient source but also stands out for its enhanced effectiveness in promoting gastrointestinal health and regulating blood sugar levels. This combination of technical benefits, along with the growing consumer demand for products that promote holistic well-being, positions our functional beverage as a remarkable and highly advantageous contribution to the current market landscape.

Description of the Invention

[024] The present invention consists of a functional beverage obtained through the processing of yacon roots containing sodium metabisulfite as a preservative and sweetened with *Lippia dulcis* essential oil.

[025] The steps for producing the yacon extract are as follows:

a) Yacon roots are carefully washed under running water and disinfected by immersing the tuberous roots in a sodium hypochlorite solution (200 ppm) for 15 minutes.

b) The roots are blanched in a copper vessel at 100°C for 10 minutes to ensure enzymatic inactivation and prevent degradation reactions.

c) The yacon roots are then sliced, peeled, blended, and filtered through organza fabric to obtain the extract.

d) Finally, 3% sodium metabisulfite is added to the extract to prevent degradation reactions.

[026] The steps for the extraction of *Lippia dulcis* essential oil and the production of the functional beverage are:

a) *Lippia dulcis* leaves are carefully washed under running water and disinfected by immersion in a sodium hypochlorite solution (200 ppm) for 15 minutes.

b) The leaves are then ground using an electric grinder to increase the surface area and optimize the extraction process.

c) The powdered material is added to a flask containing distilled water for hydrodistillation. The solid-to-liquid ratio used in the flask is 100g per 1000 mL. Oil extraction is performed using a Clevenger apparatus.

d) After extraction, the obtained extracts are combined in specific proportions to ensure the synergy of their antidiabetic effects. The beverage is then stored in a refrigerator at 4°C.

The process is carefully monitored to preserve the nutritional benefits and ensure the final beverage quality.

[027] The present invention was tested for taste and stability over time. The beverage exhibited a sweet and pleasant flavor, with no detectable changes during the evaluation period (30 days).

[028] Due to the preservation of yacon functional compounds in the beverage, this invention acts as a prebiotic, promoting the growth of beneficial gut bacteria, improving digestive health, and strengthening the immune system.

[029] The concentration of verbascosides introduced into the beverage from *Lippia dulcis* essential oil gives the product antidiabetic properties, helping regulate blood sugar levels.

[030] The presence of hernandulcin, derived from *Lippia dulcis* essential oil, provides the beverage with a balanced sweet taste without the need for refined sugar. This makes it an attractive alternative for individuals seeking to reduce sugar consumption without compromising taste.

Examples of Embodiments of the Invention

[031] Production of a functional beverage based on yacon roots and *Lippia dulcis* essential oil as a healthy substitute for traditional soft drinks or sweetened juices. This application of the present invention represents a unique opportunity to meet the growing demand for healthier and more functional beverage options. By incorporating yacon root extract, known for its prebiotic properties, and *Lippia dulcis* essential oil, with its high hernandulcin and verbascoside content, this beverage not only offers a distinctive taste but also provides significant health benefits. Additionally, the use of these natural and sustainable ingredients positions this beverage as an attractive alternative for health-conscious consumers, offering a product that combines sensory pleasure and nutritional value.

[032] Development of cereal bars or energy bars formulated with dehydrated yacon root extract containing *Lippia dulcis* essential oil. These bars represent a convenient and nutritious option for consumers seeking healthy and functional snacks. The combination of yacon extract, known for its prebiotic properties that promote gut health, with *Lippia dulcis* essential oil, rich in hernandulcin and verbascosides with antidiabetic properties, makes these bars not only flavorful but also beneficial for blood sugar control and digestion.

[033] Production of yogurts or dairy desserts enriched with yacon root extract and sweetened with *Lippia dulcis* essential oil. These products offer a healthy and indulgent option

for consumers seeking alternatives to traditional dairy products. The presence of yacon extract, with its fructooligosaccharides that promote the growth of beneficial gut bacteria, combined with *Lippia dulcis* essential oil, provides not only a unique taste but also benefits for digestive health and blood sugar control.

[034] The synergy between yacon root extract and *Lippia dulcis* essential oil represents a significant innovation in the field of food science and technology. Its versatility for both direct consumption and use in the food industry opens the door to a wide range of healthy and functional food products. This invention not only represents a business opportunity but also contributes to a more conscious and balanced diet, aligned with the needs and preferences of modern consumers.

Claims

1. "FUNCTIONAL BEVERAGE OF YACON AND *Lippia dulcis*", characterized by being a beverage obtained from the extraction of yacon root juice. The concentration of pure juice in the beverage may vary from 50% to 100%, and the water concentration may vary from 0% to 50%. This beverage also includes *Lippia dulcis* essential oil, which can be used in amounts ranging from 0.5 mL to 5 mL per liter of juice.
2. "FUNCTIONAL BEVERAGE OF YACON AND *Lippia dulcis*", according to claim 1, characterized by being a functional beverage containing different concentrations of pure yacon juice.
3. "FUNCTIONAL BEVERAGE OF YACON AND *Lippia dulcis*", according to claim 1, characterized by being sweetened with varying concentrations of *Lippia dulcis* essential oil.
4. "FUNCTIONAL BEVERAGE OF YACON AND *Lippia dulcis*", according to claim 1, characterized by the use of the Clevenger method for extracting *Lippia dulcis* essential oil, ensuring the preservation of the functional properties of hernandulcin and verbascosides.
5. "FUNCTIONAL BEVERAGE OF YACON AND *Lippia dulcis*", according to claim 1, characterized by the use of a copper vessel during the blanching stage to prevent the degradation of chlorophyll present in the roots, preserving the color.
6. "FUNCTIONAL BEVERAGE OF YACON AND *Lippia dulcis*", according to claim 1, characterized by the use of up to 3% sodium metabisulfite to prevent color alterations in the functional beverage.

7. "FUNCTIONAL BEVERAGE OF YACON AND *Lippia dulcis*", according to claim 1, characterized by the combination of yacon and *Lippia dulcis* extracts in specific proportions to ensure the synergy of their effects.