FRANCEMIR JOSÉ LOPES

SECAGEM CONVECTIVA E SECAGEM MICRO-ONDAS-VÁCUO DE YACON OSMOTICAMENTE PRÉ-TRATADO

LAVRAS – MG
2016

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

Orientador

Dr. Jefferson Luiz Gomes Corrêa

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2016

Dedico este trabalho aos meus pais,
Francisco dos Santos Lopes e Francisca Saqueto Lopes.
À minha esposa,
Keila Bacelar Duarte de Morais

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RESUMO GERAL

O presente trabalho foi realizado com o objetivo de estudar a secagem convectiva e a por micro-ondas vácuo de yacon, precedidas por desidratação osmótica com pulso de vácuo. No artigo 1 disserta-se sobre os resultados da pesquisa de secagem convectiva de yacon, enquanto no artigo 2 apresentam-se os resultados referente aos experimentos realizados em micro-ondas vácuo. Foram analisados os efeitos do tipo de processo de secagem e do uso de desidratação osmótica na retenção de frutanos, encolhimento, cor, capacidade de reidratação, difusividade e tempo de secagem. A desidratação osmótica com pulso de vácuo (PVOD) foi realizada com solução de sorbitol, 38 °Brix a 35 °C e de 681 mmHg de pulso de vácuo, nos primeiros 10 minutos da desidratação. Na secagem convectiva foram testadas temperaturas de secagem de 40 °C, 50 °C, 60 °C e 70 °C e velocidade do ar constante em 0,5 ms^{-1}. O tempo de secagem foi reduzido e a difusividade aumentada com o aumento da temperatura e o uso de PVOD. A consideração do encolhimento resultou em um melhor ajuste da cinética de secagem. A PVOD foi eficaz para reduzir o tempo de secagem e o encolhimento, mas resulta em uma amostra mais escura com menor retenção de fruto-oligossacarídeos (FOS). Os experimentos em micro-ondas vácuo foram baseados em um planejamento experimental 3^k, com três níveis de densidade de potência (DP) (3,6, 6,3 e 9,8 Wg^{-1}) e três pressões de vácuo (PV) (0, 300 e 600 mmHg). Os resultados mostraram que o aumento da densidade de potência de micro-ondas resultou em menor tempo de processo e foi menor com o uso de PVOD. Além disso, a densidade de potência mostrou influência positiva na retenção de FOS e encolhimento. A pressão de vácuo também teve efeito significativo para a retenção de FOS em amostras pré-tratados e ajudou a secagem. A presença de açúcar em PVOD escureceu o yacon. Densidade de potência de 9,8 Wg^{-1} e pressão vácuo de 600 mmHg em amostras osmoticamente desidratadas destacaram-se na secagem por micro-ondas vácuo de yacon, resultando em produto de qualidade superior, comparadas com a secagem convectiva.

Palavras chave: Frutanos, prebiótico, PVOD, sorbitol, FOS, alimento desidratado

GENERAL ABSTRACT

The present work aimed to study the convective drying and microwave-vacuum of yacon preceded by pulsed vacuum osmotic dehydration. The first article presents the results of the convective drying of yacon, while the second article presents results of microwave-vacuum drying. The influence of the type of drying and use of osmotic dehydration process the fructan retention, shrinkage, color, rehydration capacity, diffusivity and drying time. Were analyzed The pulsed vacuum osmotic dehydration (PVOD) was performed with sorbitol solution, 38 °Brix, 35 °C and 681 mmHg vacuum pulse in the first 10 minutes of dehydration. In the convective drying, the temperatures were 40; 50; 60 and 70 °C and constant air velocity 0.5 ms^{-1}. The drying time was reducedwith increment temperature and the use of PVOD. The consideration of shrinkage resulted in a better fitness of the drying kinetics. The PVOD was effective to reduce drying time and shrinkage, but results in a browned sample with lower retention of fructooligosaccharides (FOS). Experiments in microwave-vacuum are based on experimental design with three 3^k power density levels (PD) (3.6, 6.3 and 9.8 Wg^{-1}), and three vacuum pressure (VP) (0, 300 and 600 mmHg). The results showed that increasing microwave power density resulted in lower and process times were decrease with the use of PVOD. Moreover, power density showed a positive influence in retention of FOS and shrinkage. The vacuum pressure was also significant effect for retention of FOS in pretreated samples and helped drying. The sugar presence in PVOD seems to browning of yacon. Power density of 9.8 Wg^{-1} and vacuum pressure of 600 mmHg osmotically dehydrated samples stood out in the microwave vacuum drying of yacon, resulting in superior product compared to convective drying.

Keywords: Fructans, prebiotic, PVOD, sorbitol, FOS, dehydrated food

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LISTA DE SIGLAS

DCCR	Delineamento composto central rotacional
df	Degrees of freedom
FOS	Fructooligosaccharides
MWV	Microwave-vacuum drying
MS	Mean square
PD	Power density
PVOD	Pulsed vacuum osmotic dehydration
RSME	Root mean square error
RE	Regression
FV	Source of variation
SS	Sum of squares
VP	Vacuum pressure

LISTA DE SIMBOLOS

M_0	Moisture content initial
M_t	Moisture content at the instant t
M_{eq}	Equilibrium moisture content
M_R	Moisture ratio
D_{eff}	Effective diffusivity
D_0	Pre-exponential factor
E_a	Activation energy
R	Universal gas constant
K	Absolute temperature
V/V_0	Volume ratio
χ^2	Chi-square
a^*	Color parameter
b^*	Color parameter
C^*	Chroma
h°	Hue angle
ΔE	Color variation
L^*	Luminosity
S	Shrinkage
L	Half of sample thickness
z	Direction of the transfer
n	Number of terms
N	Number of parameters in the model
t	Time

l	Sample thickness
a, b	Fitness parameter
R^2	Coefficient of determination

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PRIMEIRA PARTE

1 INTRODUÇÃO GERAL

O yacon (*Smallanthus sonchifolius*) é uma planta perene da família *Asteraceae*, com origem na cordilheira dos Andes. É uma fonte particularmente abundante de fruto-oligossacarídeos (FOS) e inulina, conhecidos como frutanos. Os frutanos são definidos como carboidratos não glicêmicos. Costumam levar um efeito benéfico para a saúde, reduzindo os níveis séricos de lipídios no sangue e os níveis de glicose, e melhorando o equilíbrio intestinal.

No entanto, os FOS se hidrolisam rapidamente após a colheita, o que afeta as características funcionais do yacon. O escurecimento e as injúrias são os fenômenos comuns durante armazenamento pós-colheita e transporte, o que restringe o desenvolvimento sustentável da indústria de yacon e resulta em perdas econômicas pós-colheita. Além disso, o yacon é uma planta sazonal. Para que se conserve o produto com teores de FOS nos períodos de entressafra, é imperativo o uso de tecnologias de conservação, como a secagem.

A secagem convectiva é um método amplamente utilizado na conservação de vegetais pós-colheita e na produção de alimentos desidratados. No entanto, o alto consumo de energia em secagem convectiva torna o processo custoso. Além disso, o escurecimento não enzimático, o alto encolhimento, a baixa capacidade de reidratação e a perda de nutrientes são desvantagens comuns da secagem convectiva. A utilização de temperaturas elevadas pode resultar em degradação e oxidação de alguns nutrientes sensíveis ao calor.

Na secagem por micro-ondas, a energia é direcionada à excitação das moléculas de água no interior do alimento. Isto resulta em melhor aproveitamento energético e menor tempo de processamento, com consequente baixo tempo de exposição do alimento a temperaturas elevadas e produtos de qualidade superior. Além disso, secagem por micro-ondas pode minimizar o encolhimento da estrutura do tecido e melhorar as características de reidratação. Porém, a secagem por micro-ondas tende a ser desuniforme, com possível queima em alguns pontos do produto desidratado. O uso de vácuo, aliado ao de micro-ondas, na secagem, pode não só aumentar a taxa de secagem, mas também melhorar a qualidade do produto seco. A redução da pressão em secagem micro-ondas-vácuo promove a retirada de água em temperaturas mais baixas, causando menor degradação no alimento.

A desidratação osmótica pode, ainda, auxiliar na manutenção dos parâmetros de qualidade do material em uma secagem posterior, como cor e teor de nutrientes, além de poder reduzir o tempo de secagem. A desidratação osmótica pode ter suas taxas de transferência intensificadas, quando utilizado o pulso de vácuo.

Com base nos conceitos expostos, foram estudadas, no presente trabalho, a secagem convectiva e a por micro-ondas-vácuo de yacon, precedidas por desidratação osmótica com pulso de vácuo.

2 REFERENCIAL TEÓRICO

2.1 Yacon

O yacon (*Smallanthus sonchifolius*) é originário dos vales andinos da Colômbia, do Equador, do Peru, da Bolívia e do noroeste da Argentina, em altitudes de 2.000 a 3.100 metros. Nessa região, é cultivado desde a antiga civilização Inca e utilizado na alimentação humana (VILHENA; CÂMARA; KAKIHARA, 2000). No Brasil, a espécie foi introduzida por volta de 1989, na região de Capão Bonito, SP, por imigrantes japoneses, que utilizam suas folhas e raízes tuberosas em tratamentos contra diabetes e altas taxas de colesterol no sangue (KAKIHARA et al., 1996).

Esta espécie vem despertando o interesse do mundo científico devido ao seu potencial como alimento funcional (CASTRO et al., 2013; CHOQUE DELGADO et al., 2013; VAZ-TOSTES et al., 2014). Diferente da maioria das raízes que armazenam carboidratos na forma de amido, o yacon e várias plantas da família *Compositae* armazenam os carboidratos na forma de frutano. Os frutanos do yacon são de 60% a 70% do tipo inulina e fruto-oligossacarídeos (FOS) (CAMPOS et al., 2012; VILHENA; CÂMARA; KAKIHARA, 2000). Estes compostos presentes no yacon não são hidrolisados pelas enzimas do corpo humano e, dessa forma, passam por meio do trato digestivo sem serem metabolizados, fornecendo baixo conteúdo energético, sendo recomendados em dietas, principalmente de pessoas diabéticas e obesas (OJANSIVU; FERREIRA; SALMINEN, 2011).

Os níveis de açúcar nas raízes de yacon podem variar dependendo da localização, das condições de cultivo, das condições climáticas, do tempo de colheita e da temperatura de pós-colheita (Tabela 1). Os minerais mais abundantes no yacon são cálcio e magnésio (Tabela 2). O yacon é rico em substâncias bioativas, tais como os compostos fenólicos, derivados de éster, ésteres metílicos e glicosídeos. O suco do yacon contém compostos polifenólicos, como o ácido clorogênico, que é considerado o antioxidante primário do yacon, além de triptofano e derivados do ácido cafeico (TAKENAKA et al., 2003).

Tabela 1 Composição de carboidratos em tubérculos de yacon [%].

	Referências	
Componente	Lobo et al. (2007)	Habib et al. (2011)
Frutose	13,51	26,00
Glicose	8,97	10,01
Sacarose	13,42	10,00
FOS	55,33	52,00

FOS = fruto-oligossacarídeo

Tabela 2 Composição química do yacon [g/100g].

Componentes	Lobo et al. (2007)	Choque Delgado et al. (2012)
Umidade	ND	8,02±0,08
Proteínas	2,64±0,07	2,45±0,09
Lipídios	0,61±0,02	0,87±0,10
Cinzas	3,85±0,06	2,53±0,14
Fibra insolúvel	7,85±0,17	3,46±0,12
Carboidratos	ND	86,13
Cálcio	0,83±0,01	ND
Magnésio	0,62±0,09	ND

ND = não declarado

A indústria de alimentos, atualmente, está interessada em melhorar os benefícios nutricionais dos produtos com o menor comprometimento possível de suas propriedades sensoriais. Aliada à alta demanda por alimentos de qualidade, a inclusão do yacon como uma fonte de prebióticos, como os frutanos, na produção de diferentes alimentos para consumo humano, representa grande oportunidade para a inovação e a agregação de valor na indústria de alimentos funcionais.

2.1.1 Fruto-oligossacarídeos (FOS)

O principal açúcar acumulado nas raízes de yacon está na forma de oligossacarídeos e fruto-oligossacarídeos (FOS), também chamado de frutanos. Os FOS apresentam baixo grau de polimerização, que consistem em cadeias curtas de unidades de frutose ligadas por ligações glicosídicas β (2 → 1). Eles carregam uma única unidade d-glicosil na extremidade não redutora do α (1 → 2) como na cadeia de sacarose e são, portanto, do tipo inulina (HERMANN; FREIRE; PAZOS, 1997). Há também de 15% a 40% de açúcares simples: sacarose, frutose e glicose. Em outras palavras, os principais açúcares presentes no yacon são do tipo fruto-oligossacarídeos (FOS) e inulina. Os FOS são polímeros de frutose, contendo de 3 a 10 moléculas de frutose, enquanto a de inulina apresenta 11 ou mais moléculas de frutose. Ambos contêm uma molécula terminal de glicose (LACHMAN; FERNÁNDEZ; ORSÁK, 2003).

A ligação β (2 → 1) impede que os FOS sejam digeridos porque os seres humanos não têm enzimas para hidrolisá-los (NINESS, 1999). Os FOS são fermentados seletivamente por diversos bifidobactérias e também por lactobacilos que, por sua vez, podem ser prebióticos (PEDRESCHI et al., 2003).

Os FOS têm sido relacionados com a redução dos níveis séricos de glicose e triglicerídeos no sangue, a normalização da pressão arterial e os benefícios para a dieta de diabéticos (OJANSIVU; FERREIRA; SALMINEN, 2011). Os FOS podem ser encontrados em alcachofras, aspargos, beterraba, chicória, banana, alho, cebola, trigo, tomate (PASSOS; KUN PARK, 2014) e em tubérculos, como o yacon (OLIVEIRA et al., 2016).

O yacon é consumido, principalmente, *in natura* ou seco, mas pode também ser adicionado em forma de pó em uma ampla variedade de alimentos, tais como produtos de padaria, iogurtes e sucos. Considerando-se que a concentração prebiótica do yacon é diminuída ao longo do período pós-colheita, devido à polimerização de FOS, e que o seu período de vida útil é menor do que sete dias, em condições ambientais, é fundamental processá-lo, a fim de preservar a sua característica nutricional (PERUSSELLO et al., 2014).

2.2 Secagem

A secagem é uma operação unitária na qual ocorre eliminação de água por transferência simultânea de calor e massa. É, provavelmente, o mais antigo método de conservação de alimentos (PARK; LAMSAL; BALASUBRAMANIAM, 2014). A secagem tem sido utilizada por pequenas, médias e grandes indústrias na valorização econômica de frutas, hortaliças e farináceos, entre outros.

A secagem tem sido utilizada para a promoção da redução da atividade de água, proporcionando inibição do crescimento microbiano, diminuição da atividade enzimática e velocidades das reações químicas. Dessa forma, essa operação possibilita o aumento da vida de prateleira dos alimentos. Entre as vantagens do alimento desidratados, estão a praticidade de consumo e a diversificação de oferta de produtos. Durante a secagem, para que haja a evaporação de água da superfície do material para o ambiente, ela deve ser transportada do interior do sólido até a superfície.

Os fatores que governam a velocidade dos mecanismos de transferência de calor e massa estão relacionados com a pressão de vapor do material e do ar de secagem, temperatura e velocidade do ar, taxa de difusão da água no material, espessura e área da superfície exposta para secagem (ARSDEL; COPLEY; MORGAN JUNIOR, 1973).

Park et al. (2007) apresentam a evolução das transferências simultâneas de calor e de massa ao longo da operação de secagem (Figura 1). Este fenômeno é comum a qualquer condição de processo e, assim, a secagem pode ser dividida em três períodos de secagem.

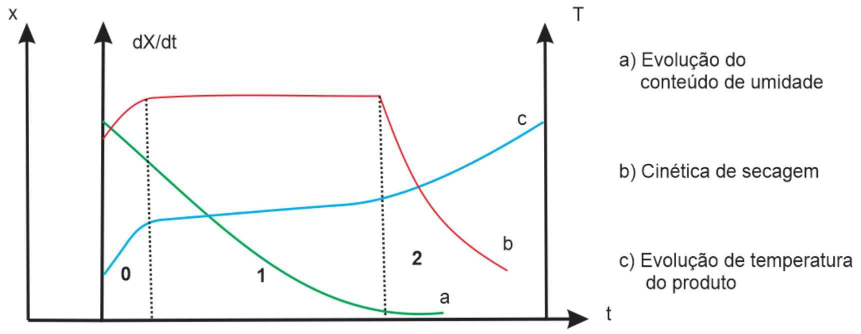

Figura 1-Evolução, com o tempo (t), do teor de umidade (X), de temperatura (T) e da taxa de secagem (dX/dt) de alimentos. Fonte: Park et al. (2007).

A curva (a) representa a diminuição do teor de umidade do produto (X) em relação ao tempo (t), durante o processo de secagem. A curva (b) mostra a velocidade ou a taxa de secagem do produto (dX/dt), isto é, a variação do conteúdo de umidade do produto por tempo, em relação ao tempo (t). A curva (c) representa a variação da temperatura da amostra (T) com o tempo (t).

O primeiro período, ou período de indução, corresponde à região 0, quando ocorre a adequação do produto às condições de secagem. No início do processo, a temperatura do produto é inferior à do ar de secagem e a pressão parcial de vapor de água na superfície do produto é baixa. Consequentemente, a transferência de massa e a taxa de secagem também são baixas. À medida que o ar entra em contato com o produto, a temperatura dele aumenta, havendo uma elevação na pressão de vapor de água e na taxa de secagem. Esse processo continua até a transferência de calor compensar exatamente a transferência de massa.

O período de taxa constante corresponde à região 1. A água evaporada é a água livre. Neste período, a migração da água do interior até a superfície do produto é suficiente para acompanhar a perda por evaporação de água na superfície. A transferência de massa e a de calor são equivalentes e, portanto, a velocidade de secagem é constante. Enquanto houver umidade na superfície do produto para compensar a evaporação, a taxa de secagem será constante. O término deste período ocorre quando a migração de água do interior para a superfície não consegue compensar a taxa de evaporação da água superficial.

No terceiro período, a taxa de secagem é decrescente. Este período é representado pela região 2, onde a transferência de calor não é mais compensada pela transferência de massa e o movimento do líquido do interior do sólido é insuficiente para manter a taxa de evaporação na superfície deste. Como consequência, a velocidade de secagem começa a decrescer e há uma elevação da temperatura da superfície, tendendo à temperatura do ar de secagem. O fator limitante neste período é a migração interna de água. Quando o produto atinge o ponto de umidade de equilíbrio em relação ao ar de secagem, o processo é encerrado.

Durante a secagem, os alimentos podem sofrer diversas alterações, tanto no seu valor nutritivo como nas suas propriedades sensoriais, pelo uso de temperaturas altas por períodos longos. As reações enzimáticas ou de oxidação, dependentes de temperatura, podem levar à alteração de cor, sabor e valor nutritivo dos alimentos.

Uma das principais mudanças físicas que ocorrem durante a secagem convectiva é o encolhimento. Este encolhimento ocorre devido à perda de água e ao aquecimento, dificultando a reidratação do alimento. Alteração na forma, encolhimento e aumento da dureza são as apontados como perda de qualidade em produtos desidratados.

2.2.1 Micro-ondas e suas interações com os alimentos

Micro-ondas são uma modalidade de radiação eletromagnética, como a luz, a radiação ultravioleta, os raios x e as ondas de televisão, rádio e infravermelho (COPSON, 1975). Estão situadas no intervalo de frequências compreendido entre 300 MHz e 300 GHz (SCHUBERT; REGIER, 2005). Em processos de aquecimento, as frequências mais utilizadas são de 915 MHz e de 2.450 MHz (DATTA; ANANTHESWARAN, 2001). Estas frequências têm sido utilizadas para aplicações domésticas, industriais, científicas e medicinais. A maioria dos fornos de micro-ondas domésticos opera a 2.450 MHz (BARBOZA et al., 2001; MARSAIOLI, 1991).

As micro-ondas são geradas por um tubo oscilador denominado magnetron, alimentado por um circuito eletrônico capaz de converter energia elétrica de frequência industrial (60 Hz) em energia eletromagnética de micro-ondas. O campo eletromagnético se propaga na forma de onda eletromagnética no interior de um guia de onda metálico (linha de transmissão), até ser injetada no aplicador (uma cavidade com paredes metálicas onde está o produto a aquecer). A penetração e o aquecimento de alimentos em um campo de micro-ondas são praticamente instantâneos, em comparação com os métodos convencionais de aquecimento (SILVA, 2005; SILVA; MARSAIOLI JUNIOR, 2009).

Segundo Chandrasekaran, Ramanathan e Basak (2013), a capacidade de um material em converter a energia de micro-ondas em calor pode ser compreendida por meio de suas propriedades dielétricas. As propriedades dielétricas são afetadas pela composição do alimento, pela temperatura de operação e pela frequência de micro-ondas. O fenômeno pode ser caracterizado pela permissividade complexa relativa (ε^*), conforme a Equação 1. A constante dielétrica, ε', mede o acoplamento do material com a energia de micro-ondas, e o fator de perda, ε'', mede a dissipação da energia acoplada em forma de calor.

$$\varepsilon^* = \varepsilon' - j\varepsilon'' \tag{1}$$

em que $j = \sqrt{-1}$.

A interação entre as micro-ondas e o material envolve dois principais mecanismos: rotação dipolar e condução iônica. Na condução iônica, os íons são acelerados pelo campo elétrico oscilante, causando sua movimentação em direção oposta à sua polaridade. Este movimento dos íons provoca colisões entre as moléculas do material, convertendo a energia cinética em energia térmica, gerando calor. Porém, nas frequências usuais definidas para aplicações domésticas, industriais, médicas e científicas, a maior parte do aquecimento por micro-ondas advém do mecanismo de rotação dipolar das moléculas polares que ocorre após o alinhamento das moléculas (que têm dipolos permanentes ou induzidos) com o campo elétrico aplicado. Quando o campo é removido, as moléculas voltam a um estado desordenado e a energia absorvida nestes dipolos é dissipada na forma de calor. Esta forma de aquecimento gera calor mais internamente e de maneira mais uniforme, de acordo com a profundidade de penetração das ondas eletromagnéticas, em vez de ser transferido a partir da superfície para o interior do material, como acontece no caso do aquecimento convectivo (CHANDRASEKARAN; RAMANATHAN; BASAK, 2013; DATTA; ANANTHESWARAN, 2001; ORSAT et al., 2007).

2.2.2 Secagem micro-ondas vácuo

Na secagem de alimentos, o objetivo é remover a umidade dos materiais com as menores alterações em sua composição física e química. É um processo importante para preservar os produtos e aumentar a sua estabilidade de armazenamento, que pode ser obtido por secagem em micro-ondas. A secagem com micro-ondas tem a vantagem de obter de altas taxas de secagem (DAK; PAREEK, 2014) e melhorar a qualidade dos alimentos secos. A energia de micro-ondas, combinada com outros métodos de secagem, pode melhorar a eficiência de secagem, assim como a qualidade dos produtos (WANG et al., 2013; ZHANG; JIANG; LIM, 2010).

A secagem micro-ondas vácuo tem sido investigada como um potencial método para a obtenção de produtos de alta qualidade de alimentos desidratados, incluindo frutas, legumes e grãos (CALÍN-SÁNCHEZ et al., 2011). Este processo de secagem combina as vantagens tanto do aquecimento por micro-ondas quanto por secagem a vácuo.

A transferência de massa é acelerada porque as micro-ondas são mais bem absorvidas pelas regiões úmidas do material do que pelas regiões secas (CHANDRASEKARAN; RAMANATHAN; BASAK, 2013). Idealmente, o gradiente de temperatura é invertido em relação ao aquecimento por convecção, fazendo com que o interior do alimento seja mais quente que a superfície. Quando se aplica vácuo, o ponto de ebulição da água é reduzido, diminuindo ainda mais o período de indução da curva de secagem e também a temperatura do processo. Quando a temperatura atinge o ponto de ebulição, a energia das micro-ondas é utilizada para evaporar a água. Assim, vapor é criado no interior do material e flui para a superfície, não apenas devido à diferença na pressão parcial de vapor, mas devido à diferença de pressão global (CALÍN-SÁNCHEZ et al., 2011).

A temperatura de processamento mais baixa e a transferência de massa elevada, proporcionadas pelo vácuo combinado com a rápida transferência de energia conferida pelo aquecimento por micro-ondas, proporcionam uma secagem muito rápida e com mínimas modificações no produto final

(YONGSAWATDIGUL; GUNASEKARAN, 1996a). Além disso, a menor exposição ao ar pode diminuir a oxidação, preservando assim a cor e o teor de nutrientes dos produtos (YONGSAWATDIGUL; GUNASEKARAN, 1996b).

A secagem por vácuo e micro-ondas pode modificar a textura do alimento. As condições de potência de micro-ondas e pressão podem ser configuradas para promover a expansão da estrutura de alguns produtos, conferindo boa capacidade de reidratação (GIRI; PRASAD, 2007; LIU et al., 2009; NAHIMANA; ZHANG, 2011).

Alguns estudos de secagem por este método foram feitos com abacaxi (CORRÊA et al., 2011), romã (DAK; PAREEK, 2014), cenoura (NAHIMANA; ZHANG, 2011), batata (BONDARUK; MARKOWSKI; BŁASZCZAK, 2007), maçã (HAN et al., 2010), morango (WOJDYŁO; FIGIEL; OSZMIAŃSKI, 2009), beterraba (FIGIEL, 2010), folha de menta (JENI; YAPA; RATTANADECHO, 2010; THERDTHAI; ZHOU, 2009), folha de chá (JENI; YAPA; RATTANADECHO, 2010), alecrim (CALÍN-SÁNCHEZ et al., 2011; SZUMNY et al., 2010), orégano (FIGIEL et al., 2010), tomate (DURANCE; WANG, 2002), cogumelo (GIRI; PRASAD, 2007) e, até mesmo, alimentos de origem animal, como mel (CUI et al., 2008), camarão (LIN; DURANCE; SCAMAN, 1999) e carpa (ZHANG et al., 2007).

Embora a energia de micro-ondas tenha aplicação em diversos tipos de alimentos, há necessidades de investigações destinadas a melhorias da qualidade final do produto, especificamente os métodos para obter produtos com qualidade nutricional precisam ser explorados. Minimizar os efeitos do escurecimento e do encolhimento é um exemplo potencialmente difícil de ser controlado.

2.2.3 Secagem de yacon

O escurecimento e as injurias são os fenômenos comuns durante o armazenamento pós-colheita e o transporte de alimentos, o que restringe o desenvolvimento sustentável da indústria de yacon e resulta em perdas econômicas pós-colheita. Além disso, o yacon é uma planta sazonal. Para que se conserve o produto com suas características químicas, físicas e nutricionais mais próximas do *in natura*, alguns autores têm estudado o processo de secagem como alternativa na conservação do yacon.

Bernstein e Norena (2014) estudaram as mudanças de cor e de volume de yacon durante a secagem. Observaram altas taxas de perdas de umidade durante os primeiros 150 minutos de secagem e 89% de redução do volume, indicando o alto encolhimento do produto. A respeito da cor, todas as amostras escureceram, o que foi intensificado pela secagem por ar quente, quando comparadas com as amostras secas por liofilização.

A textura do yacon não é muito modificada no início do processo de secagem, seguido de amaciamento (diminuição da dureza) nos instantes intermediários e endurecimento no final da secagem, conforme observado por Reis, Lenzi e Masson (2012). Com o avanço da secagem, a cor do yacon se torna mais escura. A dimensão do tubérculo é diminuída com o aumento da temperatura e a reidratação é beneficiada com o aumento da espessura das fatias.

Scher, Rios e Noreña (2009) estudaram o comportamento do yacon com e sem branqueamento durante a secagem nas temperaturas de 50 °C, 60 °C e 70 °C. Os resultados indicaram que o tempo de secagem foi menor a 70 °C, em amostras branqueadas, e que os valores de atividade de água de equilíbrio foram significativamente menores para as amostras branqueadas, em todas as temperaturas. Além disso, os autores observaram a hidrólise dos fruto-oligossacarídeos a 70 °C. Assim, o fator crítico de perda de qualidade de yacon é a alta temperatura do processo de secagem. A diminuição do tempo de secagem com o aumento da temperatura também foi relatada no trabalho de Shi, Zheng e Zhao (2013), na secagem de yacon.

A desidratação osmótica também é importante como pré-tratamento na secagem convectiva, para reduzir o teor de umidade do yacon e fornecer-lhe um gosto doce com o uso de sucralose (PERUSSELLO et al., 2014).

Kotovicz et al. (2014) estudaram a desidratação osmótica de yacon e perceberam que o aumento da concentração da solução osmótica e o aumento da temperatura favoreceram a perda de umidade, porém, aumentaram também a incorporação de sólidos. No processo de secagem convectiva, o aumento da temperatura do ar da estufa reduziu o tempo de secagem e favoreceu a diminuição da atividade de água (a_w).

Oliveira et al. (2016) estudaram a secagem de yacon precedida por desidratação osmótica por pulso de vácuo (PVOD), buscando um produto desidratado que apresentasse as menores alterações físicas, químicas e nutricionais, com relação ao produto fresco. Concluíram que a associação do pré-tratamento por PVOD com a secagem a vácuo induz a menores alterações no yacon seco, principalmente com relação à perda de frutanos.

2.3 Desidratação osmótica

A desidratação osmótica é um método de remoção parcial de água dos alimentos. Baseia-se na imersão dos alimentos em soluções hipertônicas de um ou mais solutos (sacarose, cloreto de sódio, sorbitol, glicerol, etc.), originando dois fluxos simultâneos e opostos (Figura 2), um com relação à saída de água do produto para a solução e outro que diz respeito a uma migração de solutos da solução para o produto. A saída de solutos nativos do alimento (açúcares, minerais e nutrientes) é quantitativamente desprezível, frente às demais, embora possa ser importante no que diz respeito às características sensoriais e nutricionais (PONTING, 1973; TORREGGIANI, 1993). De acordo com Rastogi e Raghavarao (2004), a força motriz responsável pela saída de água é a diferença de pressão entre o produto e a solução osmótica, enquanto, no caso da penetração dos solutos, a força motriz é a diferença de concentração entre eles.

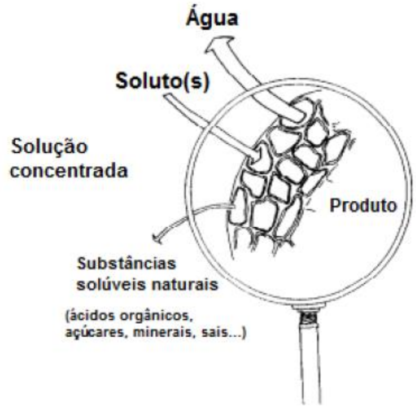

Figura 2 – Ilustração representativa do transporte de massa que ocorre em um alimento durante a desidratação osmótica. Fonte: Torreggiani (1993).

A desidratação osmótica tem sido utilizada como pré-tratamento para frutas e hortaliças e, mais recentemente, em carnes e peixes. Esta operação tem como objetivo reduzir o teor de umidade inicial do alimento. Apesar da notável redução do teor de umidade do produto, o processo de desidratação osmótica não elimina toda a água livre do alimento, o que pode possibilitar a ocorrência de reações prejudiciais à segurança do produto obtido, sendo necessária a utilização de métodos combinados de conservação. O produto de uma DO apresenta teor de umidade intermediária. A DO costuma favorecer a redução do tempo total de uma secagem posterior e, consequentemente, pode reduzir o consumo de energia e, ainda, melhorar a qualidade final dos alimentos (CORRÊA et al., 2011; FILIPOVIĆ et al., 2012; SILVA; CORRÊA; SILVA, 2010; TSIRONI; TAOUKIS, 2014; VIANA; CORRÊA; JUSTUS, 2014). Além disso, o tratamento osmótico pode inibir a degradação enzimática e oxidativa, favorecer a retenção dos pigmentos da fruta e reter aromas voláteis, o que pode melhorar os aspectos nutricionais, sensoriais e funcionais dos alimentos, sem comprometer sua integridade.

Em uma desidratação osmótica, alguns parâmetros de processo devem ser considerados, como a concentração e a temperatura da solução osmótica, presença ou não de agitação, razão entre a quantidade de alimento e solução, características internas da estrutura do produto (composição, porosidade e textura), forma e tamanho em que é processado, natureza e massa molecular do soluto e pressão em que o processo é executado (ALLALI; MARCHAL; VOROBIEV, 2010).

Na maioria dos processos de DO são utilizadas soluções de sacarose por ser um agente de elevada solubilidade em água, de baixo custo e pelo efeito positivo sobre as propriedades sensoriais do produto final (CORRÊA et al., 2010; ZOU et al., 2013). Porém, soluções de sorbitol e frutose são favoráveis para a obtenção de alimentos com menores alterações no índice glicêmico. Adicionalmente, o sorbitol é um eficiente agente desidratante, pois proporciona alta razão de perda de água por ganho de sólidos (CHAUHAN et al., 2011).

O sorbitol é o poliol mais encontrado na natureza, e sua principal característica é o poder edulcorante (com até 70% do poder adoçante da sacarose), apresentando estabilidade química, térmica e bacteriológica e baixa caloria (2,4 kcal/g) (BROCHIER; MARCZAK; NOREÑA, 2014). Segundo Patel e Goyal (2012), o sorbitol é prebiótico, com propriedades promotoras de saúde, como redução dos níveis séricos de colesterol. Ainda é considerado agente redutor de atividade de água, plastificante, estabilizante e espessante; é altamente solúvel em água, inibidor de cristalização e não cariogênico.

2.3.1 Desidratação osmótica com pulsos de vácuo (PVOD)

Muitos trabalhos têm sido desenvolvidos a respeito da aplicação da desidratação osmótica em alimentos, como desidratação de abacaxi, tomate, maçã e manga (CORRÊA et al., 2008, 2011; MAVROUDIS; GEKAS; SJÖHOLM, 1998; ZOU et al., 2013). Tais pesquisas lidam com o estudo do mecanismo do processo, do efeito das variáveis de operação na velocidade do processo e da modelagem de ganho de sólidos e perda de água. Como a desidratação osmótica é um processo lento, por ser de natureza difusiva, muitos pesquisadores dedicam-se a aumentar as taxas de transferência de massa. As técnicas para tanto são aplicação de pulsos de campo elétrico de alta intensidade (RASTOGI et al., 2002), aplicação de ultrassom (NOWACKA et al., 2014) e pulso de vácuo (FANTE et al., 2011; VIANA; CORRÊA; JUSTUS, 2014).

A desidratação osmótica com pulso de vácuo (*pulsed vacuum osmotic dehydration* - PVOD) consiste na aplicação de vácuo no sistema sólido-solução, por um curto período no início do processo, para a retirada de parte dos gases presentes no interior dos poros do alimento. Com a recuperação da pressão do sistema, o líquido que está em contato com o alimento penetra no interior dos poros, devido aos gradientes macroscópicos de pressão e à capilaridade. Este processo envolve uma rápida alteração na composição do alimento com consequências nas propriedades físicas e de transporte do tecido do alimento (FITO, 1994).

Em contraste com o processo osmótico à pressão atmosférica (DO), a PVOD utiliza o pulso de vácuo (PV) durante o processamento, dando origem à ação do mecanismo hidrodinâmico (HDM). Primeiro, a solução é transportada do interior dos poros por capilaridade (espaços intercelulares), promovidos por mudanças de pressão. Em seguida, há a expulsão do gás durante a etapa de vácuo e, por fim, a pressão atmosférica é restaurada e a compressão leva a uma grande redução no volume do gás remanescente nos poros da estrutura porosa e enchimento com um líquido (FITO et al., 2001).

Durante a utilização de pulso de vácuo na desidratação osmótica de alimentos, inicialmente, poderá ocorrer um ganho rápido de água e soluto, resultando num aumento da massa total inicial. Após certo período, esse ganho de água e perda de soluto poderão se tornar mais lentos, praticamente constante, além de alcançar a estabilidade no que diz respeito à retração (encolhimento), resultante da deformação da matriz sólida devido ao gradiente de pressão imposto pelo sistema (ATARÉS; CHIRALT; GONZÁLEZ-MARTÍNEZ, 2008).

Oliveira et al. (2016) otimizaram o processo de desidratação osmótica de yacon com o uso de pulsos de vácuo (PVOD), por meio de um planejamento experimental baseado na metodologia de superfície de resposta (DCCR). Os autores utilizaram um fatorial completo 2^3, com 6 pontos axiais e 4 repetições no ponto central. Eles realizaram dois planejamentos completos com as seguintes variáveis: pressão de vácuo (49 a 200,6 mmHg), concentração da solução osmótica (22 a 60,8 °Brix) e temperatura da solução osmótica (24 a 44 °C), diferindo o tipo de solução osmótica, frutose e sorbitol. Estabeleceram o tempo de desidratação de 300 minutos. Observaram que a desidratação em solução de sorbitol mostrou-se mais eficiente na preservação de frutanos (82,03%), quando comparada à desidratação com frutose, 39,48% do FOS inicial. Nas condições analisadas, estabeleceu-se como faixa ótima a desidratação em solução de sorbitol com concentração 38 °Brix a 35 °C e de 74 mmHg de pulso de vácuo.

Os trabalhos relacionados à técnica de PVOD indicam melhora no processo de transferência de massa, maior economia, quando comparado ao uso de pressão atmosférica ou pressão contínua de vácuo, além de proporcionar tempos mais curtos para a impregnação de solutos (CORRÊA et al., 2010; FANTE et al., 2011; VIANA; CORRÊA; JUSTUS, 2014).

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SEGUNDA PARTE

ARTIGO 1

Process and quality aspects of convective drying of yacon with pulsed vacuum osmotic dehydration as pretreatment

Running title: Convective drying of yacon: process and quality matters

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Abstract: The yacon possesses fructooligosaccharides (FOS) as the main reserve of carbohydrates. However, the tuber has to be quickly consumed after harvest or a process of conservation with fructan retention should be provided. The convective drying of sliced yacon was studied, evaluating the influences of temperature and the use of pulsed vacuum osmotic dehydration (PVOD) as pretreatment. Fructan retention, shrinkage, color, rehydration capacity, diffusivity and drying time were measured. PVOD was performed with a sorbitol solution (38 °Brix, 35 °C and 681 mmHg in the first 10 min of the total 300 min). The convective drying (40 to 70 °C; 0.5 m/s) was fitted with the diffusive model of Fick with and without consideration of shrinkage. The drying time was reduced and the diffusivity was increased with temperature and the use of PVOD. The consideration of shrinkage resulted in a more realistic fitness. The PVOD was effective to reduce drying time and shrinkage but resulted in a browned sample with lower retention of FOS.

Keywords: Fructans, PVOD, sorbitol, FOS, prebiotic, dehydrated food

1 Introduction

The yacon (*Smallanthus sonchifolius*) is a root that originated from the Andes in South America. It is known for its prebiotic property, which is attributed to its high content of fructooligosaccharides (FOS) [1, 2]. The FOS have been related to the reduction in the level of glucose and triglycerides in the blood and recommended for diabetics [3]. However, after harvesting, the FOS are hydrolyzed into simple sugars [4]. Therefore, it is essential to look for techniques to converse the product, thereby minimizing the FOS reduction.

Drying is a water removal operation by simultaneous heat and mass transfers [5, 6]. It is probably the oldest method of food preservation [7, 8]. The reduction in water activity is also observed in the drying process[9] with consequent inhibition of microbial growth and decreased enzymatic activity and rates of chemical reactions. However, exposure of the product to high temperatures for long periods may cause physical and nutritional quality losses[10, 11, 12].

The pulsed vacuum osmotic dehydration (PVOD) usually assists in minimizing structural and nutritional losses and leads to reduced drying time[13, 14, 15]. The application of vacuum in the PVOD occluded gases in the intercellular spaces of vegetal tissues are removed. Indeed, when the atmospheric pressure is restored, pores are filled with the osmotic solution thereby increasing the surface area for mass transfer. This phenomenon is known as the hydrodynamic mechanism (HDM) [16, 17].

Drying preceded by osmotic processes is an alternative to minimize shrinkage, preservation of volatile components and reducing energy consumption during the drying stage compared with the dry product without pretreatment [13, 18, 19]. Sucrose is widely used as an osmotic agent due to its high solubility in water, low cost and the positive effect on the sensory properties and final product stability [20, 21]. However, polyols such as sorbitol and xylitol are favorable for obtaining low caloric osmotic dehydrated foods [22]. The main features of sorbitol are its sweetening power (up to 70% sweetening power of sucrose), chemical stability, bacteriology and low caloric content [23]. Moreover, it is an efficient dehydrating agent, providing high rates of water loss by solids gain [24].

The drying kinetics modeling can be done using diffusive models based on Fick's diffusion theory [25]. Although the non-consideration of the external resistance, modeling of drying kinetics with the diffusive Fick model results in good adjustments [26]. Consideration of the product shrinkage during drying usually further improves the fit of the Fick model [27, 28].

This study aimed to probe the convective drying of yacon slices at different temperatures, with and without the use of pretreatment by pulsed vacuum osmotic dehydration. The variables evaluated were fructan retention, shrinkage, color parameters, rehydration capacity, diffusivity and drying time. Drying kinetics were studied and modeled.

2 Material and methods

Material

The tubers of yacon (*Smallanthus sonchifolius*) were obtained at a local market (Lavras, Minas Gerais state, Brazil). The tubers presented similar visual aspects of maturity, shape, firmness and color. Figure 1 shows the whole and sliced tubers. The uniformity of the samples were verified based on moisture content, carbohydrate, fructan content, soluble solid, and color parameters (L^*, a^* and b^*).

(a) (b)

Figure 1Tubers of whole yacon (a) and sliced (b).

Preparation of sample

The selected tubers were washed in tap water and sanitized in sodium hypochlorite solution (200 mg L^{-1}) for 15 minutes [14, 29]. The yacon roots were peeled, and the samples were cut into dimensions of 2.00 x 2.00 x 0.50 cm (length x width x thickness) with a parallelepiped shape (Figure 2) using an electric slicer (Urano, USM1-320, 2010, Brazil) and a stainless steel mold. The dimensions of the slices were verified with a digital caliper (Western, 150 mm-DC-60, China). This geometry allows the use of diffusional models with the flat plate consideration for predicting the drying rate and obtaining diffusivity coefficients [20]. The samples were dipped in a citric acid 1.0% solution at ambient temperature for one minute to prevent enzymatic browning reactions [30].

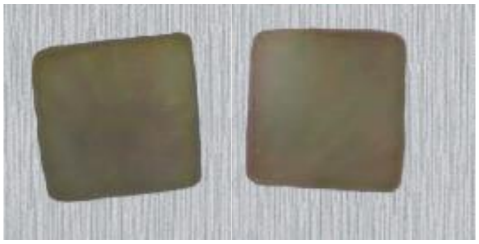


Figure 2 Examples of samples used in the experiments.

Pulsed vacuum osmotic dehydration (PVOD)

For evaluating the influence of PVOD in the convective dried yacon, the samples were divided in two sets, and one set was submitted to pretreatment. The PVOD experiments were conducted in a dehydrator composed of a stainless steel jacketed chamber (A-240-304, Biasinox LTDA, Minas Gerais, Brazil) with a volume of 50 liters and a minimum operation volume of 10 liters. A vacuum pump and a thermostatic bath were attached to the dehydrator, and the temperature and inner pressure were automatically controlled [31].

The osmotic solution was prepared with distilled water and commercial sorbitol (Singsino Group Ltd., China) at a concentration of 38 °Brix. The mass ratio of yacon by solution was 1:10 (w/w). The osmotic dehydration was carried out at 35 °C with a vacuum pressure of 681 mmHg in the first 10 minutes of processing, with total time of 300 minutes. The process conditions were optimized in a previous stage.

Convective drying

The yacon samples, previously treated or not treated by PVOD, were submitted to convective drying.

The drying was performed in a convective dryer in a fixed single layer (Conscientec, Belo Horizonte, Brazil) at 40, 50, 60, and 70 °C. The samples were supported by a stainless steel screen, low air flow up and flow rate $0.045 m^3 s^{-1}$. The velocity was maintained constant at $0.5 ms^{-1}$. The temperature and air flow rate were automatically controlled. The sample temperature was monitored by a temperature gauge (Data logger, model testo 174H with 2 channels, set in the sample). The experiments were conducted to final moisture content of 12 kg of water/100 kg sample. This value was based on the maximum moisture content of recommendation for dried vegetables, RDC 272 with ANVISA, (2005) [32].

The mass of the samples was determined by semi-analytical balance (Shimatzu, AUY220, Kyoto, Japan) with 0.1 mg precision every 10 minutes drying in the first 60 minutes and every 30 minutes the rest of the process. The drying experiments were also performed to a constant weight to determine the equilibrium moisture content. During the drying, the sample temperature was continually recorded with a logger (Testo 174, Lenzkirch, Germany) with a temperature sensor fixed inside the samples.

Characterization of the raw and dryed samples

The moisture content was determined by the gravimetric method 934.06 (AOAC, 2005)[33] in a vacuum oven (pressure $\leq$ 100 mmHg) at 70 °C to constant weight.

Determination of water activity was performed at 25 °C using a water activity meter (Aqualab Decagon Devices Inc. Pullman, model CX-2T, Washington, EUA).

The pH of the samples was obtained with 10 g of triturated samples in 100 mL of distilled water. The sample was macerated until homogeneous, then a direct reading of the pH potentiometer was performed. A digital pH meter Digimed DMpH-2 model, calibrated with solutions of pH 4.0 and 7.0, was used according to the analytical norms of AOAC (2005)[33].

The soluble solids content of the samples was performed using a digital refractometer (digital Hanna, HI 96801, USA).

The fructans content was determined by the enzymatic method, following the AOAC 997.03 method (2005) [33]. The data were evaluated with respect to the degradation of the fructans index for fresh, osmotically dehydrated and dried samples.

Color

The color of the samples was measured with an electronic colorimeter Minolta CR 400 (Minolta Camera Co. Ltd, Osaka, Japan) at 25 °C according to the standard L^* (lightness), a^* (red intensity) and b^* (intensity of yellow). The hue angle, hue (h°), which expresses the color tone, was measured by the equipment, as well as the Chroma value (C^*), which indicates how opaque or vivid is the color, ranging from 0 to 60. The variation color (ΔE) was calculated by Equation 3, considering that the index 0 indicates the fresh product.

$$^{o}h = \tan^{-1}\left(\frac{b*}{a*}\right) \tag{1}$$

$$C^* = \sqrt{a^{*2} + b^{*2}} \tag{2}$$

$$\Delta E = \sqrt{(L^* - L_0^*)^2 + (a^* - a_0^*)^2 + (b^* - b_0^*)^2} \tag{3}$$

Shrinkage

The volume of the samples were measured by digital image analysis. Pictures and the weight of the samples were taken in the same drying time. The surface area of the samples was measured directly from the photographs with the aid of the software ImageJ® [34, 35], and the thickness was taken as an arithmetical average of measurements at five different points on the sample with the use of a caliper (Western, 150 mm-DC-60, China). Moreover, five different samples were used each time.

The shrinkage was calculated with respect to the volume of the sample at each time (V) and its initial volume (V_0) according to Equation 4.

$$S = 1 - \left(\frac{V}{V_0} \right) \tag{4}$$

Rehydration

The rehydration of the dried samples were performed by immersing the samples in 250 mL flasks containing 150 mL distilled water at 25 °C. After removal from the water, the samples were placed on a paper towel to remove excess surface water. Then, weight measurements were taken in intervals of 20 minutes in the first hour of rehydration, then in intervals of 30 minutes until obtaining constant weight. The experimental results were expressed as moisture content on a dry basis.

Drying kinetics modeling

For the modeling of the drying kinetics, the Fick model was employed according to the following:

The model is based in a semi-infinite slab. Thus, the diffusion is limited by the smallest dimension, and the model is unidirectional [25]:

$$\frac{\partial M(t)}{\partial t} = \frac{\partial}{\partial z}\left(D_{eff} \frac{\partial M(t)}{\partial z} \right) \tag{5}$$

where M(t) is the amount of water at time t, D_{eff} is the effective diffusivity, and z is the direction of the transfer.

The thickness of the sample is 2 L, taking into account that the diffusion in a drying process comes from the inside surface, z=0 to the outer surfaces, z=L and z=-L. Consequently, a symmetry of concentration could be established, $\left.\frac{\partial M(t)}{\partial t}\right|_{z=0} = 0$

At the initial time, the moisture is considered uniform all over the sample, $M_{(z,0)} = M_0$;

At the surface, the condition of the sample is considered in equilibrium with the surrounding air, $M_{(L,t)} = M_{eq}$.

Taking into account these considerations, Fick's unidirectional diffusion equation for a semi-infinite plate [25] becomes:

$$M_R = \left(\frac{M_t - M_{eq}}{M_0 - M_{eq}}\right) = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left[-(2n+1)^2\frac{\pi^2}{4}\frac{D_{eff}\,t}{L^2}\right] \tag{6}$$

where D_{eff} is the water effective diffusivity (m^2s^{-1}), L is half of sample thickness (m), n is the number of terms, M_R is the moisture ratio and, and t is the drying time. M_t is the yacon moisture content at each moment, M_0 is the initial moisture content of yacon, and M_e is the equilibrium moisture content.

The dependence of D_{eff} with temperature was analyzed by the Arrhenius equation:

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{RT}\right) \tag{7}$$

where D_0 is the pre-exponential factor for the Arrhenius equation, E_a is the activation energy (kJ mol^{-1}), R is the universal gas constant, 8.314 $Jmol^{-1}K^{-1}$, and the absolute temperature (K).

The settings of the drying kinetics models and dependence of diffusivity with respect to temperature on the experimental data were obtained with the aid of Excel Solver software supplement.

To evaluate the fit of the models, the coefficient of determination (R^2), the reduced chi-square (χ^2) (Equation 8) and root mean square error (RMSE) (Equation 9) were used as follows:

$$\chi^2 = \frac{\sum_{i=1}^{n} (MR_{exp,i} - MR_{pred,i})^2}{n - N} \qquad (8)$$

$$RSME = \left[\frac{1}{n} \sum_{i=1}^{n} (M_{R\,exp,i} - M_{R\,pred,i})^2 \right]^{1/2} \qquad (9)$$

where $M_{Rexp,i}$ and $M_{Rprev,i}$ are, respectively, the experimental and predicted values of the moisture ratio for observation i, n is the number of observations, and N is the number of parameters in the model.

Usually, the biological materials shrink during the drying process. Consequently, the consideration of the dimension L as a constant could cause an agreement error, as reported by Corrêa et al. (2012)[28]. The volumetric shrinkage is a function of the moisture content.

The consideration of a linear dependence of the volumetric shrinkage to moisture content was previously successfully employed (Equation 10) [27, 28, 36].

$$\frac{V}{V_0} = a + b\frac{X}{X_0} \qquad (10)$$

where V is the volume corresponding to the moisture content X and V_0 is the initial volume of the sample, corresponding to the initial moisture content of the product (X_0). The terms a and b are the fitted parameters.

It was considered that the shrinkage was uniform in all dimensions. Consequently, l varies in the drying process as:

$$\frac{l}{l_0} = a + b\frac{X}{X_0} \qquad (11)$$

where l is the thickness of the yacon sample slices.
The adjust was performed with the Statistica 8.0 software.

Statistics analysis

The results were submitted to an analysis of variance using an F test. To obtain significance in the F test at 5%, the statistical analysis of the data was continued by applying the Tukey test. These analyses were performed by the computational Statistica 8.0 software (Statistical Analysis System Institute, 1996). Were assigned to a completely randomized design with five replications.

3 Results and discussion

Centesimal composition and physics-chemical characterization of the raw material

The results of centesimal composition and physics-chemical characterization of the yacon tuber *in nature* and treated by pulsed vacuum osmotic dehydration are shown in Table 1.

Table 1 Centesimal composition of yacon pulp *in nature* and osmotically dehydrated by pulsed vacuum osmotic dehydration (PVOD).

Component [%]	*In nature* Samples	Treated samples*
	Mean value (Integral matter)	Mean value (Integral matter)
Moisture	91.71 ± 0.34	69.42 ± 0.01
Protein	4.49 ±0.024**	3.10±0.06**
Lipids	0.02 ±0.004	0.07±0.01
Fibers	0.22±0.02	1.82±0.01
Ash	0.27±0.03	0.59±0.03
Carbohydrate	7.48±0.37	27.15±1.82
Fructans§	5.19±0.10	4.81±0.05

* treated samples by PVOD (35 °C, 38 ºBrix sorbitol, 10 min 681 mmHg vacuum, total time 300 min) and ** calculated in dry matter. § The content of fructans is part of the carbohydrate content.

It was observed (Table 1) that the main constituents of yacon *in nature* are water and carbohydrates. The main carbohydrates are the fructans. The high moisture percentage of 91.71±0.34% is compatible with the literature values [15, 37, 38, 39]. The amount of carbohydrates increased by 262.96% after the PVOD due to the incorporation of sorbitol. The incorporation of solutes in a PVOD process is part of the transfer in an osmotic process. However, sorbitol is known as a sugar alcohol and a less-digestible carbohydrate with slower and incomplete absorption from the intestine [40]. Furthermore, the increased amount of carbohydrates in PVOD in the amount of FOS represented 61.11±0.42% of dry matter in osmotically dehydrated samples. This value is similar to the amount of FOS in yacon found *in nature*, i.e., 63.26±1.38% of dry matter. The results of FOS are similar to those reported in previous studies with yacon, such as Oliveira et al.(2016) [15] and Graefe et al.(2004)[4], who reported approximately 64.80±0.39% and 50-62% fructan, respectively, in the amount of dry matter.

The PVOD led to a 24.30% reduction in moisture content with respect to the tubers *in nature*. The PVOD assists the flow of water and solution between food and immersion means. The native gases present in the porous structure of the foods are removed with the vacuum application. As a consequence, the osmotic solution penetrates the pores, thereby improving the mass transfers between the phases in hydrodynamics and capillary diffusion process [16]. The final product (Table 2) will present lower moisture content, higher soluble solids content and, as a consequence, lower water activity[15, 20].

Table 2 Physical and chemical analyzes of yacon pulp *in nature* and in samples treated by PVOD.

Characteristics	*In nature* sample	Treated samples *
	Mean value	Mean value
Water activity (a_w)	0.990±0.001	0.976±0.001
Soluble solids (°Brix)	6.50±0.10	10.20±0.25
pH	4.80±0.089	5.96 ±0.15
L^*	54.93±2.17	49.11±0.57
a^*	2.85±0.51	-0.84±0.19
b^*	13.34±1.31	13.00±0.18
C^*	13.64±1.37	13.03±0.19
H°	77.97±1.18	93.83±1.05

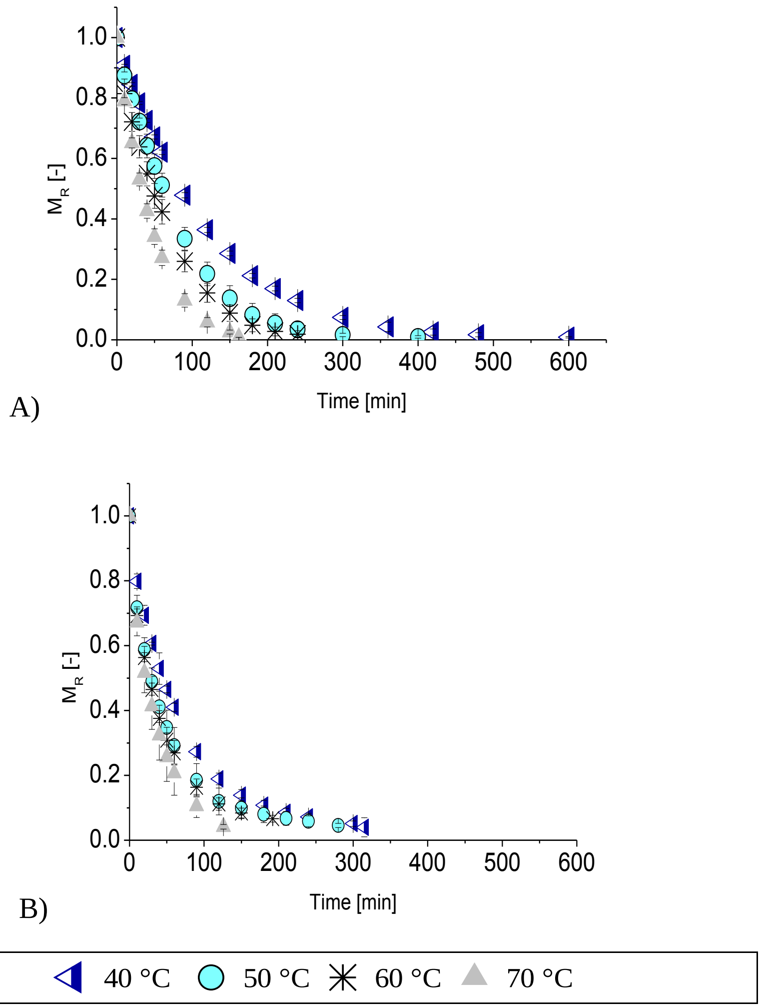
* Treated samples by pulsed vacuum osmotic dehydration (35 °C, 38 ºBrix sorbitol, 10 min 74 mmHg vacuum, total time 300 min).

The pulp of yacon *in nature* showed a tendency to yellow, according to its color parameters, i.e., positive values of the parameter b^* and an inclined light for a clearer region (*L* above 50).

The relation between the values of a^* and b^* chroma is represented by 13.64±1.37% and 77.97%±1.18 saturation. With PVOD, there was a decrease in values a^* and b^* with a tendency to enter the darker yellow region according to the CIELAB 1976 color system, comprising a sample slightly darker compared to the product *in nature*. In PVOD, the concentration of the solid mass occurs by partial removal of water during dehydration, leaching tuber pigments to the solution and non-enzymatic browning of the samples impregnated with sorbitol. The occurrence of three factors led to a decrease of a^* and b^* assigning the color change in PVOD.

Drying

Figures 3 and 4 show yacon drying kinetics curves as a function of the moisture ratio (M_R). Table 3 displays the final drying times.



A)

B)

Figure 3 Drying kinetics of yacon at different temperatures (A) without pretreatment by pulsed vacuum osmotic dehydration (PVOD) and (B) with PVOD pretreatment.

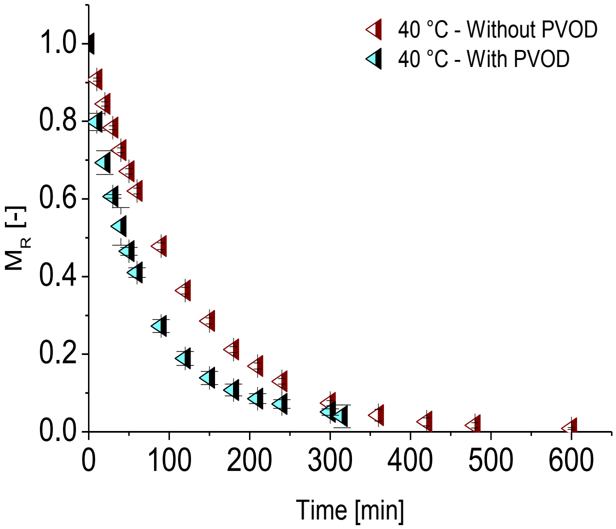


Figure 4 Drying kinetics of yacon at 40 °C with and without pulsed vacuum osmotic dehydration (PVOD).

Table 3 Drying time to obtain dried yacon with a moisture content of 12% (w.b) and water activity (a_w).

Pretreatment*	Temperature [°C]	Drying time [min]	Water activity (a_w)
Yes	40	315±26	0.411±0.011
	50	280±35	0.426±0.008
	60	192±27	0.364±0.016
	70	126±17	0.374±0.005
No	40	600±21	0.451±0.003
	50	400± 35	0.548±0.032
	60	240±17	0.485±0.009
	70	162±16	0.443±0.014

*Pulsed vacuum osmotic dehydration (PVOD).

It was observed (Figure 3, Table 3) that the increase in temperature led to a reduction in drying time, independent of the use of pretreatment. Furthermore, water activity less than 0.548±0.032. The time was reduced in from 11.11% of 40 °C to 50 °C and 60% by increasing 30 °C in the temperature in sample

PVOD. The influence of the drying temperature is well reported by several authors [10, 41]. The increase in temperature results in a higher excitation of water molecules inside the material, resulting in increased diffusivity and higher vapor pressure [42].

The use of PVOD as a pretreatment decreased drying time until 79% (Table 3) compared to samples without PVOD. Figure 4 illustrates the drying kinects for treated and untreated samples at 40 °C. It is possible to see that the treatment aided the moisture removal from the very beginning of the drying process. Moreover, the temperature inside the osmotically dehydrated samples reached the air temperature at lower drying times, thus contributing to the reduction of drying time (Figure 5). All these phenomena make the drying faster and could all be addressed to the structural changes caused by the PVOD, which has been observed by Chiralt et al (2005) [43]. The hydrodynamic mechanisms established in the first minutes of PVOD by the vacuum application removes the occluded gases, which eases the entrance of the osmotic solution. The cellular membrane is then deformed or broken, and the internal liquids come to the outer spaces. The final osmotically dehydrated product is more porous than the fresh food, which improves the heat transfer between the phases.

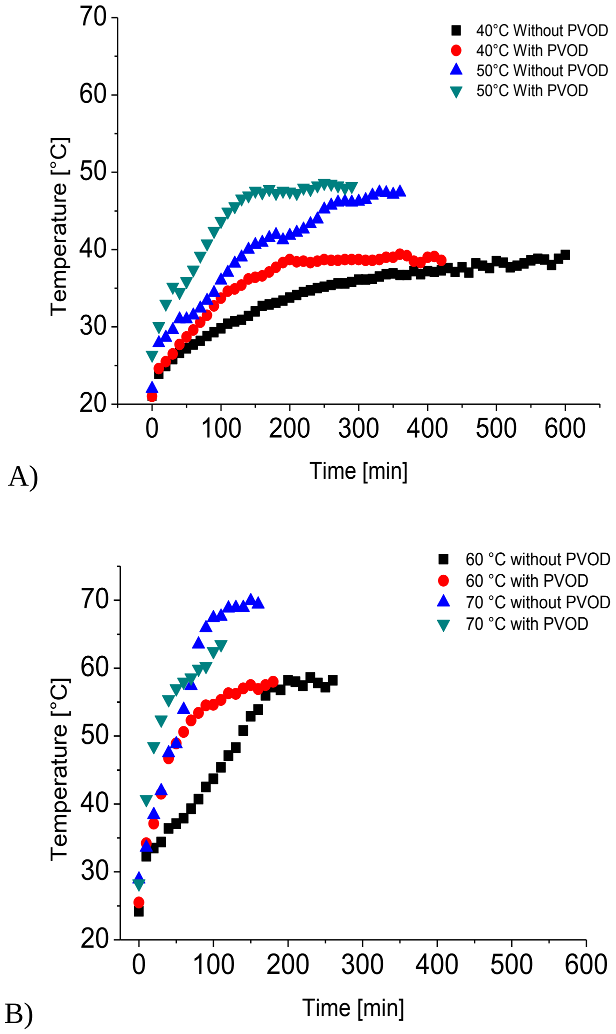


Figure 5 Curve of yacon samples temperature for convective drying experiments with and without osmotic pretreatment by PVOD in drying temperature 40 to 50 °C (A) and 60 to 70 °C (B).

According to Ahmed et al. (2016)[44], after the initiation of the hydrodynamic mechanism (HDM), the absorption of solid and water loss is maximized, thereby reducing the drying time.

Shrinkage

Table 4 shows the volume ratio results (V/V_0) at different temperatures. The use of osmotic pretreatment and higher temperatures carried out to lower shrinkage. Kowalski and Mierzaw (2013)[45] observed that osmotically dehydrated apple samples showed less shrinkage after drying. Osmotic dehydration promotes the softness of tissue and lower shrinkage during drying due to impregnation of the osmotic solution during processing [46]. This causes the solid inlets to aid the compression resistance of the product compared to the non-osmotically dehydrated. As noted previously, the lower initial moisture content and the modified structure are responsible for less time of contact of the food with high temperature air. The negative effect of the temperature on shrinkage for treated and untreated samples is due to the rapid reduction of the moisture content at high temperatures, which causes rapid transition from the elastic state to the glassy state, resulting in a reduction in shrinkage[47]. Bernstein and Norena (2014)[36] reported that the yacon sample dried at 50 and 75 °C and shrank approximately 89%. According to Karunasena et al.(2014)[48], when higher drying temperatures are used, the surface moisture tends to decrease rapidly, and the outer layer of the tissue tends to dry first. Then, these outer tissues generally become more rigid and obtain a hardened form, thereby resisting the mass transfer of the fabric inside to the outside, which eventually restricts the shrinkage of the material. However, if a lower drying temperature is used, the moisture removal occurs more slowly, but mass transfer is relatively uniform through the material from the center to the outer layers. This eases the removal of the continuous moisture material along the drying cycle, which eventually leads to higher shrinkage. This was clearly observed for yacon during air convection drying.

Table 4 Volume ratio (V/V_0) and shrinkage at different temperatures.

	Samples dried without pretreatment		Samples dried with pretreatment	
Temperature [°C]	V/V_0	Shrinkage [%]	V/V_0	Shrinkage [%]
40	0.10 ± 0.01^{b}	89.02 ± 1.64^{b}	0.37 ± 0.01^{d}	62.46 ± 1.58^{d}
50	0.17 ± 0.02^{a}	82.21 ± 2.97^{a}	0.45 ± 0.01^{b}	54.36 ± 1.15^{b}
60	0.15 ± 0.009^{ab}	84.87 ± 0.90^{ab}	0.41 ± 0.0^{1c}	58.56 ± 1.05^{c}
70	0.15 ± 0.006^{ab}	84.84 ± 0.66^{ab}	0.50 ± 0.03^{a}	49.88 ± 3.29^{a}

Means followed by the same letter in the column do not differ significantly ($p < 0.05$) by Tukey test. Pretreatment is pulsed vacuum osmotic dehydration.

Drying Kinetic Modeling

Table 5 shows the D_{eff} and the adjustment parameters obtained with the use of the Fick model with and without the consideration of shrinkage. It can be observed that in terms of the coefficient of determination, root mean square error and reduced chi-square the Fick model satisfactorily represents yacon drying kinetics ($R^2 > 0.940$, RSME < 0.089 and $\chi^2 < 0.01$). The differences between the fitted and the experimental values could be addressed, among other factors, with consideration of the external resistance of the only diffusional model [5]. On the other hand, as stated below, the used models could represent some phenomenological aspects.

Table 5 Coefficient of effective diffusivity (D_{eff}), coefficient of determination (R^2), root mean square error (RMSE) and the reduced chi-square (χ^2) of a Fick model for the different temperatures studied.

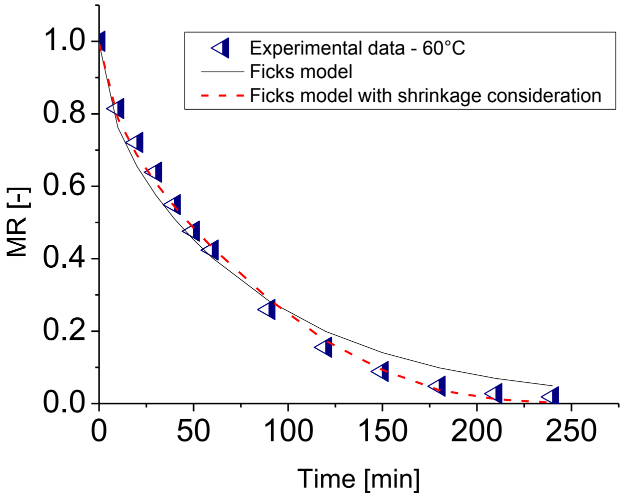
PVOD	T [°C]	Fick model properties							
		Without shrinkage				With shrinkage			
		D_{eff} [m^2s^{-1}]	R^2	RSME	χ^2	D_{eff} [m^2s^{-1}]	R^2	RSME	χ^2
Yes	40	7.48×10^{-11}	0.996	0.017	0.005	2.66×10^{-10}	0.958	0.060	0.012
	50	1.09×10^{-10}	0.993	0.022	0.002	4.09×10^{-10}	0.975	0.062	0.016
	60	1.23×10^{-10}	0.995	0.059	0.0005	4.10×10^{-10}	0.940	0.068	0.010
	70	1.53×10^{-10}	0.999	0.049	0.00001	6.26×10^{-10}	0.970	0.049	0.002
No	40	1.06×10^{-9}	0.974	0.054	0.002	3.04×10^{-10}	0.988	0.036	0.005
	50	1.56×10^{-9}	0.965	0.063	0.001	5.17×10^{-10}	0.990	0.033	0.002
	60	1.97×10^{-9}	0.981	0.043	0.0001	7.09×10^{-10}	0.996	0.019	0.001
	70	2.87×10^{-9}	0.980	0.044	0.00003	1.12×10^{-9}	0.991	0.089	0.0003

Where T means drying temperature and PVOD signify Pulsed vacuum osmotic dehydration.

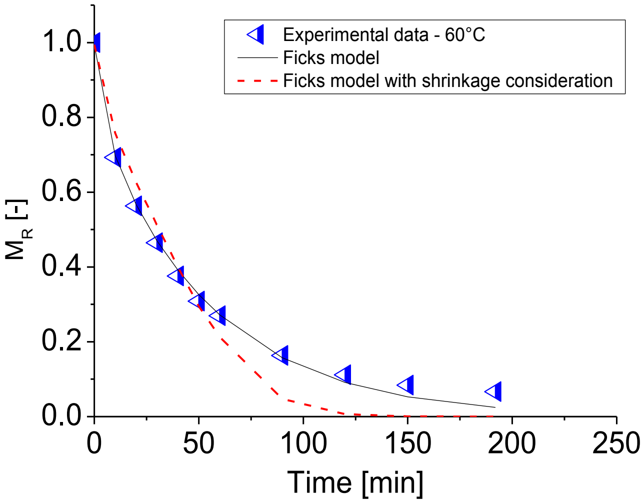
The values of D_{eff} are in accordance with the range of values found in the literature for foods such as strawberry, apple and pineapple [26, 49]. The diffusivity is a function of food characteristics such as composition, texture, porosity and process characteristics like sample geometry, air temperature, velocity and humidity [50].

It was observed that the D_{eff} was higher with the temperature for pretreated and non-pretreated samples, either considering or not considering the shrinkage in the model. This difference decreases with increasing drying temperature, i.e., 71% higher than 40 °C to 61% at 70 °C. The increase in the effective diffusivity (D_{eff}) with elevated drying air temperature demonstrated that for lower temperatures, yacon has offered resistance to internal water transport, resulting in smaller diffusion coefficients. Thus, the drying air temperature increase indicates a higher intensity inside the water migration phenomenon to the surface of the tuber.

As shown in Table 3 and Figure 4, the use of PVOD as a pretreatment diminishes drying time. This is linked to an increase in diffusivity. Table 5 shows that although the fitness parameters obtained by considering the shrinkage were lower than the opposite, the consideration corroborated the higher diffusivity with PVOD. Table 5 and Figure 6 illustrate that the consideration of shrinkage in the model improved the fitness only for the no pretreated samples.



A)



B)

Figure 6 Experimental 60 °C and predicted moisture content during the drying of yacon slices in experiments without treatment osmotic PVOD (A) and with PVOD (B). The continuous red line represents the model with shrinkage, and the continuous black lines represent the model without shrinkage.

The dependence of diffusivity with temperature is well reported in the literature [51, 52, 53]. Table 6 shows the values of the pre-exponential factor (D_o) and activation energy (E_a) obtained by setting D_{eff} as a function of temperature by the Arrhenius equation. It was observed that the fit was quite satisfactory, with an R^2 greater than 0.95, which is similar to those found by Taheri-Garavand et al.(2011)[51]. Moreover, the E_a values are found by the next Doymaz et al. (2014)[52] and within the range of 12.7 a 110 kJ mol^{-1} defined by Zogzas et al.(1996)[53] for food products.

Table 6 Values for the activation energy and pre-exponential factor of the Arrhenius equation.

Pretreatment	E_a [kJ mol^{-1}]	D_0 [m^2s^{-1}]	R^2	RSME
Yes	20.07	1.97×10^{-6}	0.95	0.053
No	28.66	2.92×10^{-5}	0.99	0.031

Content of fructans (FOS)

The values of fructan content of the treatments with and without the use of PVOD as pretreatment are shown in Table 7. The results were expressed as dry matter, excluding the gain solids in the samples with PVOD. The retention results of the fructan content after processing are also presented.

Table 7 Fructans retention [%] in dried yacon with and without PVOD at different drying temperatures.

Temperature [°C]	Content of fructans [%,d.b]		Fructans retention [%]	
	Without PVOD	With PVOD*	Without PVOD	With PVOD
40	37.32±2.57	28.60±0.30	58.99±4.07^{cA}	45.21±0.48^{bB}
50	32.86±0.11	23.82±0.95	51.95±0.18^{cA}	37.66±1.50^{bB}
60	56.04±0.36	25.63±3.54	88.58±0.58^{aA}	40.51±5.60^{bB}
70	47.85±2.28	38.12±0.70	75.64±3.60^{bA}	60.26±1.11^{aB}

* The data are on a dry basis and products subjected to osmotic dehydration disregarded the gain solids. Means followed by the same lowercase letter in the column do not differ significantly ($p < 0.05$) by Tukey test, and capital letters on the same line do not differ significantly ($p < 0.05$) by the Tukey test.

It was observed that for samples without PVOD as pretreatment, there was no significant difference in fructan retention from 40 °C to 50 °C and, for treated samples, from 40 to 60 °C. The temperatures of 60 °C and 70 °C were used to carry out the highest fructan retention for untreated and treated samples, respectively, providing a retention of 88.58±0.58% and 60.26±1.11, respectively. The temperature elevation reduced drying time up to 39.04%, favoring the retention of fructan at a temperature of 60 °C. Once the compound is heat-sensitive and less prolonged exposure to elevated temperatures, it is interested in this type of compound [37]. For convective drying of yacon without pretreatment, Scher et al.(2009)[37] observed lower concentrations of reducing sugars at 70 °C, highlighting the care in application temperatures near 70 °C for inhibiting the hydrolysis of FOS. In PVOD, the fructan retention benefited when the samples were dried at 70 °C. Furthermore, the temperature increase of 40 °C to 70 °C reduced the drying time by up to 73%, thereby decreasing the exposure time of fructan at high temperatures. It was also observed that PVOD dried samples resulted in lower percentages of fructans (23.82±0.95% and 38.12±0.70%) in the final product than those dried without pretreatment (32.86%±0.11 to 56.04±0.36%). Tables 3, 4, 5 and 7 show that although the PVOD resulted in faster drying with higher diffusivity and lower shrinkage, the fructan retention was lower than those obtained in convective drying without the pretreatment. As stated previously, the PVOD may cause mechanical damage to the cell structure, such as cell separation associated with the deformation of the sample, also resulting in a more porous material [54]. This exposes the internal material of the samples to the heated air, causing degradation of the fructans.

Color

Table 8 shows the results of the colorimetric analysis of the dried yacon without and with osmotic treatment. Independent of the use of pretreatment, the color intensity was increased by drying with a higher chroma value (C^*) compared with fresh samples. The change of dry yacon color was evident. It is considered that during drying a browning non-enzymatic or Maillard reaction occurs [55]. Moreover, for the same temperature, the L^* values were significantly higher ($p<0.05$) in yacon without osmotic pretreatment, except at 70 °C. According to Akbarian et al. (2014)[46], the intense presence of sugar in a moisture content food from 10 to 20% favors non-enzymatic browning reactions. Table 1 shows that the carbohydrate contents are increased by the incorporation of sorbitol in the PVOD process.

Table 8 Chroma (C^*), hue angle, hue (h°) color variation (ΔE) and luminosity (L^*) of yacon submitted to different drying temperatures.

Pretreatment	T [°C]	Color parameters			
		C^*	h°	ΔE	L^*
Yes	40	24.10 ± 1.71^{d}	74.26 ± 0.87^{d}	13.91 ± 0.94^{ab}	46.18 ± 2.39^{e}
	50	24.65 ± 2.43^{cd}	76.69 ± 1.54^{cb}	13.09 ± 1.47^{b}	49.02 ± 1.47^{cde}
	60	25.92 ± 0.80^{cbd}	78.41 ± 1.03^{ab}	12.49 ± 0.56^{b}	51.83 ± 0.56^{cd}
	70	29.09 ± 1.37^{a}	74.4 ± 0.76^{d}	16.91 ± 0.82^{a}	48.37 ± 0.82^{de}
No	40	28.79 ± 2.05^{ab}	75.35 ± 1.33^{cd}	15.45 ± 1.95^{ab}	52.81 ± 2.07^{cb}
	50	26.80 ± 0.78^{abcd}	78.68 ± 1.58^{a}	13.54 ± 0.65^{ab}	57.95 ± 2.11^{a}
	60	27.25 ± 0.80^{abc}	78.53 ± 0.46^{a}	11.90 ± 4.22^{b}	56.70 ± 0.84^{ab}
	70	28.56 ± 1.34^{ab}	75.69 ± 0.54^{cd}	15.60 ± 0.69^{ab}	51.27 ± 2.10^{cd}

Means followed by the same letter in the column do not differ significantly ($p < 0.05$) by Tukey test: T signify drying temperature.

The hue values (h°) in Table 8 indicate the difference in tonality between treated and untreated samples. It is noted that in untreated samples, there is a significant increase in tonality at 50 °C compared to CP 50 °C. However, this trend differed significantly ($p<0.05$) for yacon dried at 70 °C. These results indicate that temperatures around 70 °C with osmotic treatment represent a decrease of tonality. Furthermore, it was observed that the values of yacon dried at 50 °C and 60 °C are closer to the tonality of the fresh tuber, which was 77.9±1.18.

In spite of the observed differences in L^*, C^* and h°, the total color difference (ΔE) was not significantly different for treated and untreated samples at the same temperature and among the temperatures for the same drying condition.

Kinetics of rehydration

Figure 7 shows the rehydration kinetics of dried yacon with and without PVOD. The rehydration progressed with time and higher water absorption in the beginning due to the quick rehydration of capillary cavities near the surface, which are rapidly filled with water [56]. Moreover, the cell rupture and shrinkage during the drying process is irreversible, resulting in loss of integrity and shrinkage, reducing the hydrophilic properties, as reflected by the inability to absorb sufficient water to completely hydrate the product [57].

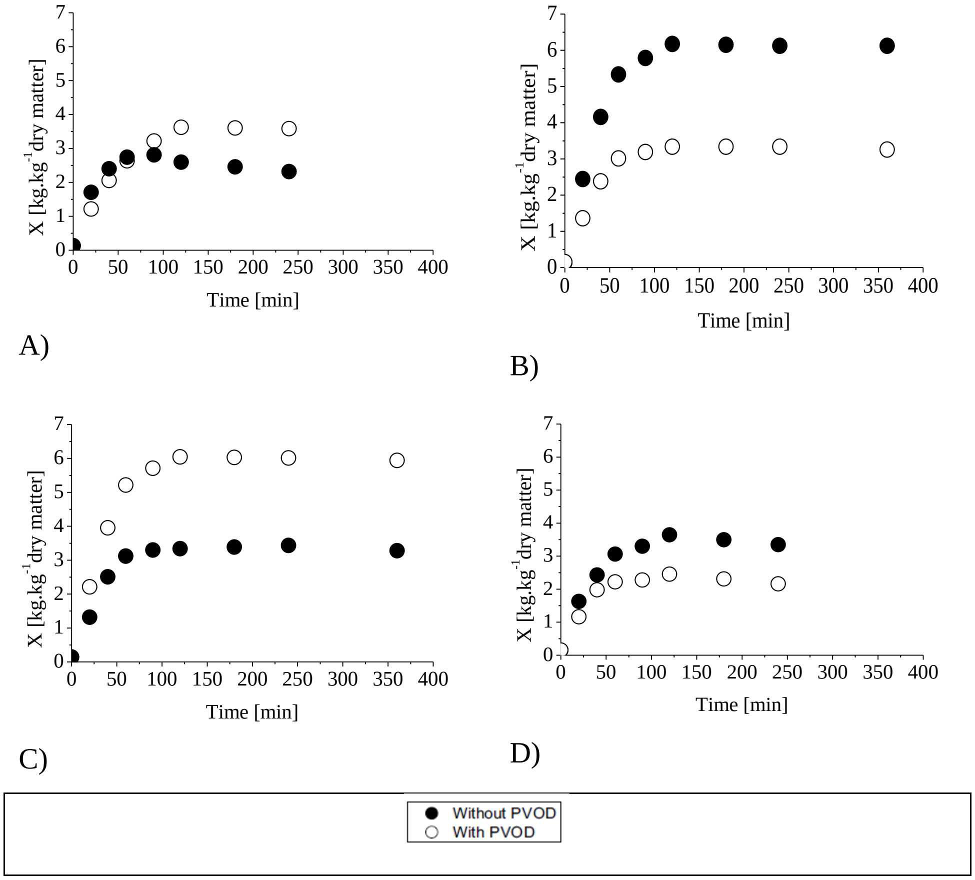


Figure 7 Rehydration kinetics of dried yacon at 40 °C (A), 50 °C (B), 60 °C (C) and 70 °C (D).

It was observed that the dried yacon without pretreatment at the temperatures of 50 and 60 °C achieved the highest moisture saturation, reaching an approximate value of 6.17 and 6.04 (d.b) [kg kg^{-1}] in approximately 120 minutes. The rehydration rate was 50 °C higher in temperature compared with the other process conditions. The dried samples at temperatures of 40 °C had the lowest rate of water absorption and the lowest saturation moisture content (3.62 (d.b) [kg kg^{-1}]). Reis et al.[58] observed that the rate of rehydration of dry yacon is greater with increasing temperature at the temperature range of 45 to 65 °C.

Pretreated sample temperatures of 50 and 60 °C also achieved a higher moisture saturation of 3.35 and 3.45 (d.b) [kg kg^{-1}] at 120 and 240 minutes, respectively. Therefore, the rehydration rate was higher at temperatures of 60 °C, despite the need for higher moisture saturation time. Samples dried at temperatures of 40 °C and 70 °C obtained the lowest water absorption rate and the lowest moisture content saturation, 2.80 and 2.45 (d.b) [kg kg^{-1}], respectively. The negative effect of high temperature and prolonged drying time on rehydration, as observed at temperatures of 40 to 70 °C, respectively, is due to the caramelization of the sugars, and thus resulted in the clogging of pores on the surface. High temperature leads to lower diffusion of water through the surface during rehydration [59]. The carbohydrate contents are increased by the incorporation of sorbitol in the PVOD process (Table 1). This is in agreement with a study by Lewicki et al.[60] that observed a reduction of 2- to 4-fold rehydration capacity pretreated with sucrose dried tomatoes and a study by An et al.[61] in osmotic dehydration sucrose with pulsed vacuum of cherry tomatoes.

The results show that the dry yacon at temperatures at approximately 50 and 60 °C, without PVOD, resulted in higher capacity rehydration, thus recovering the original fresh yacon structure.

4 Conclusion

The research results presented in this article show that the efficiency of PVOD before the convective drying of yacon resulted in a reduction of drying time and shrinkage and an increase of effective water diffusivity. Despite the PVOD advantages in drying, the fructan retention, color and rehydration were lower than those obtained in convective drying without pretreatment. However, these disadvantages have been small. The high temperatures contributed to FOS retention and shrinkage minimization. The effective diffusivity is greater with increasing drying temperature and with consideration of shrinkage. The yacon drying kinetics are represented by the Fick model considering shrinkage without the use of PVOD. The dependence of diffusivity in relation to temperature is described by the Arrhenius equation. Thus, convective drying PVOD possesses adequate prospects for industrial use, competing with other drying processes employed for producing dry food.

Nomenclature

M_0	Moisture content initial
M_t	Moisture content at the instant t
M_{eq}	Equilibrium moisture content
M_R	Moisture ratio
D_{eff}	Effective diffusivity
D_0	Pre-exponential factor
E_a	Activation energy
R	Universal gas constant
K	Absolute temperature
V/V_0	Volume ratio
a^*	Color parameter
b^*	Color parameter

C^*	Chroma
h°	Hue angle
ΔE	Color variation
L^*	Luminosity
S	Shrinkage
PVOD	Pulsed vacuum osmotic dehydration
FOS	Fructooligosaccharides
L	Half of sample thickness
Z	Direction of the transfer
N	Number of terms
T	Time
L	Sample thickness
a, b	Fitness parameter
RSME	Root mean square error
R^2	Coefficient of determination

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ARTIGO 2

Hybrid drying of yacon pretreated with pulsed vacuum osmotic dehydration by microwave-vacuum drying

Running title: Microwave-vacuum drying of yacon

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Abstract: Sliced yacon, untreated or pretreated with pulsed vacuum osmotic dehydration (PVOD) were dried in a vacuum in a microwave. The PVOD was performed with a sorbitol solution, 38 °Brix, 35 °C and 681 mmHg during the first 10 minutes. The experiments were based on a 3k experimental design with three initial power density levels (PD) (3.6, 6.3 and 9.8 W/g) and three vacuum pressures (VP) (0, 300 and 600 mmHg). The final product had 12 kg water/100 kg sample. The results showed that increasing microwave PD reduced the processing time with PVOD. Moreover, PD had a positive influence on FOS retention and shrinkage. The vacuum pressure also significantly affected the retention of FOS in pretreated samples and aided drying. The presence of sugar induced by PVOD appeared to brown the yacon. Processing conditions with a PD of 9.8 W/g and vacuum pressure of 600 mmHg for osmotically dehydrated samples are ideal for drying by microwave-vacuum.

Keywords: PVOD, prebiotic, osmotic dehydration, tubercle, Fructans

1 Introduction

The yacon (*Smallanthus sonchifolius*) is a perennial plant in the *Asteraceae* family from the Andean region [1]. It is a particularly rich source of fructo-oligosaccharides (FOS) and inulin. The FOS are prebiotic with a low caloric content and have beneficial effects on health, reducing blood lipids and glucose levels [2]. However, these saccharides hydrolyze rapidly after harvest, affecting the functional characteristics of yacon. Moreover, yacon is a seasonal plant. To keep the FOS content of in a product available during the off-season, a preservation technology such as drying is necessary [1, 3].

Microwave drying results from a mechanism involving the dipolar rotation of polar molecules, which occurs after molecules (which have permanent or induced dipoles) are aligned with the applied electric field. When the field is removed, the molecules return to a disordered state, and the energy absorbed in the dipoles is dissipated as heat. This form of heating creates more even internal heat according to the depth of penetration of electromagnetic waves. The heat is not transferred from the surface to the interior of material, as in the case of convective drying with hot air [4, 5]. Thus, convective drying results in a better use of energy, a shorter processing time, and consequently, a low exposure time of the food to high temperature, yielding a superior quality product [6, 7]. However, the geometry of the microwave cavity can cause the direction of the waves to be irregular, with a possible burning at some points of the dehydrated product. Microwave drying combined with other techniques, such as the use of a vacuum, combines the advantages of the different techniques, minimizing the disadvantages and resulting in better quality.

Microwave-vacuum drying combines heat transfer by microwave and reduced pressure [8, 9]. As a consequence, this technology has the potential to improve energy efficiency and product quality [8, 10, 11]. Studies have shown that microwave-vacuum drying is suitable for the drying of temperature sensitive products such as enzymes [12], volatile compounds [13], and bioactive compounds [14] such as the FOS.

Osmotic pretreatment is recommended to improve the quality of the dried product or reduce the drying time with microwaves [8, 15]. Pulsed vacuum osmotic dehydration (PVOD) implies a reduction in the system pressure at the beginning of the process. The vacuum applied to the product during PVOD gives rise to hydrodynamic mechanisms (HDM). The vacuum during PVOD removes occluded gases in the intercellular spaces of vegetal tissues, and when atmospheric pressure is restored, the pores are filled with the osmotic solution, thereby increasing the surface area for mass transfer [16, 17].

The objective of this study was to investigate the effects of the power density, vacuum pressure and pretreatment with pulsed vacuum osmotic dehydration on the retention of fructan, shrinkage, browning and the final drying time of sliced, dried yacon.

5 Material and methods

Material

Tubers of yacon (*Smallanthus sonchifolius*) were obtained from the local market (Lavras, Minas Gerais state, Brazil). The roots were selected based on the degree of ripeness, the color intensity and uniform firmness. The lack of disease, physical injuries and fissures were also considered. Due to the variation of the fructan content after harvest [3, 18], the tubers were stored in a climate chamber at 6.0±2.0°C and a relative humidity of 90.0±1.8% for a maximum of 5 days before the dehydration experiments were carried out [3].

Preparation of sample

The selected tubers were washed in running water and sanitized in a 200 mg L^{-1} sodium hypochlorite solution for 15 minutes [19, 20]. The yacon roots were peeled, and the samples were cut into in a parallelepiped shape in the dimensions of 2.00 x 2.00 x 0.50 cm (length x width x thickness) using an electric slicer (Urano, USM1-320, 2010, Brazil) and a stainless-steel mold (Figure 1). The dimensions of the slices were verified with a digital caliper (Western, 150 mm-DC-60, China). This geometry allowed the use of diffusional models with the flat plate consideration for predicting the drying rate and obtaining diffusivity coefficients [21].

The samples were dipped in a 1% citric acid solution at ambient temperature for one minute to prevent enzymatic browning [22].

Figure 1 Examples of the yacon tuber and the samples used in the experiments

Sample characterization

The raw material and dried yacon were characterized with respect to chemical composition, moisture content, ether extraction, the ash, protein, carbohydrate and crude fiber, and fructan content, the amount of soluble solids, water activity and color.

Determination of moisture content

The moisture content was determined by the gravimetric method 934.06 AOAC (2005)[23] in a vacuum oven (pressure ≤ 100 mmHg) at 70 °C to constant weight.

Water activity (a_w)

The a_w was determined at 25°C with a water activity meter (Aqualab Decagon Devices Inc. Pullman, model CX-2T, Washington, EUA).

pH

A 10-g sample was triturated in 100 mL of distilled water to determine pH. The sample was macerated until it was homogeneous, and then the pH was directly read from a potentiometer. A digital pH meter (Digimed model DMpH-2,São Paulo, Brazil) was used and calibrated with pH 4.0 and 7.0 solutions, according to the analytical norms of AOAC (2005)[23].

Content of soluble solids

The soluble solids content of the samples was determined using a digital refractometer (Hanna, HI 96801, USA).

Color

The color of the samples was measured with an electronic colorimeter (Minolta CR 400 - Minolta Câmera Co. Ltd, Osaka, Japan) at 25 °C, according to the standard L^* (lightness), a^* (red intensity) e b^* (intensity of yellow). The hue angle (h°) (Equation 1) expressing the color tone was measured with this equipment, as well as the chroma value (C^*) (Equation 2), which indicates the opacity or vividness of the color, ranging from zero to 60. The total color difference (ΔE) was calculated by Equation 3, and an index of 0 indicates a fresh product.

$$^{o}h = \tan^{-1}\left(\frac{b*}{a*}\right) \tag{1}$$

$$C^{*} = \sqrt{a^{*2} + b^{*2}} \tag{2}$$

$$\Delta E = \sqrt{(L^{*} - L_0^{*})^2 + (a^{*} - a_0^{*})^2 + (b^{*} - b_0^{*})^2} \tag{3}$$

Fructans content (FOS)

The fructan content was determined by an enzymatic method (method 997.03 AOAC 2005)[23]. The data were evaluated considering the degradation of fructans index of since its assessment *in nature* and after osmotic dehydration and drying.

Volume and shrinkage

The sample volumes was measured by digital image analysis. Pictures and the sample weight were taken after the same drying time. ImageJ® software was used to measure the surface area of the samples directly from the photographs [24, 25]. The thickness was determined by the arithmetical average of measurements at five different points on the sample with a caliper (Western, 150 mm-DC-60, China). The volume data were obtained by multiplying the image surface area by the average thickness of the material.

The shrinkage (S) was calculated with respect to the volume of the dried sample (V) and its initial volume (V_0) according to Equation 4.

$$S = 1 - \left(\frac{V}{V_0} \right) \tag{4}$$

Experiments

The yacon was dried by microwave-vacuum with and without pretreatment by pulsed vacuum osmotic dehydration. The procedures are described below.

Pulsed vacuum osmotic dehydration (PVOD)

The PVOD experiments were conducted in a dehydrator comprised of a 50-liter jacketed stainless steel chamber (A-240-304, Biasinox LTDA), with a minimum operating volume of 10 liters accessed through the upper part. The temperature was monitored by a thermostat coupled to the chamber, allowing working temperature in the range of 5 to 70 °C. A vacuum pump was attached to the system [26] to carry out low pressure processes.

An osmotic solution was prepared at a concentration of 38 °Brix with distilled water and commercial sorbitol (Singsino Goup Ltd., China). The mass ratio of yacon in the solution was 1:10 (w/w). Osmotic dehydration was carried out at 35 °C and a pressure of 681 mmHg during the first 10 minutes of the process. The total time was 300 minutes. The processing conditions were optimized in by previous trials. After the PVOD treatment, the samples were immediately immersed in an ice bath for 10 seconds. The surface washing water was removed by drying the surface with a paper towel. This procedure was used to terminate dehydration and remove the excess osmotic solution from the sample surface [20].

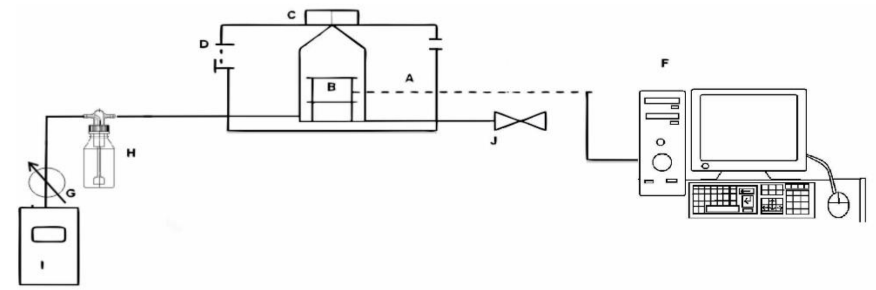
Microwave-vacuum drying (MWV)

The MWV experiments were conducted in a system composed of a domestic microwave oven, vacuum pump, vacuum trap, catheter tube and a polycarbonate sample holder (Figure 2). The microwave oven (Electrolux, MEC41 Inox, BMC38-A model Manaus, Brazil) had a cavity volume of 31 liters with a nominal 1500 W maximum power. The polycarbonate sample holder was adapted to the inside of the microwave cavity and attached to a vacuum pump by a catheter tube. Water vapor arising from drying was sequestered in a condenser (vacuum trap) between the sample holder and the vacuum pump to avoid damaging the vacuum pump. The sample holder was also coupled to a analytical balance (OHAUS, ARC 120, China, 3000 g ± 0.001 g) that sent the weight variation during the drying experiments to a computer, allowing the continuous measurement of the sample weight during the microwave vacuum experiments.

A sample with a mass of approximately 27 g was used in each experiment. At intervals of 5 to 10 minutes, the surface temperature of the sample was measured with an infrared thermometer (Fluke, Max 62 MAX, USA).

The average final moisture content of the dried samples was 12.00±1.04% (w.b). This value was in line with the maximum moisture content recommendation for dried vegetables by ANVISA [27].

The initial microwave power density and the vacuum pressure used in the experiments were preliminarily tested, to ensure that the dried samples had not been burned. The MWV experiments, untreated or pretreated by PVOD, were conducted in a 3^k experimental design (Table 1) with three initial power density levels (PD) (3.6, 6.3 and 9.8 Wg^{-1}), and three vacuum pressures (VP) (0. 300 and 600 mmHg) [28]. The conditions shown in Table 1 were the same for treated and untreated samples, resulting in 18 assays. Three assays were performed for replications of the central points. The dependent variables were fructan retention, shrinkage, rehydration capacity, color (ΔE, h°, C^*, L^*) and processing time.



A - microwave oven, B - polycarbonate sample holder, C – analytical balance, D- hot air outlet and - signal to the computer, F – computer, G - vacuum gauge, H - condenser (steam trap), I - vacuum pump, J - vacuum control valve.

Figure 2 Experimental microwave-vacuum drying system

Table 1 Experimental design for microwave vacuum drying of yacon

Assay	Coded variables		Actual variables	
	X_1	X_2	PD [Wg^{-1}]	VP [mmHg]
1	-1	-1	3.6	0^*
2	-1	0	3.6	300
3	-1	1	3.6	600
4	0	-1	6.3	0^*
5	0	0	6.3	300
6	0	1	6.3	600
7	1	-1	9.8	0^*
8	1	0	9.8	300
9	1	1	9.8	600

VP- vacuum pressure; and PD- initial power density microwave.
[*] Vacuum pressure of 0 mmHg corresponds to atm pressure.

Microwave Oven Power Measurement

The power of the microwave oven in the experiments was determined by the "IMPI 2 - Liter" test method according to Soysal et al.(2009)[29]. The oven was turned on with the nominal voltage network, set at the highest power (100%), and loaded with 2000±5.0 g water contained in two 1 L beakers. Initially, the water was at 20°C. The beakers of water were placed in the center of the oven side by side across the width of the cavity and touching each other. The microwave oven was turned on for 2 minutes and 2 seconds. Afterwards, the beakers were immediately removed from the oven, and the final temperature was measured and recorded. The microwave power was calculated by Equation 5. This procedure was performed 5 times.

$$P_m = \frac{mc_p\left(\Delta T_1 + \Delta T_2\right)}{2\Delta t} \,. \tag{5}$$

P_m is the average power (W), ΔT_1 and ΔT_2 are the water temperature increases in both beakers, m is the total mass of the water (kg), c_p is the specific heat of water (J kg^{-1} K^{-1}), and Δt is time (s).

The oven was preheated by heating the 2 L of water for 5 minutes, wiping the walls with a damp rag and cooled. The water in each beaker was stirred before measuring the temperature.

Statistics

An analysis of variance (ANOVA) to determine the regression coefficients and the generation of response surfaces was performed with the Statistica 8.0 software. The establishment of the optimum conditions of the drying process was based on the greater retention of fructans, less color change, less shrinkage and a shorter drying time. However, the condition that provided highest fructan content was designated as optimum.

Statistical reparameterization models were generated to predict the best conditions. We chose this model because we only worked with significant variables. According to Silveira et al. (2016) [30], reparameterization models can be a very useful mathematical tool for precise and reliable modeling with fewer parameters to be estimated, providing more degrees of freedom for statistical analysis and good precision of the results.

Validation of the experimental model

The experimental model was validated by performing the vacuum microwave drying process with statistically significant variables at their optimal concentration of the greatest retention of fructan with an average of three replications. The rehydration kinetics were determined under optimal conditions.

Drying kinetics mathematical modeling

The drying kinetics were experimentally obtained by determining the moisture content with time. The experimental curve was mathematically modeled with a model of Fick Equation 7.

The model was based on a semi-infinite slab, so the diffusion was limited by the smallest dimension and the model was unidirectional [31]:

$$\frac{\partial M(t)}{\partial t} = \frac{\partial}{\partial z}\left(D_{eff}\,\frac{\partial M(t)}{\partial z}\right). \tag{6}$$

where M(t) is the amount of water at time t, D_{eff} is the effective diffusivity, and z is the direction of transfer.

The effective diffusivity of the Fick's model is based on the variation of the moisture with time and space. The thickness of the sample is 2 L, assuming the diffusion in a drying process goes from the inside surface, z=0 to the outer surfaces, z=L and z=-L. The symmetry of concentration is $\left.\frac{\partial M(t)}{\partial t}\right|_{z=0} = 0$; a uniform initial amount of moisture, $M_{(z,0)} = M_0$; and the equilibrium content at the material surface, $M_{(L,t)} = M_{eq}$.

With these assumptions, the Fick's unidirectional diffusion equation for a semi-infinite plate [31] becomes:

$$MR = \left(\frac{M_t - M_{eq}}{M_0 - M_{eq}}\right) = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left[-(2n+1)^2 \frac{\pi^2}{4} \frac{D_{eff}\, t}{L^2}\right]. \tag{7}$$

where D_{eff} is the effective diffusivity (m^2s^{-1}) of water, L is half the sample thickness (m), n is the number of terms, M_R is the moisture ratio, t is the drying time, M_t is the yacon moisture content at each moment, $M_{0\ is}$ initial moisture content of the yacon, and M_e is the equilibrium moisture content.

We used the coefficient of determination (R^2), reduced chi-square (χ^2) (Equation 8) and root mean square error (RMSE) (Equation 9) to evaluate the model fit.

$$\chi^2 = \frac{\sum_{i=1}^{n} (MR_{exp,i} - MR_{pred,i})^2}{n - N} \tag{8}$$

$$RSME = \left[\frac{1}{n} \sum_{i=1}^{n} (MR_{exp,i} - MR_{pred,i})^2\right]^{1/2}. \tag{9}$$

where $M_{Rexp,i}$ and $M_{Rprev,i}$ are, respectively, the experimental and predicted values of the moisture ratio for observation i, n is the number of observations, and N is the number of parameters in the model.

It is given that the shrinkage observed while drying food is a function of the moisture content. The assumption of the linear dependence of the volume shrinkage on the moisture content was previously employed successfully (Equation 10) [32, 33, 34]. Assuming that dimension L is a constant could cause error [34].

$$\frac{V}{V_0} = a + b\frac{X}{X_0} \cdot \tag{10}$$

V is the volume corresponding to the moisture content X, and V_0 is the initial volume of the sample corresponding to the initial moisture content of the product (X_0). The terms a and b are the fitted parameters.

Assuming shrinkage in the Fick model, l was taken as the experimental value for each set of measured data according to the equation 11 [34]. Thus, the effective diffusivity was obtained assuming sample shrinkage:

$$\frac{l}{l_0} = a + b\frac{X}{X_0} \tag{11}$$

where l is the thickness of the yacon sample slices.

Kinetics of rehydration

Dried samples were immersed in 150 mL of distilled water at (25±1°C) in a 250-ml beaker.

The weight of the samples was measured at 20 minute intervals for the first hour and 30 minutes thereafter until constant weight was attained. At each weighing, the samples were placed on a paper towel to remove excess surface water. At the end of the rehydration process, the moisture content and the water activity of the samples were determined. The experimental results were expressed as moisture content on a dry weight basis.

6 Results and discussion

Characterization of fresh yacon

The moisture, soluble solids, water activity and FOS of the fresh samples were 91.7±0.34 g/100 g of sample 6.50±0.10 °Brix, 0.990±0.001 and 63.26±1.38% of dry matter, respectively. The color parameters were a^*=2.85±0.511; b^*=13.34±1.311; L^*=54.93±2.17; C^*=13.64±1.37 and h°=77.97±1.18. The samples treated by PVOD had a moisture content, soluble solids, water activity and FOS of 69.42±0.04 g/100 g of sample 10.20±0.25 °Brix, 0.976±0.001 and 61.11±0.42% of dry matter, respectively. The color parameters were a^*=-0.84±0.195; b^*=13.00±0.179; L^*=49.11±0.57; C^*=13.03±0.186; and h°=93.83±1.046 in osmotically dehydrated samples.

Drying microwave-vacuum

The results of the experiments were analyzed based on the experimental design, and the regression coefficients were expressed in terms of the codified units and coefficients of determination for the seven response variables analyzed: drying time, retention of FOS, shrinkage and color parameters (color variation (ΔE), angle hue (h°) Chroma (C^*) and luminosity (L^*)).

Although a statistical model has several parameters, for practical purposes, it is desirable to have the simplest model with the fewest parameters that reflects the effects of the principal variables. According to Silveira et al.(2016)[30], reparameterization provides an accurate and reliable model with fewer estimated parameters with more degrees of freedom for statistical analysis and accurate results. Table 2 shows a reparameterized model.

The ANOVA for the reparameterized regression model (Table 3) indicated that the model was statistically significant for all responses ($p<0.05$) and calculated F value was greater than the tabulated value. All regressions of the responses showed a good fit (R^2 range 75.07% to 97.8% and 76.4% to 95.07% with and without PVOD), allowing response surfaces to be generated.

Table 2 Regression Coefficients for drying time, retention fructans, shrinkage and color parameters (ΔE, h°, C^{*} and L^{*})

Factor	Drying time		Retention fructans		Shrinkage		ΔE		h°		C^{*}		L^{*}	
	RE	p	RE	p	RE	p	RE	p	RE	p	RE	p	RE	p
Without PVOD														
M/I	400.667	0.003	54.28	0.00	72.283	0.00	6.82	0.00	76.05	2.5 x 10^{-11}	19.29	1.05 x10^{-7}	52.66	1.9 x 10^{-11}
PD (L)	-361.333	0.001	17.83	0.00	-6.37	0.002	-	-	-2.81	0.01	-1.24	0.01	-	-
PD (Q)	266.333	0.042	-	-	-	-	-1.66	0.01	-	-	-	-	-	-
VP (L)	-	-	-	-	-	-	-	-	3.69	0.00	2.56	0.00	4.52	-
VP (Q)	-	-	-	-	-	-	1.40	0.01	-	-	-1.63	0.03	-	-
R²	0.951	-	0.764	-	0.764	-	0.833		0.851		0.951		0.799	
With PVOD														
M/I	331.000	0.0001	86.33	0.00	52.11	0.00	10.85	0.00	68.73	0.00	12.79	0.00	44.47	0.00
PD (L)	-306.500	0.0000	6.34	0.01	-7.26	0.001	1.94	0.02	-	-	-	-	-2.15	0.02
PD (Q)	162.500	0.0078	-	-			-	-	-5.30	0.03	-	-	-	-
VP (L)	-79.500	0.0150	6.05	0.01			-	-	-	-	1.58	0.03	-	-
VP (Q)	-	-	-	-			-	-	5.37	0.03	-	-	-	-
R²	0.978	-	0.806	-	0.822		0.785		0.757		0.750		0.797	

Note: PVOD-pulsed vacuum osmotic dehydration; RE- regression; M/I-means interaction; VP-vacuum pressure; and PD- power density microwave.

Table 3 Analysis of variance for drying time, retention fructans, shrinkage and color parameters (ΔE, h$^{\circ}$, C*and L*)

Souces		Without PVOD						
		Drying time	Retention fructans	Shrinkage	ΔE	h°	C*	L^{*}
SS	Regression	9252.38	1906.61	243.20	9.42	129.16	53.81	122.71
	Error	1280.58	693.58	75.11	1.88	22.51	2.79	30.77
	Total	10532.96	2600.19	318.31	11.29	151.67	2.79	153.49
df	Regression	2	1	1	2	2	3	1
	Error	6	7	7	6	6	5	7
	Total	8	8	8	8	8	8	8
MS	Regression	4626.19	1906.61	243.20	4.72	64.58	17.94	122.71
	Error	213.43	99.08	10.73	0.31	3.75	0.56	4.4
F_{cal}	Regression	21.68	19.24	22.66	14.99	17.22	32.15	27.91
p-value	Regression	0.001	0.003	0.002	0.00	0.00	0.00	0.00
F_{tab} 0.05%	Regression	5.14	5.59	5.59	5.14	5.14	5.41	5.59
R²		0.950	0.764	0.764	0.833	0.851	0.950	0.799
		With PVOD						
SS	Regression	6543.87	460.71	316.44	22.66	113.91	15.07	27.61
	Error	143.78	111.20	68.78	16.04	40.62	13.36	18.72
	Total	6687.66	571.99	385.23	38.7	154.52	28.42	46.31
df	Regression	3	2	1	1	2	1	1
	Error	5	6	7	7	6	7	7
	Total	8	8	8	8	8	8	8
MS	Regression	2181.29	230.35	316.44	22.66	56.95	15.07	27.61
	Error	28.76	18.53	9.83	2.29	6.77	1.91	2.67
F_{cal}	Regression	75.85	12.429	32.20	9.89	8.41	7.92	10.33
p-value	Regression	0.00	0.007	0.0007	0.02	0.016	0.03	0.01
F_{tab} 0.05%	Regression	5.41	5.14	5.59	5.59	5.14	5.59	5.59
R²		0.978	0.806	0.821	0.785	0.757	0.751	0.797

Note: PVOD is pulsed vacuum osmotic dehydration

Power density (PD)

PD significantly affected the drying time, the retention of FOS, shrinkage and parameter variation (ΔE) and angle hue (h°) with and without PVOD. However, luminosity (L^*) and chroma (C^*) variables were only affected by the presence and absence of the PVOD pretreatment, respectively. Table 2 shows that significant linear and quadratic effects on the drying time were found for the untreated and treated samples.

Table 4 shows the drying time for each microwave-vacuum drying condition. The drying time ranged from 28.5 to 130 min for untreated samples and from 12.3 to 95.2 min for the treated samples. The osmotic pretreatment reduced the drying time by 36.5%. The lowest PD was 2.31 times faster at higher levels (Assay 9). The application of pulsed vacuum osmotic dehydration (PVOD) for a short time at the beginning of dehydration proved beneficial to the kinetic drying process. The application of PVOD technology is a mass transfer operation between a porous solid structure with a liquid phase that is immersed; pressure gradients generated in the system cause a gas to be expelled and liquid to be taken into the interior of a porous structure [17, 35]. The structural changes resulting from the PVOD treatment, such as complete plasmolysis, and lysing of the membrane [36, 37], results in the movement of internal liquids to the outside. Such changes facilitate further drying via transfer phenomena.

Table 4 Drying times for microwave-vacuum drying of yacon with and without pulsed vacuum osmotic dehydration (PVOD) as a pretreatment and Water activity (a_w).

Assay	Drying time [min]			
	Without PVOD	Water activity (a_w)	With PVOD	Water activity (a_w)
1	130.0	0.480±0.055	95.2	0.485±0.026
2	96.8	0.539±0.017	77.8	0.367±0.038
3	81.7	0.560±0.004	67.0	0.376±0.062
4	38.8	0.552±0.021	36.8	0.474±0.064
5	45.7	0.551±0.289	35.5	0.498±0.009
6	35.7	0.533±0.022	27.0	0.460±0.069
7	32.2	0.573±0.019	22.0	0.472±0.021
8	31.0	0.554±0.053	21.8	0.485±0.043
9	28.5	0.549±0.031	12.3	0.407±0.097

As observed in the response surfaced in Figures 3A and 3B, when the microwave power density is greater, the drying time is shorter. Power densities in the range of 8.05 and 9.8 Wg^{-1} caused shorter drying times. Similar results were also reported by Wojdyło et al. (2009)[14] and Koné et al. (2013)[7] for drying pineapple, strawberry and tomato. The microwave heating results from the dipolar rotation mechanism of polar molecules, which occurs after alignment of the molecules (which have permanent or induced dipoles) with the applied electric field. When the field is removed, the molecules return to a disordered state, and the energy absorbed by these dipoles is dissipated as heat. Therefore, microwave absorption provokes internal heating and evaporation of water, greatly increasing the internal pressure and concentration gradients and thus the effective water diffusion [38].

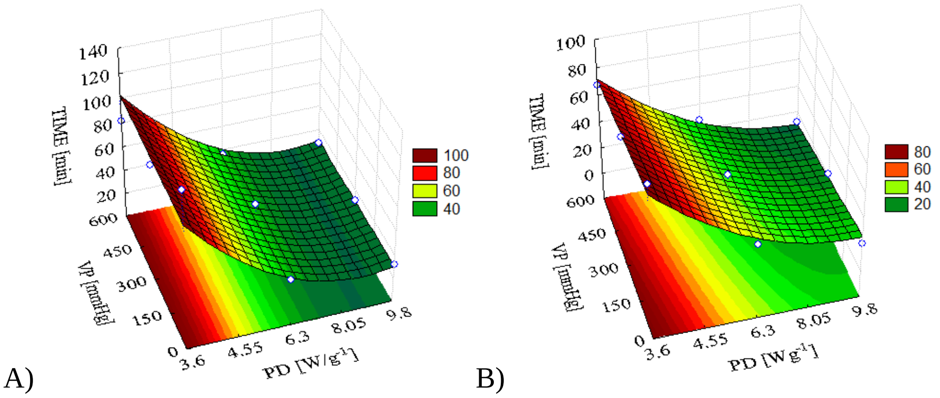


Figure 3 Surface response for yacon drying time in samples untreated with PVOD (A) and pretreated with PVOD (B). PVOD is pulsed vacuum osmotic dehydration

The yacon drying kinetics are shown in Figures 4A and 4B for untreated and treated samples, respectively. It was observed that the moisture content of yacon decreased with drying time under all the conditions. It was evident that the moisture ratio decreased with PD at any pressure. Assawarachan and Noomhorm (2011)[39] also observed that the PD shortened the evaporation time for concentrated pineapple juice.

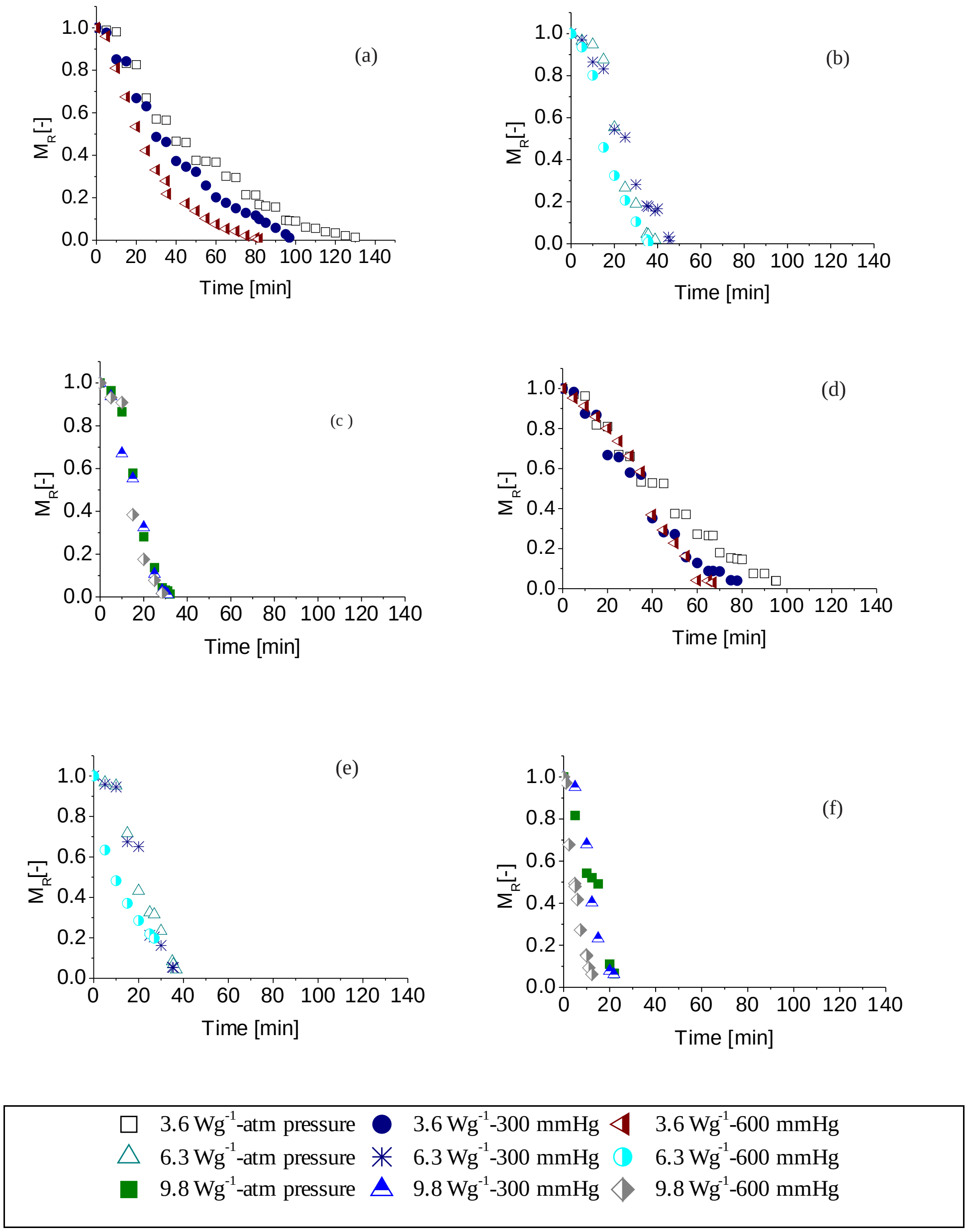


Figure 4 Kinetics of drying of yacon samples without PVOD (a, b, c) and with PVOD (d, e, f).

The temperature curves of the samples during microwave-vacuum drying are shown in Figures 5. It is important to note that the surface temperature of the osmotically dried yacon samples reached the highest value in less time, which contributed to the shortening of drying time with PVOD as observed in Figure 4B. The PVOD pre-treatment reduced the amount of water in the product initially and changed the dielectric properties of the material [35]. Moreover, the osmotic treatment caused structural modifications such as plasmolysis and led to a more porous material, which was more suitable for heat and mass transfer. At the end, the sample temperature remained stable, independent of pretreatment. According to Wang et al. (2013)[40], that occurred because powered microwave heating is equilibrated by evaporative cooling. This result is very interesting with respect to the preservation of heat sensitive compounds in the yacon, such as fructans. Scher et al. (2009)[1] reported that temperatures above 70 °C indicated the hydrolysis of fructo-oligosaccharides present in the yacon.

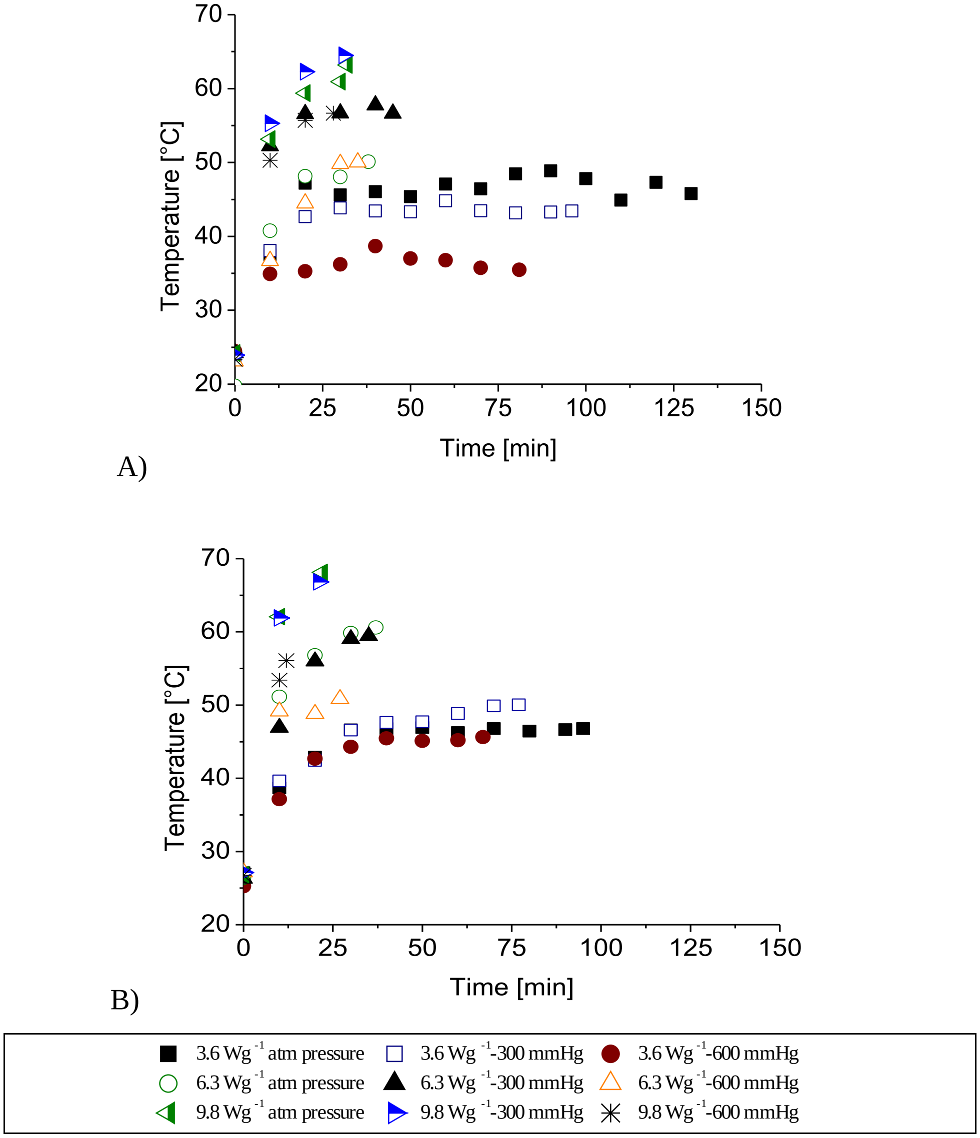


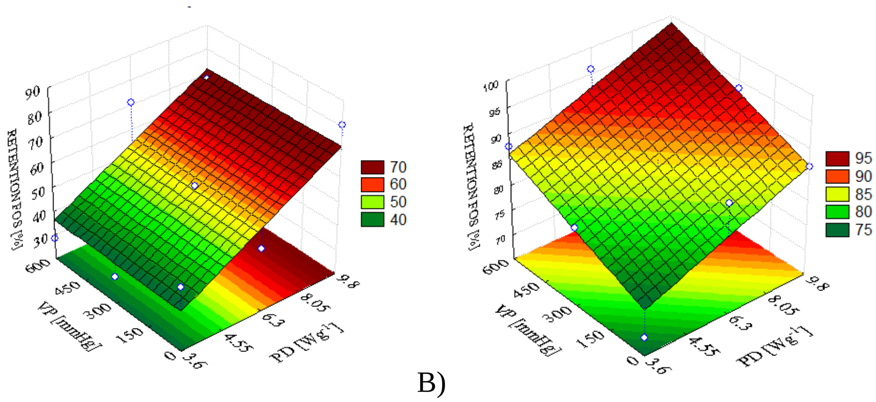
Figure 5 Curves of sample temperature of yacon without PVOD (A) and with PVOD (B) with drying time

The responses obtained for the content and retention of fructans with respect to PVOD are shown in Table 6. The fructan content and the fructan retention were as high as 51.05 and 80.63%, respectively, for untreated samples and up to 60.57 and 95.74% for PVOD-treated samples. Pretreatment with PVOD improved the fructan content and retention, up to 210% (Assay 3, Table 5). Fructans are thermosensitive [1]. Consequently, a shorter exposure to high temperature leads to a higher fructan content. A shorter drying time combined with a decrease in product temperature (Table 4, Figure 5) resulted from osmotic treatment. As observed in Figures 6A and 6B, power densities (PD) in the range of 8.05 and 9.8 Wg^{-1} facilitate FOS retention. It can be inferred that higher PD causes less exposure of the samples, and therefore, a greater amount of FOS at higher temperatures. This assists in the preservation of the FOS in the sample. A higher power density leads an accelerated drying process (Table 4). The water evaporation in the sample is accelerated by the preferred absorption of microwave energy by the water molecules [41, 42].

Table 5 Content of fructans in dry yacons*

	Content of fructans [%,d.b]		Retention of fructans [%]	
Assay	Without PVOD	With PVOD*	Without PVOD	With PVOD
1	29.20	43.32	46.15	68.47
2	19.73	50.97	31.19	80.56
3	17.95	55.37	28.37	87.53
4	28.87	54.85	45.64	86.70
5	33.91	52.75	53.59	83.38
6	44.87	60.57	70.98	95.74
7	51.04	54.68	80.68	86.43
8	40.63	59.16	64.22	93.51
9	42.87	59.87	67.77	94.64

* The data are on a dry weight basis and products subjected to osmotic dehydration disregarded the gained solids



A) B)

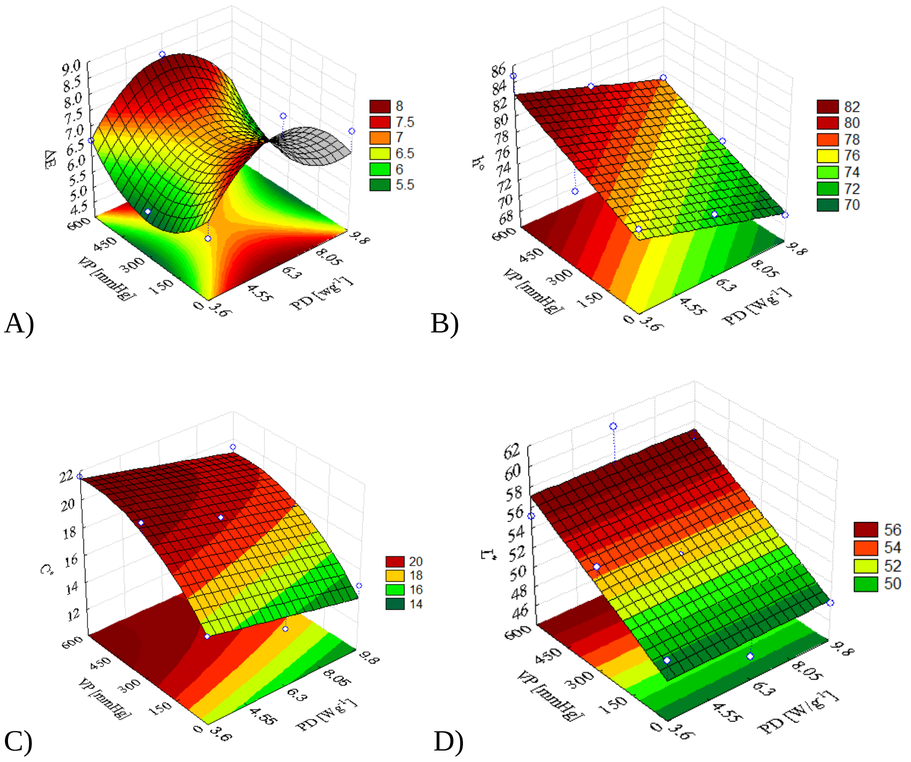
Figure 6 Response surface for FOS retention as a function of vacuum pressure (PV) and power density (PD) for untreated samples (A) and osmotically treated samples (B)

Table 6 shows that the luminance values (L^*) of the samples dried in a microwave-vacuum were lower with osmotic pretreatment, indicating the browning of the yacon with PVOD. Moreover, the color change (ΔE) was greater in treated samples, confirming that osmotic dehydration due to sorbitol solution penetration caused by the vacuum pulse caused sample browning. The results show that dimming was 66.48% in the treated samples. The treated yacons had lower values of the hue angle (h°) expressed in degrees compared to untreated sample - the trend was from yellow (= 90°) to red (= 0°) with pretreatment. The chroma, which represents the intensity or purity of tone, increased in samples in the absence of PVOD; however, slight variations in the osmotic treatment yielded values close to those found in yacon *in nature*.

Table 6 Responses of color variation parameters (ΔE), hue angle, hue (h°), Chroma (C^{*}) and luminosity (L^{*}) of dried yacon

Assay	ΔE	h°	C^{*}	L^{*}
	Without PVOD			
1	5.99	76.39	16.34	50.15
2	5.52	75.73	21.16	54.59
3	6.52	84.73	21.62	55.11
4	8.68	73.82	14.21	46.38
5	6.26	74.04	19.18	52.01
6	8.37	79.78	19.66	60.58
7	7.23	69.26	14.76	47.87
8	5.36	73.61	17.53	51.41
9	5.92	77.11	19.39	55.81
	With PVOD			
1	10.95	72.43	11.23	44.33
2	10.48	64.88	12.66	45.06
3	6.72	69.21	17.28	49.48
4	9.72	76.49	11.52	45.28
5	10.08	67.09	12.98	44.98
6	9.89	73.34	13.69	45.07
7	13.69	65.88	10.94	41.83
8	13.70	63.60	12.52	41.29
9	12.41	66.03	12.28	42.87

The effect of color variation was significantly and exclusively regulated by the power density of the applied microwaves in pre-treated samples, and the DP was also significant in the untreated samples. The response surfaces generated by the proposed model for the color parameters are shown in Figure 7A-D and E-H for the untreated and treated samples, respectively. Figure 7A-D shows that the least color change was achieved at a PD at the lowest and highest level. Additionally, lower values of h° were observed at a higher PD. These results indicate that a higher PD may preserve the color of the tubers. A significant influence of PD in the chroma parameter was also observed, for which a PD greater than 8.05 Wg^{-1} produced values approaching those of natural yacon (13.64±1.37). In the treated samples, Figure 7E-H shows that a DP in the range from 3.6 to 6.3 Wg^{-1} indicated less color variation. Furthermore, a higher hue angle (h$^{\circ}$) was observed (4.55 to 8.05 Wg^{-1}). For the lightness (L^*), a higher PD leads to a lower L^*, indicating a darkening of samples pretreated with sorbitol. In general, all treatments led to the browning of the yacon (i.e., a lower L^*value compared with values obtained or the tuber *in nature*) independently of the PD, except for treatments 3, 5 and 9 without PVOD, which exhibited higher luminosity values than fresh samples.



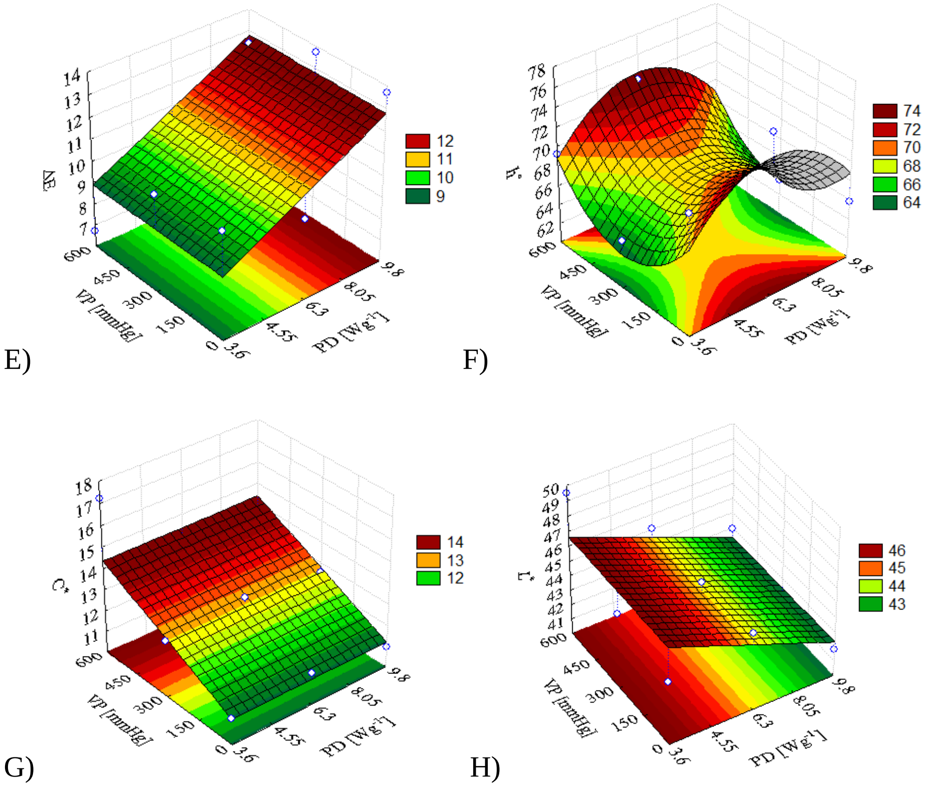


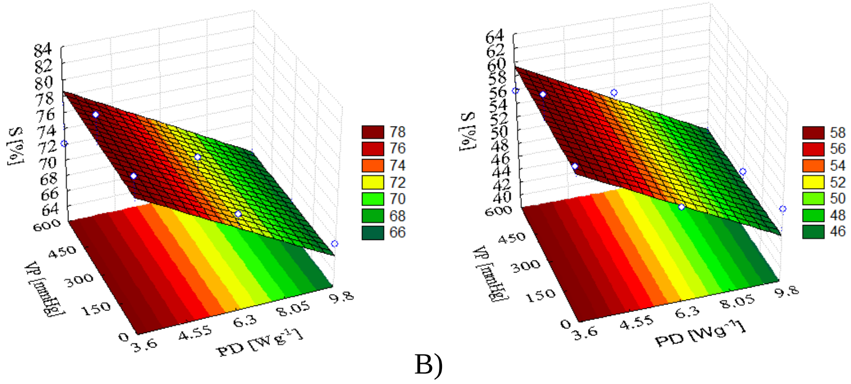
Figure 7 Response surface for ΔE, h°, C^* and L^* as a function of vacuum pressure (VP) and power density (PD) for untreated samples (A, B, C, D) and osmotically treated samples (E, F, G, H)

Table 7 shows the volumetric shrinkage in each microwave-vacuum drying assay. Shrinkage was observed under all processing conditions studied and was associated with product deformation and the collapse of the cellular structure due to the removal of the moisture occupying a certain volume of the product. Shrinkage ranged from 64.06 to 81.88% and from 40.11 to 60.32% for untreated and treated samples, respectively. Osmotic pretreatment resulted in less shrinkage of the dried yacon samples. It is known that the material structure begins to change during drying and reaches a critical value that generates disintegration and shrinkage of the tissue cells. In this study, the osmotic dehydration processing conditions necessary to induce shrinkage stress in the samples during drying were less extreme, causing lower shrinkage and facilitating water removal, as shown in Table 2. According to Changrue et al. (2008)[10] osmotic dehydration promotes tissue softness and less shrinkage during drying due to impregnation with the desiccant solution during processing. This causes the higher the solids inlet and a lower resistance to compression of the product compared to non-osmotically dehydrated products. Corrêa et al. (2011)[8] and Al-Harahsheh et al. (2009)[41] also reported that the use of osmotic dehydration resulted in lower retraction in pineapple and dried tomatoes, respectively, when microwave-vacuum dried.

Table 7 Responses of the volumetric shrinkage [%] of dried samples yacon with and without osmotic treatment

Assay	Shrinkage [%]	
	Without PVOD	With PVOD
1	81.16	60.32
2	81.88	62.59
3	72.12	55.75
4	73.90	51.88
5	74.22	50.25
6	70.27	53.04
7	67.47	48.83
8	64.43	46.15
9	65.06	40.11

The response surfaces in Figure 8A and B clearly show that the PD affected the shrinkage of the dry yacon. The results demonstrate that a PD of 8.05 to 9.8 Wg^{-1} caused less shrinkage. Low power microwave drying resulted in a decreased of shrinkage (Figures 4A and B), which may have favored a volume reduction corresponding to less stiffening of the product cell wall.



A) B)

Figure 8 Response surface without PVOD (A) and with PVOD (B) for the shrinkage of dry yacon

The effects of microwaves on shrinkage was also observed by Therdthai and Zhou (2009)[9] in the microwave-vacuum drying of mint. The authors reported a more porous structure in a microwave-vacuum allowing the rapid vaporization of moisture. Han et al. (2010)[43] observed that microwave-vacuum drying of pieces of apple and pineapple resulted in less shrinkage than with convective drying. The ratio of the lesser shrinkage in microwave-vacuum compared to convective drying could be a function of the electromagnetic energy absorbed by the water, which penetrates directly into the material and causes volumetric heating (i.e., from the inside to the outside). The rapid absorption of energy by water molecules causes the rapid evaporation of water, creating an outward flow of steam. In addition to improving the drying speed, this flow to the outside helps to prevent the shrinkage of the fabric structure, which happens in most conventional drying techniques. Hence, the best rehydration characteristics can be expected in the microwave [44].

Vacuum pressure (VP)

The drying time, FOS retention and color chroma (C^*) and angle hue (h°) variables were affected by the vacuum pressure for PVOD-pretreated samples. However, only the color (i.e., C^*, h°, L^* and ΔE) varied significantly ($p<0.05$) with vacuum pressure in the untreated samples (Table 2). The vacuum pressure did not affect the drying time of the untreated samples, as shown in Figure 3A. A reduction of the processing time due to PV in the treated samples was observed in a range of 450 mmHg to 600 mmHg, which showed an even greater effect (Figure 3B). The FOS retention in pretreated samples was also a function of the vacuum pressure. A vacuum pressure (VP) in a range of 450 and 600 mmHg increases FOS retention (Figure 6B). Because microwaves are better absorbed by polar molecules such as water, fat and sugars[4], the incorporation of the solute in the pretreatment tests allowed a larger coupling energy in the presence of microwaves, and the low pressure produced by the vacuum affected the FOS retention. In addition, changes in the tissues caused by PVOD provided adequate samples for pressure variation in the presence of a vacuum. This also justifies significant influence VP in reducing the drying time with PVOD samples.

The data presented in Table 2 indicate significant differences in color parameter of the yacon sample dried in a microwave-vacuum and L^* and ΔE varied significantly ($p<0.05$) with the vacuum pressure in the untreated samples. However, the vacuum pressure had a significant effect on the chroma (C^*) parameter in the untreated and treated samples. The response surfaces generated by the proposed model for the color parameters are shown in Figures 7A-D and 7E-H for untreated and treated samples, respectively. Figure 7A-D shows that the least color change occurred at VP levels close to 300 mmHg. Additionally, smaller values of h° were observed when the VP levels was lower. These results indicate that low pressure might preserve the color of the tubers. However, a lower VP resulted in a low L^* value, so the processing conditions must be carefully chosen if pretreatment is not used. A plausible explanation for this phenomenon is that the Maillard reactions were eliminated due to lack of oxygen or the heat-sensitive polyphenoloxidase activity was probably blocked by vacuum drying. Vacuum effects were also observed by Mothibe et al. (2014)[22] when drying apple cubes in a microwave-vacuum.

A significant effect of VP on the chroma parameter was observed - the application of a VP less than 150 mmHg resulted in the values approaching those of natural yacon. A higher h° was also observed at a VP at the lowest and highest level. In general, browning of yacon (i.e., a lower value L^* when compared with the values obtained for the tuber *in nature*) was observed in all treatments independent of the PD and VP in the absence of PVOD, and higher luminosity values than in fresh samples were observed.

Mathematical modeling

The effective diffusivity (D_{eff}) was obtained via the Fick diffusion model and is shown in Table 8. An increase in DP and VP increased the diffusivity coefficient up to 82% when shrinkage was considered, especially with an increasing PD. In the pretreated samples, shrinkage also increased the diffusivity coefficient. In assay 9, the PVOD increased by 67% compared to the D_{eff} of untreated samples. Impregnation of the solution during osmotic dehydration causes less tissue retraction in the product and facilitates the removal of water [8, 10]. Although the diffusivity varies depending on the composition, texture, porosity, sample geometry, temperature and the type of drying process, the range of values for foods dried in a microwave is usually between 10^{-11} and 10^{-6} [9, 41].

In some cases, the diffusion model did not show a satisfactory adjustment of the drying kinetics, with R^2 values between 99 and 71%. However, RSME and χ^2 for the shrinkage assumption resulted in lower values and better described the drying kinetics. This lack of fit can be observed in Figure 9A in the assay 3. However fine fit can be observed with PVOD and shrinkage (Assay 9 samples, Figure 9B), and the RSME was lower.

Table 8 Effective diffusivity coefficient, coefficient of determination (R^2), root mean square error (RMSE), and reduced chi-square (χ^2) for a Fick model for the various conditions studied with and without shrinkage

Without PVOD								
Assay	Without shrinkage				With shrinkage			
	D_{eff} [m^2s^{-1}]	R^2	RSME	χ^2	D_{eff} [m^2s^{-1}]	R^2	RSME	χ^2
1	$1.05x10^{-10}$	0.894	0.102	0.017	$3.15\ x10^{-10}$	0.917	0.062	0.017
2	$1.32\ x10^{-10}$	0.904	0.097	0.003	$4.69\ x10^{-10}$	0.963	0.060	0.011
3	$1.99\ x10^{-10}$	0.916	0.094	0.001	$8.16\ x10^{-10}$	0.965	0.061	0.009
4	$2.21\ x10^{-10}$	0.807	0.101	0.017	$6.01\ x10^{-10}$	0.917	0.013	0.020
5	$2.04\ x10^{-10}$	0.779	0.165	0.009	$7.59\ x10^{-10}$	0.924	0.097	0.011
6	$3.03\ x10^{-10}$	0.887	0.171	0.004	$1.36\ x10^{-9}$	0.938	0.128	0.008
7	$3.31\ x10^{-10}$	0.758	0.194	0.004	$1.04\ x10^{-9}$	0.921	0.111	0.010
8	$3.43\ x10^{-10}$	0.809	0.164	0.003	$1.99\ x10^{-9}$	0.841	0.149	0.002
9	$3.21\ x10^{-10}$	0.713	0.215	0.015	$1.06\ x10^{-9}$	0.877	0.141	0.018
With PVOD								
1	$1.06\ x10^{-10}$	0.853	0.120	0.009	$3.00\ x10^{-10}$	0.922	0.050	0.007
2	$1.36\ x10^{-10}$	0.832	0.138	0.008	$3.08\ x10^{-10}$	0.974	0.054	0.007
3	$1.22\ x10^{-10}$	0.746	0.176	0.017	$3.60\ x10^{-10}$	0.950	0.078	0.007
4	$2.29\ x10^{-10}$	0.750	0.110	0.011	$6.42\ x10^{-10}$	0.922	0.100	0.008
5	$2.28\ x10^{-10}$	0.841	0.202	0.014	$6.49\ x10^{-10}$	0.907	0.114	0.011
6	$3.53\ x10^{-10}$	0.999	0.002	0.001	$9.88\ x10^{-10}$	0.854	0.101	0.001
7	$3.87\ x10^{-10}$	0.814	0.141	0.002	$1.08\ x10^{-9}$	0.982	0.043	0.001
8	$3.94\ x10^{-10}$	0.749	0.183	0.009	$1.55\ x10^{-9}$	0.852	0.140	0.008
9	$8.98\ x10^{-10}$	0.914	0.094	0.003	$3.26\ x10^{-9}$	0.974	0.051	0.002

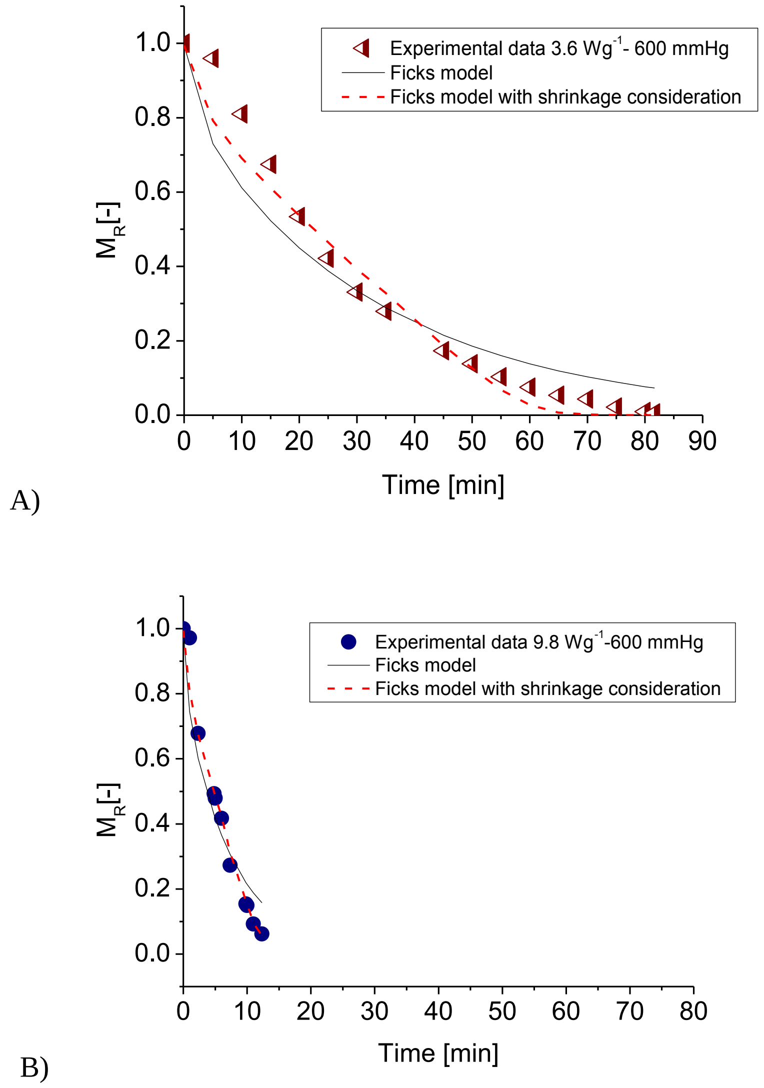


Figure 9 Experimental values and predicted moisture content during drying of yacon slices in experiments without osmotic PVOD (A) and with PVOD (B) treatment *The solid line red represents the model with shrinkage, and the solid black lines represent the model without shrinkage.

Validation

An analysis of the response surfaces allowed the actual processing conditions that would provide the desired characteristics for drying via microwave-vacuum to be obtained by using the statistically significant variables in their optimum significant results. These processing conditions are a power density of 9.8 Wg^{-1} and a vacuum pressure of 600 mmHg for osmotically dehydrated samples. This combination was selected on the basis of the highest FOS retention.

The experimental results for FOS retention, drying time, shrinkage and color were 97.83±083% 12.5±0.33 min, 42.62±2.20% (mean of three replicates), respectively. The values of chroma, hue, luminosity and color variation were 23.34±1.08, 80.01±2.09, 48.04±2.69 and 12.22±1.09, respectively. Table 9 shows that the results predicted by the model are similar to the experimental results. The small differences between the predicted values and the experimental responses can be attributed to the reparameterization models. Therefore, the validation results are satisfactory, and the process is reproducible.

Table 9 Values predicted by model reparameterization

Parameters	Predicted values
FOS retention [%]	98.717
Time [min]	10.77
Shrinkage [%]	44.85
C^*	14.37
h°	68.8
L^*	42.32
ΔE	12.79

Kinetics of rehydration

Figure 10 shows the rehydration kinetics of dried yacon in a microwave-vacuum under optimal conditions. The product achieved a lower moisture saturation compared to convective-dried yacon - a value of approximately 2.53 [kg kg^{-1}] dry matter was reached in approximately 90 minutes. PVOD-pretreated and convective dried yacon at 40 °C, 50 °C and 60 °C showed a moisture content saturation of 2.80, 3.35, 3.45 (d.b) [kg.kg^{-1}], respectively, between 120 and 240 min. In addition, the rehydration rate was higher than for the conventional drying process, which has also been reported by other workers [45, 46]. Rehydration is related to the structural changes of the yacon during the drying and osmotic dehydration process. The use of PVOD and microwave-vacuum contributed to the rupture of the cell walls, which consequently was avoided by preserving intercellular spaces for water filling the pores.

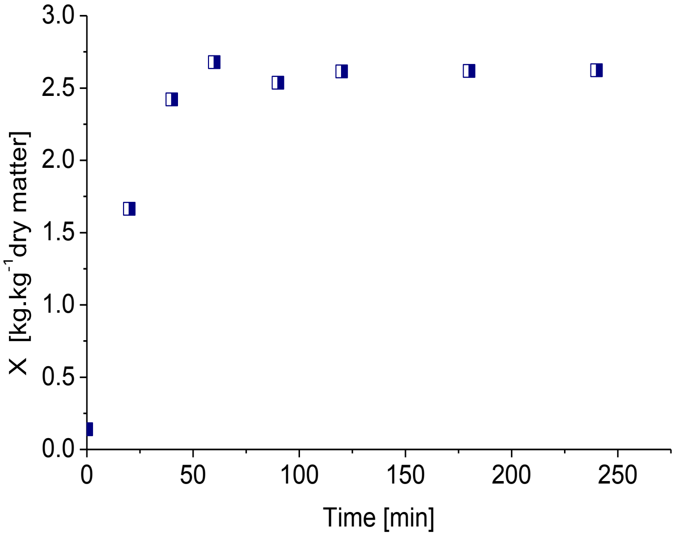


Figure 10 Evolution of moisture content (dry weight basis) for rehydrating dried yacon under 9.8 Wg^{-1} - 600 mmHg optimal conditions.

7 Conclusion

It is possible to retain FOS in yacon in pulsed vacuum osmotic dehydration and subsequent application of microwave-vacuum drying. The PVOD-pretreatment reduced the moisture content of the yacon and consequently reduced the drying time. The power density was significantly reduced the drying time and the shrinkage. Microwaves with a higher power density increased the effective diffusivity, leading to shorter processing times, and facilitated FOS retention. The vacuum pressure also affected the drying and FOS retention of pretreated samples. In general, browning of the yacon occurred in all treatments, independent of pre-treatment. Our data suggest that PVOD followed by microwave-vacuum drying at a power density of 9.8 Wg^{-1} and a vacuum pressure of 600 mmHg has been demonstrated to be an alternative technology for drying yacon and facilitates rehydration of the product.

Nomenclature

M_0	Moisture content initial
M_t	Moisture content at the instant t
M_{eq}	Equilibrium moisture content
M_R	Moisture ratio
D_{eff}	Effective diffusivity
V/V_0	Volume ratio
a^*	Color parameter
b^*	Color parameter
C^*	Chroma
h°	Hue angle
ΔE	Color variation
L^*	Luminosity
S	Shrinkage
MWV	Microwave-vacuum drying

PVOD	Pulsed vacuum osmotic dehydration
FOS	Fructooligosaccharides
PD	Power density
VP	Vacuum pressure
L	Half of sample thickness
z	Direction of the transfer
n	Number of terms
t	Time
l	Sample thickness
a, b	Fitness parameter
RSME	Root mean square error
R^2	Coefficient of determination

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8 CONCLUSÃO GERAL

A secagem micro-ondas vácuo precedida de desidratação osmótica com pulso de vácuo apresentou ser uma técnica mais promissora na secagem de yacon comparadas com a secagem convectiva em termo de qualidade e tempo de processo. Esta técnica apresentou efeito importante na conservação dos fruto-oligossacarídeos (FOS), diversificando a oferta do produto.