MATHEUS DE SOUZA CRUZ

SECAGEM CONVECTIVA DE MAMÃO FORMOSA (*Carica Papaya* L.): INFLUÊNCIA DO REVESTIMENTO NO PRÉ-TRATAMENTO UTILIZANDO ETANOL E DESIDRATAÇÃO OSMÓTICA COM ISOMALTULOSE

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

Prof. Dr. Jefferson Luiz Gomes Corrêa
Orientador

Prof. Dra. Bruna de Souza Nascimento
Prof. Dr. Leandro Levate Macedo
Coorientadores

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CONVECTIVE DRYING OF PAPAYA FORMOSA (*Carica papaya* L.): INFLUENCE OF THE COATING ON PRE-TREATMENT USING ETHANOL AND OSMOTIC DEHYDRATION WITH ISOMALTULOSE

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

APROVADA em 29 de maio de 2024.
Dr. Jefferson Luiz Gomes Corrêa UFLA
Dra. Miriam Dupas Hubinger UNICAMP
Dr. João Renato de Jesus Junqueira UFMS

Prof. Dr. Jefferson Luiz Gomes Corrêa
Orientador

Prof. Dra. Bruna de Souza Nascimento
Prof. Dr. Leandro Levate Macedo
Coorientadores

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RESUMO

O mamão é um fruto apreciado mundialmente por seus atributos sensoriais e nutricionais. Porém, é altamente perecível. A secagem é uma alternativa que promove a redução do teor de umidade, prolongando a vida útil do produto, mas degradações qualitativas ocorrem. Os pré-tratamentos de secagem podem ser utilizados para melhoria do processamento e obtenção de um produto de qualidade. O objetivo deste estudo foi avaliar a cinética de secagem ao ar quente e os parâmetros de qualidade do mamão formosa (*Carica papaya* L.) revestido com alginato de sódio e pré-tratado osmoticamente com isomaltulose e por imersão em etanol. Os mamões foram selecionados, lavados, higienizados e assim obtidos cubos de 10 mm da sua polpa, com auxílio de um molde de aço inoxidável. Após o corte, as amostras foram imersas em solução de 1% (m/v) de alginato de sódio e em solução de 2,5% (m/v) de cloreto de cálcio para formação do revestimento. Em seguida, diferentes pré-tratamentos foram aplicados nas amostras: desidratação osmótica por 300 min com ou sem aplicação de vácuo nos primeiros 20 min utilizando isomaltulose em diferentes concentrações (25% e 35%) como agente osmótico em amostras frescas ou revestidas e imersão em etanol 95% (v/v), na proporção de 1:5 (m/v), por 2 min, a 25 °C. A secagem foi realizada em um secador convectivo de túnel com circulação de ar forçada com velocidade do ar de secagem de 1,5 m/s e temperatura de 60°C até 13% de umidade final. Os resultados obtidos após o processo osmótico mostraram que a aplicação do revestimento reduziu em até 26% o ganho de sólidos quando combinada com utilização do vácuo e a solução com 35% de isomaltulose, sem prejudicar o fluxo de perda de água e a redução de umidade das amostras. Quando analisados os efeitos do pré-tratamentos na secagem convectiva verificou-se que o uso do etanol reduziu em aproximadamente 20% o tempo de secagem em relação às amostras previamente desidratadas ou não tratadas, visto que ambas tiveram o mesmo tempo de secagem, 340 min. Entretanto, o menor tempo de secagem foi observado quando associado o uso do etanol com pré-tratamento osmótico de amostras não revestidas e revestidas, 240 min em ambos os tratamentos. Também foram observadas através do modelo de Fick maiores difusividades efetivas para os tratamentos com uso do etanol, consequentemente menor consumo energético. Em relação à qualidade, conclui-se que os pré-tratamentos revestidos apresentaram maior conservação para carotenoides, atividade antioxidante e compostos fenólicos.

Palavras-chave: desidratação osmótica com pulso de vácuo; açúcar alternativo; palatinose; cobertura comestível; cinética de secagem.

ABSTRACT

Papaya is a fruit appreciated worldwide for its sensory and nutritional attributes. However, it is highly perishable. Drying is an alternative that promotes the reduction of moisture content, extending the shelf life of the product, but qualitative degradations occur. Drying pre-treatments can be used to improve processing and obtain a quality product. The objective of this study was to evaluate the hot air drying kinetics and quality parameters of Formosa papaya (*Carica papaya* L.) coated with sodium alginate and osmotically pre-treated with isomaltulose and ethanol immersion. The papayas were selected, washed, sanitized, and 10 mm cubes of their pulp were obtained using a stainless steel mold. After cutting, the samples were immersed in a 1% (w/v) sodium alginate solution and in a 2.5% (w/v) calcium chloride solution for coating formation. Subsequently, different pre-treatments were applied to the samples: osmotic dehydration for 300 minutes with or without vacuum application in the first 20 minutes using isomaltulose at different concentrations (25% and 35%) as an osmotic agent in fresh or coated samples and immersion in 95% (v/v) ethanol, at a ratio of 1:5 (w/v), for 2 minutes, at 25 °C. Drying was carried out in a convective tunnel dryer with forced air circulation at a drying air velocity of 1.5 m/s and a temperature of 60 °C until 13% final moisture content. The results obtained after the osmotic process showed that the application of the coating reduced the solid gain by up to 26% when combined with vacuum application and the solution with 35% isomaltulose, without affecting the water loss flow and moisture reduction of the samples. When analyzing the effects of the pre-treatments on convective drying, it was found that the use of ethanol reduced the drying time by approximately 20% compared to the previously dehydrated or untreated samples, as both had the same drying time, 340 minutes. However, the shortest drying time was observed when ethanol use was associated with osmotic pre-treatment of non-coated and coated samples, 240 minutes in both treatments. Higher effective diffusivities were also observed through Fick's model for treatments with ethanol use, consequently lower energy consumption. Regarding quality, it is concluded that the coated pre-treatments showed better preservation of carotenoids, antioxidant activity, and phenolic compounds.

Keywords: vacuum pulse osmotic dehydration; alternative sugar; palatinose; edible coating; drying kinetics.

INDICADORES DE IMPACTO

A pesquisa sobre a secagem convectiva do mamão, com o uso de etanol como pré-tratamento e desidratação osmótica, trouxe potenciais impactos em diversas áreas, refletindo avanços sociais, tecnológicos e econômicos. O uso do etanol como pré-tratamento no processo de secagem foi determinante para reduzir tanto o tempo necessário quanto o consumo energético, otimizando o processo e contribuindo para uma produção mais sustentável e eficiente. Além disso, a desidratação osmótica se mostrou uma estratégia eficaz para reduzir o teor de umidade do mamão antes da secagem, facilitando a incorporação de isomaltulose, um açúcar alternativo com baixo índice glicêmico e benéfico para esportistas, o que agrega valor ao produto final. O uso de revestimento de alginato de sódio antes da desidratação osmótica foi uma inovação crucial para evitar o excesso de incorporação de açúcares no mamão durante o processo de osmose. Esse revestimento formou uma barreira seletiva que permitiu o controle na absorção de açúcares, garantindo que o produto final tivesse características nutricionais equilibradas, sem o aumento excessivo de açúcares indesejados. Esse detalhe do processo preserva a qualidade físico-química do mamão, alinhando-se ao objetivo de manter o valor nutricional enquanto aumenta a vida útil do produto, contribuindo para a redução do desperdício de alimentos, especialmente aqueles altamente perecíveis, como o mamão. Os impactos sociais dessa pesquisa são notáveis, especialmente no que tange às metas estabelecidas pelos Objetivos de Desenvolvimento Sustentável (ODS) das Nações Unidas. O trabalho apoia diretamente o ODS 2, "Fome Zero e Agricultura Sustentável", ao aprimorar técnicas que preservam alimentos perecíveis, diminuindo as perdas pós-colheita e possibilitando maior acesso a alimentos nutritivos ao longo do tempo. Além disso, está associado ao ODS 3, "Saúde e Bem-Estar", uma vez que o uso de isomaltulose no mamão desidratado oferece uma alternativa saudável para esportistas e pessoas que buscam melhorar sua dieta. No campo tecnológico, essa pesquisa está alinhada ao ODS 9, "Indústria, Inovação e Infraestrutura", pois promove inovações no processamento de alimentos ao incorporar novas técnicas e prétratamentos que tornam o processo de secagem mais eficiente e sustentável. A diminuição do consumo de energia no processo e a incorporação de ingredientes benéficos ao produto final revelam uma abordagem moderna para o setor alimentício. Do ponto de vista econômico, o trabalho também favorece o ODS 12, "Consumo e Produção Responsáveis", ao promover a utilização eficiente de recursos e a redução do desperdício alimentar. Com um processo mais otimizado, a indústria pode reduzir custos operacionais e oferecer produtos de maior valor agregado, impactando positivamente a economia local e global. Finalmente, ao reduzir o consumo de energia, especialmente com o uso do etanol para acelerar a secagem, o trabalho contribui para o ODS 13, "Ação Contra a Mudança Global do Clima", demonstrando que é possível otimizar processos industriais, reduzir o desperdício e minimizar a pegada de carbono associada à produção de alimentos, avançando em direção a um futuro mais sustentável.

IMPACT INDICATORS

The research on convective drying of papaya, using ethanol as a pre-treatment and osmotic dehydration, has had significant impacts in various areas, reflecting social, technological, and economic advances. The use of ethanol as a pre-treatment in the drying process was crucial in reducing both the necessary drying time and energy consumption, optimizing the process and contributing to more sustainable and efficient production. Additionally, osmotic dehydration proved to be an effective strategy to reduce the moisture content of papaya before drying, facilitating the incorporation of isomaltulose, an alternative sugar with a low glycemic index that is beneficial for athletes, adding value to the final product. The use of sodium alginate coating before osmotic dehydration was a critical innovation to prevent excessive sugar incorporation into the papaya during the osmosis process. This coating formed a selective barrier that allowed for control over sugar absorption, ensuring that the final product maintained balanced nutritional characteristics without an excessive increase in unwanted sugars. This detail of the process preserves the physicochemical quality of the papaya, aligning with the goal of maintaining nutritional value while increasing the product’s shelf life, thus contributing to the reduction of food waste, especially for highly perishable items like papaya. The social impacts of this research are notable, especially in relation to the goals set by the United Nations' Sustainable Development Goals (SDGs). The work directly supports SDG 2, "Zero Hunger and Sustainable Agriculture," by improving techniques that preserve perishable foods, reducing post-harvest losses, and enabling greater access to nutritious food over time. Furthermore, it is linked to SDG 3, "Good Health and Well-being," as the use of isomaltulose in dehydrated papaya offers a healthy alternative for athletes and individuals seeking to improve their diet. In the technological field, this research aligns with SDG 9, "Industry, Innovation, and Infrastructure," as it promotes innovations in food processing by incorporating new techniques and pre treatments that make the drying process more efficient and sustainable. The reduced energy consumption in the process and the incorporation of beneficial ingredients into the final product reveal a modern approach to the food sector. From an economic standpoint, the work also supports SDG 12, "Responsible Consumption and Production," by promoting efficient resource use and reducing food waste. With a more optimized process, the industry can lower operational costs and offer higher value-added products, positively impacting the local and global economy. Finally, by reducing energy consumption, especially with the use of ethanol to speed up drying, the research contributes to SDG 13, "Climate Action," demonstrating that it is possible to optimize industrial processes, reduce waste, and minimize the carbon footprint associated with food production, moving toward a more sustainable future.

SUMÁRIO

1 INTRODUÇÃO

Frutas e hortaliças desempenham um papel importante na nutrição e saúde humana, servindo como fontes de vitaminas, minerais, lipídios e fibras alimentares. Em contrapartida, são altamente perecíveis e estão propensas a alterações fisiológicas e bioquímicas devido a fatores ambientais (como temperatura, umidade e concentração de gases) e genéticos, condições pré-colheita, estádio de colheita, manejo, tratamentos pós-colheita e deterioração por fungos e bactérias. Apesar do desenvolvimento tecnológico, as perdas pós-colheita e os resíduos de frutas e hortaliças no mundo podem chegar a 50% a cada ano (Islam *et al*., 2017; Lurol *et al*., 2019; Pacifico *et al*., 2022).

Estas perdas pós-colheita resultam em uma limitação ao desenvolvimento da agricultura orgânica, baixa disponibilidade *per capita* e enormes perdas monetárias. Além disso, o desperdício de alimentos gera impactos ambientais devido ao uso intensivo dos recursos hídricos, exacerbação da perda de biodiversidade e emissões de gases do efeito estufa durante a produção dos alimentos. Consequentemente, aumentam os custos de transporte e comercialização e isso atua como um dos principais obstáculos para disponibilizar esses produtos nutritivos aos consumidores (Ahmad; Abubakar; Sale, 2020; Bayram *et al*., 2021; Elik *et al*., 2019; Singh; Sharma, 2018).

O mamão (*Carica papaya* L.) é uma fruta tropical apreciada mundialmente por apresentar sabor e aroma como características sensoriais únicas e uma importante fonte de vitaminas A, B, C, sais minerais e enzimas. Também contém carotenoides e compostos fenólicos, que atuam como antioxidantes, sendo uma cultura economicamente importante em muitos países (Ferreira *et al*., 2020; Monteiro *et al*., 2022; Polido; Pizato; Silva, 2021). Embora o mamão apresente um período de colheita relativamente longo, permitindo que esteja disponível durante todo o ano, o fruto também apresenta alta perecibilidade. A qualidade máxima do fruto é atingida no período de 6 a 12 dias dependendo do estádio de colheita. Isso pode ser associado ao seu elevado teor de umidade e atividade água, causando alterações físicas e químicas percebidas, principalmente, pelos consumidores, devido ao amolecimento da polpa e alterações na coloração da casca, resultando em perdas pós-colheita em toda a sua cadeia (Braga *et al*., 2020; Garcia *et al*., 2014; Germer *et al*., 2014).

Uma alternativa empregada para conservação pós-colheita de frutos é a secagem com ar quente por sua simplicidade e baixo custo, comparada a outros métodos de secagem. Este método visa remover a umidade dos alimentos e reduzir a atividade de água, sendo utilizado para diversos fins: aumentar a vida de prateleira, retardar a ação de enzimas, evitar o crescimento de microrganismos deteriorantes, modificar atributos sensoriais, reduzir os custos de embalagem, transporte e armazenamento. No entanto, os frutos submetidos à secagem em alta temperatura e longo tempo, apresentam degradação na sua qualidade provocando alterações na cor, aroma, conteúdo nutricional, capacidade de reidratação, perda de vitaminas, eliminação de compostos bioativos e mudanças indesejáveis de textura em produtos secos (Haneef *et al*., 2022; Prosapio; Norton, 2017; Silva *et al*., 2015).

A aplicação do etanol como pré-tratamento na secagem pode ser eficaz na modificação da estrutura das matrizes alimentares, alterando a espessura das paredes celulares e removendo o ar dos espaços intercelulares, o que resulta em alterações na pressão de vapor. O efeito Marangoni, induzido pela mistura de água com etanol, acelera o processo de secagem por meio da vaporização superficial da mistura, reduzindo o tempo de secagem e o custo energético (Silveira *et al*., 2024; Santos *et al*., 2023; Macedo *et al*., 2021).

Também se utiliza a desidratação osmótica por ser responsável pela remoção parcial de água de frutas e vegetais através da imersão destes em uma solução hipertônica de sal, açúcar ou um componente fisiológico ativo a uma determinada temperatura e tempo (Jiménez-Hernández *et al*., 2017; Rascón *et al*., 2018). Além disso, auxilia a manter a integridade celular, reduz a perda de compostos sensíveis ao calor, cor e sabor das frutas. Por outro lado, a desidratação osmótica tem algumas desvantagens, incluindo absorção excessiva de agente osmótico que pode resulta na textura cristalizada dos produtos e lixiviação de vitaminas, minerais e ácidos orgânicos solúveis em água durante o processo (Gulzar *et al*., 2018; Sakooei-Vayghan *et al*., 2020).

Ademais, a aplicação de revestimentos comestíveis nos alimentos antes da desidratação osmótica tem sido investigada como forma de minimizar a absorção de sólidos osmóticos. Os revestimentos comestíveis são camadas finas de um material digerível à base de lipídios, proteínas e polissacarídeos, que após a formação de um filme é aplicado diretamente na superfície do alimento, contribuindo assim para o prolongamento da vida útil dos frutos minimamente processados, fornecendo uma barreira semi permeável a gases e vapor de água, reduzindo a perda de umidade, as trocas gasosas, a respiração e a reação oxidativa e mantendo intacta a integridade estrutural do produto revestido (Nottagh *et al*., 2020; Oliveira; Silva, 2017; Silva *et al*., 2015).

Diante do exposto, o presente trabalho avaliará o processo combinado da aplicação de revestimento comestível, desidratação osmótica e imersão em etanol como pré-tratamentos à secagem convectiva e sua influência na qualidade de cubos de mamão seco.

2 REFERENCIAL TEÓRICO

2.1 A cultura do mamoeiro

O mamoeiro, de acordo com a classificação botânica, pertence ao reino *Plantae*, divisão *Magnoliophyta* (ou *Angiospermae*), classe *Magnoliopsida*, ordem *Brassicale*s e família *Caricaceae*, dividida em seis gêneros, com 35 espécies. Dos gêneros, destaca-se o *Carica* com a espécie *Carica papaya* L., que possui frutos comestíveis e de interesse comercial, por isso é a única com a qual se trabalha geneticamente (Kumar; Ps, 2017).

É uma planta herbácea, originária do continente americano, tendo sido descoberta pelos espanhóis na região compreendida entre o sul do México e as terras baixas da América Central, porém alguns historiadores discutem que devido a dispersão do gênero e a máxima diversidade genética seu local de origem localiza-se à noroeste da América do Sul, na Bacia Amazônica Superior (Serrano; Cattaneo, 2010).

Após a colonização espanhola das Américas, independente da sua localização de origem, sabe-se que o cultivo deste fruto tropical foi amplamente difundido em todo território nacional e em diversas regiões de clima tropical e subtropical, principalmente África e Ásia, no princípio por colonizadores espanhóis e, posteriormente, por navegadores portugueses e mercadores árabes (Oliveira *et al*. 2021).

No Brasil, historicamente, o cultivo do mamoeiro teve sua possível introdução em 1587, entretanto, com expressão comercial passou a ser registrado somente a partir da década de 1970, principalmente nos seguintes estados: Rio de Janeiro, São Paulo e Pará. Porém, em meados da década (1975-1976), teve a incidência de doenças causadas pelo vírus do mosaico, levando os produtores a erradicarem grande número de plantas e iniciar um processo migratório para outros locais do país (Ruggiero *et al*., 2003).

A cultura deslocou-se para os estados do Espírito Santo e da Bahia, sendo nas últimas décadas os principais estados brasileiros produtores de mamão contribuindo com 34,97% e 31,86% respectivamente na produção nacional da fruta. Também, é importante destacar o crescimento na participação dos estados do Ceará, Rio Grande do Norte e Minas Gerais que surgem como centros emergentes no cultivo do fruto no país como observado na Tabela 1. Em 2021, o Brasil produziu 1.256.703 toneladas de mamão, tornando-se um dos principais países produtores de mamão juntamente com Índia, México, Indonésia, República Dominicana e Nigéria.

Tabela 1 - Produção dos principais estados produtores de mamão no Brasil em 2018.

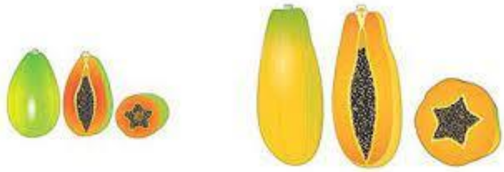
Estado	Produção (t)	Participação da produção (%)
Espírito Santo	439.550	34,97
Bahia	400.438	31,86
Ceará	140.979	11,22
Rio Grande do Norte	103.431	8,23
Minas Gerais	48.415	3,85
Outros	123.890	9,87
Brasil	**1.256.703**	**100,00**

Fonte: Adaptado de IBGE (2021).

Ademais, o mamão tornou-se um item importante na exportação agrícola para os países em desenvolvimento. Embora a maior parte da produção brasileira de mamão seja destinada ao mercado interno, o Brasil estabeleceu-se com o terceiro maior volume de exportação de mamão fresco com participação 39,1 mil toneladas (11%) de fruto exportado para mercado internacional, precedido apenas por México (44%) e Guatemala (16%). Neste sentido, é importante destacar que o México é o principal fornecedor dos Estados Unidos enquanto a produção brasileira tem como destino a União Europeia, sendo possível observar que ambos possuem um país fornecedor exclusivo, devido às limitações de transporte na pós-colheita (FAO, 2020).

Apesar da importância econômica do mamoeiro para a fruticultura brasileira, seu cultivo sustenta-se em uma estreita base genética, sendo o número de cultivares plantadas, nas principais regiões produtoras, bastante reduzido. As cultivares comercialmente mais exploradas no país estão classificadas em Solo e Formosa (Figura 1), são muito bem aceitos no mercado, tanto pelo sabor como pelos preços compensadores. No entanto, apresentam diferenças com relação aos padrões fenotípicos, às arquiteturas vegetais e às características morfológicas e físico-químicas (Moreira *et al*., 2018).

Figura 1 - Os principais cultivares comercializados no Brasil.



SOLO FORMOSA

Fonte: Adaptado de Fapesp (2010) citado por Oliveira *et al*. (2021).

O grupo "Formosa" é caracterizado por frutos comerciais que possuem polpa laranja-avermelhada, casca verde-clara e são alongados com peso variando de 1.000 a 1.300 g, possuindo um ciclo de maturação de 5 a 6 meses, após o início da floração. Além disso, apresentam alto teor de sólidos solúveis, facilidade para obtenção de sementes e grande estabilidade genética. Os cultivares mais populares deste grupo são: Tainung nº 1, Tainung nº 2 e Calimosa que são adequadas à comercialização no mercado interno, devido ao tamanho grande, falta de uniformidade de formato e tamanho, porém vêm conquistando espaço tanto no mercado internacional, no qual percebe-se um crescimento das exportações, principalmente para Europa, Canadá e Estados Unidos (Reis *et al*., 2015).

Os frutos do grupo “Solo” são cultivados em várias regiões do mundo sendo também conhecidos como “Papaya” ou “Havaí”, possuem polpa avermelhada, tamanho pequeno, com peso variável de 300 g a 650 g e alcançam maturação fisiológica em torno de 4 a 5 meses. Suas principais cultivares são: Sunrise Solo e Improved Sunrise Solo, as quais são geneticamente mais uniformes, possuem alto potencial de endogamia e maior resistência ao armazenamento sendo os preferidos no processo de exportação (Moro *et al*., 2012).

Tabela 2 - Composição química (por 100 g de parte comestível) do mamão dos grupos Formosa e Solo.

Variável	**Formosa**	**Solo**
Umidade (%)	86,9	88,6
Carboidratos (g)	11,6	10,4
Proteína (g)	0,8	0,5
Fibra alimentar (g)	1,8	1,0
Cinzas (g)	0,6	0,4
Magnésio (mg)	17	22
Ferro (mg)	0,2	0,2
Potássio (mg)	222	126
Cálcio (mg)	25	22
Vitamina C (mg)	78,5	82,2

Fonte: Adaptado de Lima *et al*. (2011).

O mamão destaca-se no mercado nacional e internacional de frutas tropicais devido às suas características sensoriais, nutricionais e terapêuticas que trazem benefícios à saúde. Conforme apresentado na Tabela 2, o fruto é rico em açúcares, possui boa concentração de fibras, cálcio, ferro, potássio, flavonóides, compostos fenólicos (miricetina, fisetina, morina, quercetina, kaempferol e isorametina) e compostos bioativos como os carotenóides (β-caroteno, licopeno e β-criptoxantina), polifenóis, vitaminas A, vitamina C e vitamina E, além de apresentar sabor e aroma agradáveis (Alara, O.; Abdurahman; Alara, J., 2022).

As pesquisas com relação às características do mamão mostram-se importantes por contribuírem diretamente para o aporte de nutrientes e de compostos bioativos na dieta, porém nota-se que a água é responsável por mais de 85% da composição da fruta (Tabela 2), elevando os níveis de atividade água, o que pode variar de acordo com os seguintes fatores: tipo de cultivar, clima, solo, localidade e época em que é produzido e o grau de maturação (Souza *et al*., 2009).

O mamoeiro é uma planta tipicamente tropical que apresenta um rápido crescimento e produz frutos de boa qualidade necessitando que suas regiões tenham luz solar direta por longos períodos durante todo ano, porém é importante ressaltar que existe uma maior disponibilidade nos meses de dezembro, janeiro e fevereiro, e menor oferta em junho e julho. O crescimento regular com o máximo do potencial genético de produção do fruto demanda pluviosidade de 1.800 mm a 2.000 mm anuais, com faixa ideal de temperaturas de 21 e 32 °C, umidade relativa entre 60% e 85%, o solo deve ter uma textura areno-argilosa, com pH de 5,5 a 6,7, quando devidamente adubado e a área escolhida pode ser desde o nível do mar até uma altitude de 1.000 metros (Alara, O.; Abdurahman; Alara, J., 2022; Rodrigues *et al*., 2021).

De modo geral, o momento ideal para realizar a colheita em culturas de mamão é quando a maturidade fisiológica é atingida, este processo exige que o pomar seja monitorado para verificar as mudanças na coloração da casca dos frutos para determinação do ponto de colheita. Mas a distância em relação ao mercado consumidor também pode influenciar no momento da colheita, pois os frutos destinados à exportação necessitam ser colhidos quando estiverem com a casca verde-clara, com a polpa laranja-avermelhada e as sementes escuras, com atenção para que não seja realizada a colheita de frutos imaturos. Por outro lado, os frutos designados para o comércio interno podem aguardar o surgimento de manchas amarelas na casca para sua colheita, visto que sua distribuição e comercialização acontecem de forma mais rápida (Faria *et al*., 2009).

Como mencionado anteriormente, as alterações da cor da casca são um ponto chave para determinação dos estádios de amadurecimento, que podem ser classificados considerando os critérios mencionados na Tabela 3.

Tabela 3 - Classificação do estádio de maturação do mamão.

Estádio de maturação		Maturação	Descrição
	0	Verde	Fruto desenvolvido com casca 100% verde
	1	Amadurecendo	Até 15% da superfície da casca amarela, rodeada de verde claro
	2	¼ madura	Entre 15 e 25% da superfície da casca amarela, com áreas próximas em verde-claro
	3	½ madura	Entre 25 e 50% da superfície da casca amarela, com áreas próximas em verde-claro
	4	¾ madura	Entre 50 e 75% da superfície da casca amarela, com áreas próximas em verde-claro
	5	Madura	Entre 75 a 100% da superfície da casca amarela, somente a extremidade do pedúnculo é verde

Fonte: Adaptado de Garillos-Manliguez e Chiang (2021).

Essa classificação mostra-se importante para o momento da colheita por interferir diretamente na qualidade dos frutos, já que os mamões colhidos no estádio de maturação adequado possuem melhores propriedades sensoriais (aroma e sabor) e físico-químicas (maciez da polpa e teor de sólidos solúveis) promovendo o prolongamento da sua vida útil. E além da mudança na cor da casca, o ponto para colheita do fruto leva em consideração as alterações no tamanho, no peso, no teor de sólidos solúveis e na acidez, visto que são transformações que também fazem parte da fase de maturação (Garillos-Manliguez; Chiang, 2021).

Apesar do seu alto valor nutricional e demanda no mercado, o mamão é uma fruta que devido ao seu comportamento climatérico, apresenta um ciclo de maturação muito rápido que após a colheita é caracterizado por uma série de atividades metabólicas, desencadeadas pelo aumento da taxa respiratória e a produção de etileno. Em determinado estádio de maturação, o mamão libera altas doses de etileno que se liga ao seu receptor na célula, para estimular o processo de amadurecimento e senescência dos frutos, causando alterações fisiológicas, químicas e físicas (Asmar *et al*., 2010; Maringgal *et al*., 2020).

Essas mudanças podem ser percebidas pelos consumidores através da perda de firmeza da polpa, das modificações na coloração da casca e da polpa devido a degradação da clorofila, da produção de compostos voláteis, da síntese de carotenóides, do aumento do teor de ácidos orgânicos e ácido ascórbico, o que resultam em curto prazo de vida útil, diminuindo resistência do fruto ao manejo e ao transporte, consequentemente, dificultando sua conservação, armazenamento e comercialização (Escamilla-García *et al*., 2018).

Dada essa alta perecibilidade, muitas pesquisas têm sido conduzidas visando prolongar a vida útil do mamão e minimizar os danos mecânicos, injúrias pelo frio ou altas temperaturas, doenças pós-colheita e perdas devido ao avançado estádio de maturação. Dessa forma, é importante que sejam adotadas tecnologias de conservação como: tratamento térmico, tratamento químico, pré-resfriamento, armazenamento refrigerado, armazenamento sob atmosfera modificada ou controlada, o uso de reguladores vegetais, a irradiação, entre outras (Kumari *et al*., 2017; Rodrigues *et al*., 2021).

Neste contexto, outra técnica antiga e amplamente utilizada pela indústria alimentícia que também têm se mostrado viável para a conservação do mamão é a secagem. Existem diferentes métodos de secagem: secagem solar, secagem com ar quente, secagem por radiação infravermelha, secagem a vácuo, secagem a vácuo por micro-ondas, liofilização, desidratação osmótica e desidratação osmótica assistida por ultrassom, independente do processo os atributos de qualidade do mamão são conservados e um aumento na vida útil é estabelecido, de forma que garante sua oferta no mercado nacional e internacional (Pacifico *et al*., 2022; Vega-Gálvez *et al*., 2021).

O consumo do mamão vai além da polpa, as demais partes do mamão também podem ser aproveitadas, as sementes são utilizadas como um aditivo na ração animal, as flores e folhas são consumidas como salada em países orientais, as raízes e a casca são exploradas como remédio e a papaína extraída do látex pode ser usada no processo de clarificação de cervejas e no amaciamento das carnes (Alara, O.; Abdurahman; Alara, J., 2022).

Deste modo, fica evidente que os problemas relativos à qualidade e a distribuição do mamão podem ser melhorados a partir do aproveitamento daquilo que não serve para o mercado de frutas frescas. Assim, a ciência e a tecnologia de alimentos sugerem que novos processos de industrialização podem ser uma alternativa, oferecendo a oportunidade de agregar valor ao produto final, reduzir as perdas e gerar empregos e renda (Germer *et al*., 2014).

Além disso, os produtos processados apresentam maior valor agregado, são mais práticos e convenientes. E apesar do mamão ser preferencialmente consumido *in natura*, existe uma alta demanda na indústria de alimentos para descobrir outras alternativas para seu consumo, como exemplo, a utilização da sua polpa na formulação de sucos, doces, patês, néctares, geléias, purês, licores, compotas, conservas, concentrados congelados e pedaços da fruta minimamente processados e desidratados (Bautista-Baños *et al*., 2013).

2.2 Secagem convectiva

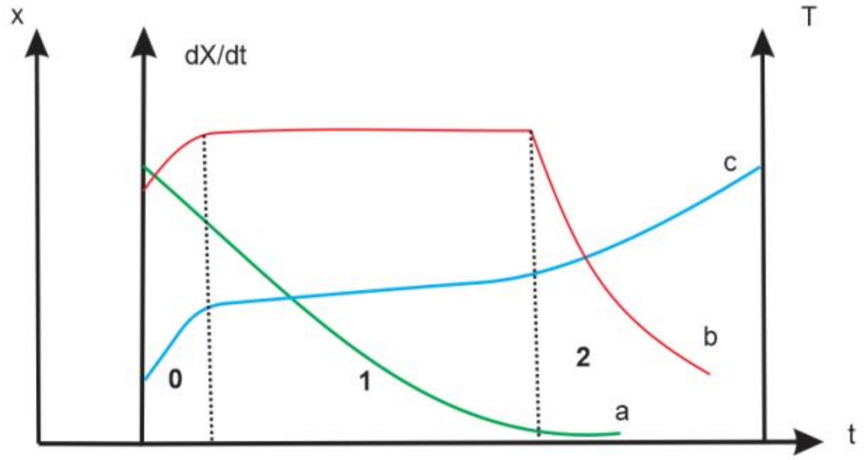
A secagem convectiva baseada no uso de ar quente é um dos métodos convencionais de conservação mais utilizados pela indústria de alimentos, principalmente para produtos altamente perecíveis, como frutas e hortaliças. A utilização da secagem permite a redução do teor de umidade o que contribui para o aumento da estabilidade, devido à redução da atividade de água, inibindo o crescimento de microrganismos e minimizando os processos de deterioração bioquímicos, químicos e microbiológicos. Outros benefícios estão associados a obtenção de produtos alimentícios com uma vida útil prolongada, novas formas de consumo, redução substancial do peso e volume do produto, diminuindo o custo de transporte e armazenamento (Kroehnke *et al*. 2021; Silva *et al.* 2016).

O princípio básico da secagem pode ser descrito como uma operação unitária onde a água ou outras substâncias voláteis líquidas presas dentro da estrutura microscópica de um material sólido são removidas na forma de vapor, através da aplicação de uma energia térmica com temperaturas inferiores à da ebulição. Neste processo, o ar quente desempenha duas funções principais: a função de fornecer calor sensível e latente para causar a evaporação da umidade, e atua como um gás de arraste, afastando o vapor de água formado da superfície de secagem, permitindo assim a evaporação (Adnouni *et al.*, 2022.)

Durante a secagem ocorre um processo de transporte simultâneo de calor e massa, acompanhado de mudança de fase, pois para que haja a evaporação de água da superfície do material, deve haver o seu transporte do interior do sólido até a superfície. Vários parâmetros afetam a velocidade deste transporte: pressão de vapor do material e do ar de secagem, temperatura e velocidade do ar, velocidade de difusão da água no material, espessura e superfície exposta para secagem. Além disso, as características específicas de cada produto determinam diversas condições da cinética de secagem (Rojas; Silveira; Augusto, 2019).

Deste modo, a cinética de secagem pode ser acompanhada através da obtenção dos dados experimentais que relacionam em geral o conteúdo de umidade com o tempo. Com base nos fenômenos de transferência de calor e de massa, as curvas características do processo de secagem podem ser subdivididas em três períodos, conforme representados na Figura 2.

Figura 2 - Curvas típicas de evolução da temperatura e da umidade do produto durante a secagem em função do tempo.



Legenda: A evolução temporal da umidade (x), da taxa de secagem (dX/dt) e da temperatura (T) do produto em função do tempo (t), para um processo utilizando ar com propriedades constantes.

Fonte: Adaptado de Park *et al*. (2007).

A curva que acompanha a evolução do conteúdo de umidade é representada por (a) e representa a diminuição do teor de umidade do produto em relação ao tempo, durante o processo de secagem. A curva (b) mostra a cinética de secagem do produto, isto significa, a variação do conteúdo de umidade do produto por tempo. A evolução de temperatura do produto representa a variação da temperatura da amostra com o tempo, sendo este processo demonstrado pela curva (c) (Park *et al*., 2007).

O início do processo de secagem é representado na Figura 2 através da região 0, conhecido como período de indução, no qual ocorre a adequação do produto que se encontra em uma temperatura inferior ao ar de secagem e da pressão parcial de vapor de água na superfície do produto é baixa até atingir o equilíbrio. Consequentemente, a transferência de massa e a taxa de secagem também são baixas. À medida que o ar entra em contato com o produto, inicia-se uma elevação gradual da sua temperatura, havendo uma elevação na pressão de vapor de água e na taxa de secagem. Esse processo de ajuste continua até que a transferência de calor seja equivalente à transferência de massa, sendo que a duração deste período é insignificante em relação ao período total de secagem (Yao *et al*., 2022).

O segundo período (região 1) caracteriza-se pela taxa constante de secagem, pois a temperatura da superfície alcança a temperatura de bulbo úmido, de modo que a perda de calor devido a evaporação seja igual ao calor fornecido pelo ar. Nesta etapa, o alimento contém grande quantidade de água disponível para evaporação, como água livre presente na superfície do material, renovada por movimento capilar ou por forças capilares desde as zonas internas do alimento. A taxa de evaporação é diretamente dependente da transferência do calor e massa fornecida para o material que está sendo seco, portanto, a taxa de secagem é 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 (De Lima *et al*., 2016).

O terceiro período é descrito na região 2 onde a transferência de calor não é mais compensada pela transferência de massa pois a quantidade de água do alimento presente na superfície diminui. Como consequência, quando o teor de umidade do alimento cai além do teor crítico, a velocidade de secagem começa a decrescer e a temperatura do material aumenta, atingindo a temperatura do ar de secagem. Portanto, a migração interna da umidade é o mecanismo que governa esta fase. Esse período é conhecido como o período de taxa decrescente, quando o produto atinge o ponto de umidade de equilíbrio em relação ao ar de secagem, a taxa de secagem tende a zero e o processo é encerrado (Yao *et al*., 2022).

No processo da secagem, após a obtenção das curvas e da caracterização dos períodos de secagem, existe uma dificuldade em descrever os fenômenos de transferência de calor e massa sendo necessário a utilização de modelos matemáticos para ajustar a evolução do teor de umidade com o tempo (Moura *et al*. 2021).

De acordo com Perry (1984) esses modelos podem ser categorizados como teóricos, semi-empíricos e empíricos. Os modelos teóricos consideram os diferentes mecanismos de transporte de umidade e consistem na solução das equações da transferência de massa e de calor no material. Os modelos semi-empíricos levam em conta a transferência de massa e admitem o processo como isotérmico. Já os modelos empíricos são amplamente usados para a obtenção da cinética de secagem, resultando em equações ajustadas com dados experimentais que descrevem de modo simples a umidade do material com o tempo para condições específicas do processo de secagem.

O modelo teórico mais comumente utilizado segundo Silva *et al*. (2016) é a segunda lei de difusão de Fick, que tem sido usada com sucesso para descrever a cinética de secagem de alguns produtos alimentícios. Sendo utilizado os dados experimentais, incluindo as características físicas ou geométricas, na tentativa de solucionar a equação dos fenômenos de transporte utilizando amostras com geometria conhecida, como cubos, cilindros ou fatias.

Conforme apresentado na Tabela 4, existem diversos modelos empíricos propostos pela literatura que utilizam as informações sobre as propriedades termofísicas do alimento como uma ferramenta para melhorar os processos e minimizar problemas como danos ao produto, consumo excessivo de energia, desgaste excessivo dos equipamentos de secagem e diminuição de rendimentos.

Tabela 4 - Modelos empíricos utilizados no ajuste das cinéticas de secagem.

Modelo	Equação matemática	Referências
Henderson e Pabis	$MR = a.exp(-k.t)$	Henderson e Pabis (1961)
Logaritmo	$MR = a.exp(-k.t) + c$	Yagcioglu (1999)
Midilli	$MR = a.exp(-k.t^n) + b.t$	Midilli *et al.* (2002)
Newton	$MR = exp(-k.t)$	Nellist (1987)
Page	$MR = exp(-k.t^n)$	Roberts *et al.* (2008)
Page modificado	$MR = exp[(-k.t)^n]$	Togrul (2006)
Wang e Singh	$MR = 1 + at + b.(t^2)$	Wang e Singh (1978)

Legenda: MR - razão de umidade do produto (adimensional); t - tempo de secagem (min); k - constantes de secagem (h^{-1}); a, b, c e n - são coeficientes dos modelos.

Fonte: Do autor (2022).

Assim sendo, a utilização da modelagem é necessária por se tratar de processamento térmico com uso de temperaturas de secagem elevadas e longos tempos de processo, a secagem convectiva implica em alterações prejudiciais aos atributos de qualidade. Existem alguns inconvenientes relacionados às alterações indesejáveis de cor e sabor, encolhimento, deformações e textura rígida, devido à formação de uma crosta na superfície do produto pelo ressecamento. Além disso, pode-se promover degradação fenólica total, redução da atividade antioxidante e perda de nutrientes (Kroehnke *et al*. 2021; Rojas; Silveira; Augusto, 2019).

2.3 Etanol

O etanol, também conhecido como álcool etílico, é um solvente orgânico com fórmula molecular CH_3-CH_2-OH. Pertence à família dos álcoois e tem ponto de ebulição de 78°C. A Food and Drug Administration (FDA) classifica o etanol como uma substância GRAS (geralmente reconhecida como segura), o que significa que é geralmente considerado seguro para consumo humano em certas concentrações e condições. Além disso, o etanol é econômico em comparação com outros solventes, tornando-o uma opção viável para processos industriais em larga escala (De Arruda *et al*., 2023; Santos *et al*., 2023; Macedo *et al*., 2021).

A adição de etanol reduz o calor de vaporização da água presente nos alimentos devido à formação de uma mistura água e etanol. Como resultado, a rápida evaporação do etanol e das misturas etanol e água cria canais de fluxo e poros nos alimentos, promovendo o movimento da água pura de dentro do produto para o ar seco. Portanto, o uso de etanol pode remover efetivamente a umidade dos produtos alimentícios devido à sua capacidade de reduzir a atividade da água. Isto é essencial para a preservação dos alimentos, pois inibe o crescimento microbiano e a deterioração química (Santos *et al*., 2023; Junqueira *et al*., 2021; Guedes *et al*., 2021).

Outro comportamento observado é o efeito Marangoni que promove a transferência de massa na interface entre dois fluidos com diferentes tensões superficiais. Isso ocorre, pois, a água tem uma tensão superficial maior que o etanol. Sendo assim, espera-se que em alimentos pré-tratados com etanol, os gradientes de tensão superficial causem maior deslocamento de água à medida que o etanol evapora primeiro. Além disso, o etanol aumenta a permeabilidade das paredes celulares dos alimentos, tanto no sentido de desidratação quanto de reidratação, uma vez que o uso do etanol provoca alterações nos tecidos que promovem a dissolução e desintegração dos compostos da parede celular (Wang *et al*., 2019; Corrêa *et al*., 2012).

Silveira *et al.* (2024) realizaram uma investigação sobre o impacto do etanol e da temperatura (50 °C e 70 °C) nos parâmetros de qualidade e cinética de secagem de fatias de yacon. O uso do etanol promoveu a redução do tempo de secagem (até 28,00%) e no consumo de energia (até 22,72%). Além disso, preservou a atividade antioxidante, teor de fenólicos e retenção de frutanos, com destaque para os tratamentos realizados a 50 ºC com pré-tratamento de etanol.

Macedo *et al*. (2021) também avaliou o uso do etanol como pré-tratamento no processo de secagem de cubos de morango. E concluiu que a utilização do etanol é um procedimento interessante para ser aplicado na secagem convectiva de morangos. Embora tenha aumentado o encolhimento das amostras, também reduziu a higroscopicidade e o tempo de secagem em até 30%. Além disso, contribuiu para a preservação dos teores de antocianinas totais e fenólicos totais, e capacidade antioxidante, parâmetros importantes para garantir a qualidade do fruto.

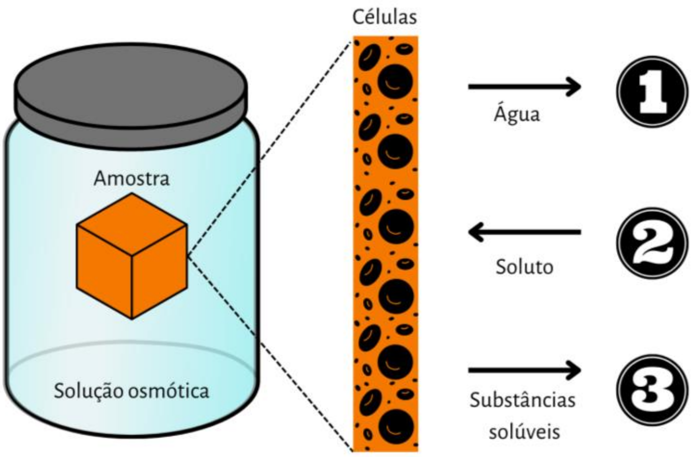
2.4 Desidratação osmótica (DO)

A desidratação osmótica pode ser aplicada como pré-tratamento para superar os efeitos indesejáveis da secagem convectiva. Devido ao baixo consumo de energia, é um método simples e de baixo custo que consiste na imersão do alimento em uma solução hipertônica, para reduzir parcialmente o teor de umidade e aumentar o teor de sólidos solúveis por meio de fluxos simultâneos, que se estendem da superfície do produto até o centro do material alimentar devido à diferença de pressão osmótica entre o alimento e a solução. Além de induzir a troca de água e solutos, o processo oferece a possibilidade de preservar as propriedades estruturais, nutricionais, sensoriais e outras funcionais da matriz alimentar (Etemadi; Alizadeh; Sirousazar, 2020).

No início do processo, a matéria-prima é colocada em soluções concentradas, normalmente de açúcares, sais ou um componente fisiológico ativo, com maior pressão osmótica e menor atividade de água. Em seguida, como consequência da sua diferença de gradiente com a solução, a primeira camada de células do material começa a perder água, ocasionando uma retração tecidual na camada. Depois que as células da primeira camada se encolhem, é estabelecida uma diferença de potencial químico da água entre a primeira e a segunda camada de células (Kaur et al., 2022).

Posteriormente, a água contida nas células da segunda camada começa a ser bombeada para as células da primeira camada e depois também encolhem. Os fenômenos de transferência de massa (Figura 3) e retração tecidual acontecem desde a superfície até o centro do material em função do tempo de operação. O processo finaliza quando a diferença entre as pressões osmóticas é quase zero, caracterizando o estado de equilíbrio osmótico (Kaur et al., 2022).

Figura 3 - Transferência de massa durante a desidratação osmótica entre solução e produto.



Fonte: Do autor (2022).

Como esquematizado na Figura 3, este método resulta em três fluxos de transferência de massa em contracorrente. O primeiro fluxo (1) representa a água que difunde do produto para a solução, havendo uma taxa de transferência mais rápida inicialmente e lentamente depois. O outro fluxo (2) refere-se a uma transferência de soluto que ocorre da solução osmótica para o produto, sendo necessário controlar a quantidade que é incorporado pois o excesso no ganho de solutos pela amostra pode causar malefícios ao alimento. Por outro lado, pode ser uma possibilidade de introduzir um princípio ativo de interesse nutricional ou uma melhoria da qualidade sensorial do produto final. Também ocorre a lixiviação de substâncias solúveis: açúcares, ácidos orgânicos, minerais, vitaminas, entre outros compostos, sendo esse o terceiro fluxo (3) que é quantitativamente desprezível, mas pode resultar em mudanças significativas qualitativamente (Abrahão; Corrêa, 2023).

Durante a desidratação osmótica de frutas e vegetais, os mecanismos de transferência de massa são afetados por vários parâmetros de controle de taxa, como características físico-químicas da matriz alimentar, composição e concentração do agente osmótico e as condições do processo: tempo de imersão, velocidade de agitação e temperatura (González-Pérez; Ramírez-Corona; López-Malo, 2021).

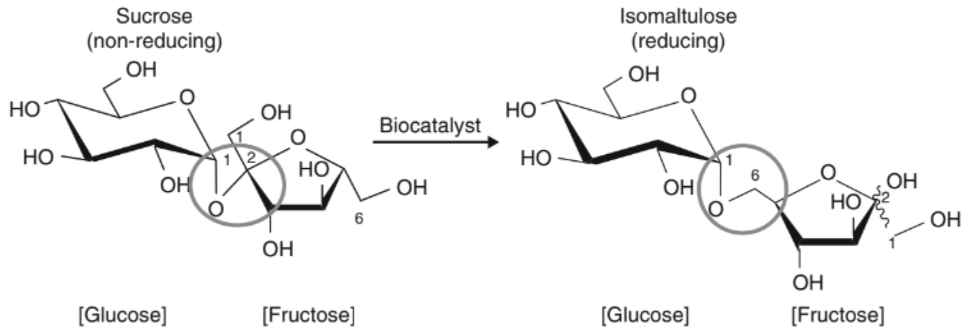
A escolha das condições ótimas para cada fator de processo depende das características desejadas do produto osmodesidratado no estado de equilíbrio. A exemplo disso, a seleção do soluto para o processo osmótico deve levar em consideração as suas propriedades físico-químicas: peso molecular, estado iônico e solubilidade do soluto em água pois estas características determinam a taxa de difusão que é responsável pela eficiência da desidratação (Ramya; Jain, 2017; Vieira; Pereira; Hubinger, 2012).

Geralmente, os agentes osmóticos de baixo peso molecular favorecem o processo de impregnação nas células de frutas e vegetais, enquanto o soluto de alto peso molecular é útil para efeitos de desaguamento. Outra característica importante está relacionada ao tamanho das moléculas de soluto, pois é inversamente proporcional a taxa de penetração e diretamente associada à concentração da solução (Ramya; Jain, 2017).

Dentre os diversos solutos que podem ser empregados em soluções osmóticas o principal é a sacarose, devido ao seu baixo custo e disponibilidade. Trata-se de um carboidrato que é rapidamente digerido, induzindo uma alta resposta glicêmica e insulinêmica (Do Carmo *et al*., 2022). Porém, sua aplicação como soluto osmótico tem como malefício a sua absorção excessiva, pois confere aos produtos textura cristalizada e doçura, o que pode levar o produto alimentício a ser rejeitado pelo consumidor. Uma forma de contornar esses aspectos negativos é combinar a desidratação osmótica com outras técnicas como a aplicação de revestimentos comestíveis, que permite controlar a difusão do agente osmótico no produto ou substituir a sacarose por outros carboidratos (Rodriguez; Soteras; Campañone, 2021).

Uma alternativa é a utilização da isomaltulose, um dissacarídeo redutor composto de glicose e frutose unidos por ligação glicosídica do tipo α-1,6 presente de forma natural no mel e na cana-de-açúcar, incluindo produtos derivados, como melaço, mesmo que em pequena quantidade. Também sendo possível ser obtida comercialmente por meio de um processo enzimático a partir da sacarose (Figura 4), sendo conhecida como Palatinose®. O interesse recente pela isomaltulose acontece devido ao baixo índice glicêmico, minimizando os picos glicêmicos e a produção de insulina. Além disso, é um carboidrato não cariogênico, contribuindo para a saúde bucal (Sawale *et al*., 2017; Shyam; Ramadas; Chang, 2018).

Figura 4 - Rearranjo enzimático da sacarose em isomaltulose (fórmulas estruturais).



Fonte: Sawale *et al*. (2017).

Em razão disso, esse dissacarídeo vem sendo cada vez mais utilizado por desportistas e pessoas diabéticas, obesas e cardiopatas. Nesse sentido, a isomaltulose pode ser impregnada em frutas por desidratação osmótica e produtos industriais de panificação, confeitaria e bebidas esportivas, como uma estratégia para enriquecimento e obtenção de um produto saudável e funcional (Do Carmo *et al*., 2022). Em comparação com a sacarose, a isomaltulose possui valor calórico similar (~4 kcal/g) e menor solubilidade, higroscopicidade e poder adoçante, sendo considerada um adoçante saudável sendo digerida mais lentamente pela α-glicosidase no intestino delgado do que a sacarose (Macedo *et al*., 2022a).

De acordo com o estudo apresentado por Kim *et al*. (2018) sobre a aplicabilidade da isomaltulose como substituto da sacarose na extração osmótica de suco de ameixa *(Prunus mume*). Eles determinaram que o suco extraído pela isomaltulose apresentou valores de pH e acidez titulável semelhantes aos dos demais açúcares. A capacidade de eliminação de radicais do suco de ameixa extraído por isomaltulose foi significativamente maior do que em sucos extraídos por outros açúcares, assim como o teor de polifenóis do suco.

Além disso, eles avaliaram os benefícios para a saúde do suco preparado por extração usando isomaltulose, medindo as alterações de glicose no sangue após a ingestão do suco. declararam que o nível de glicose foi aumentando lentamente em comparação com o suco que utilizou a sacarose como agente osmótico. Portanto, o uso de isomaltulose na fabricação do suco de ameixa auxiliou na redução da ingestão de açúcar.

O agente osmótico também foi destacado por Rubio-Arraez *et al*. (2015) visto que no trabalho a isomaltulose originou os maiores valores de perda de massa nas fatias de limão osmodesidratados, em contraste ao efeito de diferentes combinações de tagatose, oligofrutose e estévia no comportamento cinético de fatias de limão a fim de obter modelos matemáticos usando novos adoçantes.

Outro fator é a concentração da solução que desempenha um papel importante nos processos de DO, pois tem efeito nas propriedades organolépticas, solubilidade do soluto e na permeabilidade da membrana celular. Estudos indicam que quanto maior a concentração da solução resulta em maior perda de água, ganho de soluto e a necessidade de mais tempo para atingir o estágio de equilíbrio. Além disso, observa-se que as soluções osmóticas, principalmente de NaCl e sacarose, ficam mais viscosas dificultando a penetração dos solutos na matriz alimentar (González-Pérez; Ramírez-Corona; López-Malo, 2021).

Além da comprovada influência do tipo de soluto e sua concentração na desidratação, o tempo de imersão é outro aspecto relevante. A taxa de transferência de massa é mais intensa nas fases iniciais do processo osmótico, tendendo a diminuir gradualmente com o tempo, até que o equilíbrio seja alcançado. Nos primeiros minutos de processo osmótico, a rápida perda de água e ganho de soluto é resultante da grande força motriz entre a solução hipertônica e o conteúdo celular. Com a progressão do tempo, a membrana celular vai sofrendo modificações e assim, passa a não fornecer barreira efetiva ao soluto e a diferença no conteúdo de água entre o alimento e a solução osmótica diminui, causando redução na velocidade do processo osmótico (Ahmed; Qazi; Jamal, 2016).

O uso de agitação durante o processo pode garantir a minimização ou eliminação da resistência à transferência de massa do lado do líquido e melhorar isso mantendo a solução homogênea no contato entre produto e solução. A utilização de soluções de açúcares viscosos altamente concentrados gera grandes problemas como a flutuação de pedaços de alimentos, dificultando o contato entre o material alimentar e a solução osmótica, causando uma redução nas taxas de transferência de massa. Assim, para aumentar a transferência de massa e evitar a formação de um filme de solução diluída ao redor das amostras, o processo de agitação pode ser aplicado durante a desidratação osmótica (González-Pérez; Ramírez-Corona; López-Malo, 2021).

A temperatura é um parâmetro que afeta o fenômeno de difusão durante a desidratação osmótica. De acordo com alguns estudos, amostras colocadas em temperaturas de solução elevadas proporcionam uma perda de água e ganho de sólidos mais eficiente por pressão osmótica, isso ocorre devido ao aumento na taxa de difusão. Além disso, à medida que a temperatura aumenta, a viscosidade da solução diminui, a permeabilidade e seletividade da parede diminuem e a lixiviação dos compostos naturais é favorecida por conta do colapso causado na estrutura celular do alimento. No entanto, altas temperaturas podem afetar a cor, a textura e o sabor interferindo negativamente na qualidade do produto (Mokhtarian *et al*., 2014).

A influência deste parâmetro pode ser observada no estudo de Pekoslawska e Lenart (2008) sobre os fenômenos ocorridos durante a desidratação da abóbora utilizando como agente osmótico uma solução de xarope de amido. Determinaram que quanto maior a temperatura e a concentração utilizada, maior a eficiência do processo. Ambos os fatores afetam essencialmente a cinética de troca de massa durante o processo osmótico de desidratação.

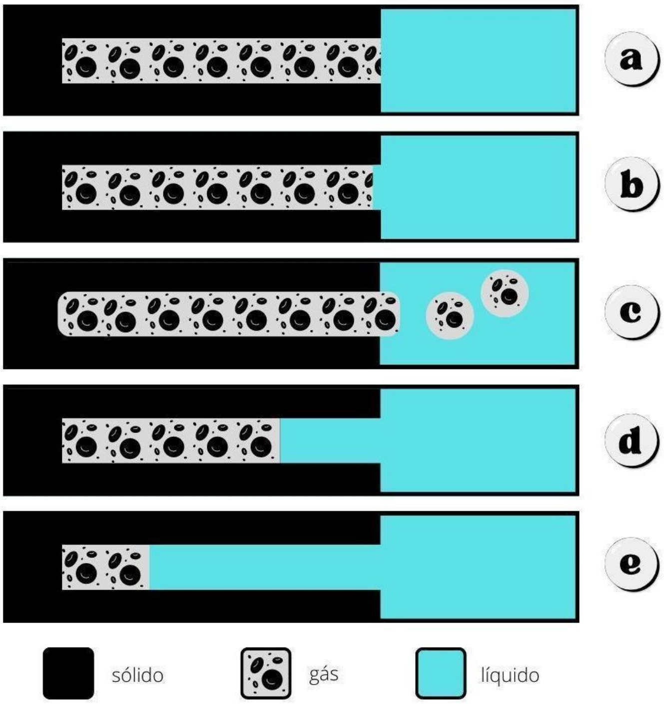
Por fim, é importante ressaltar que no processo de DO pode acarretar a perda de alguns compostos bioativos do alimento e ganho de sólidos elevado, afetando o perfil nutricional do alimento. Outro problema é o tratamento da solução de desidratação osmótica que ainda não possui um aproveitamento específico e geralmente é usada em grandes proporções de fruta:solução. Essas soluções, que possuem altas concentrações de sólidos, têm custo elevado e ocasionam um problema quanto a sua reutilização pela dificuldade de controle do processo. No entanto, estudos têm sido realizados com a finalidade de reuso da solução osmótica ou de separação de compostos extraídos do alimento (Egea; Lobato, 2014).

2.5 Desidratação osmótica com pulso de vácuo (PVOD)

Como a desidratação osmótica é um processo lento, pesquisas são direcionadas ao aumento das taxas de transferência de massa, uma vez que a membrana celular do material alimentar de origem vegetal possui alta resistência ao processo de desidratação. Diversas técnicas como: pulsos de campo elétrico de alta intensidade, aplicação de ultrassom e pulso de vácuo, podem ser combinadas com DO, visando maximizar o rendimento e a eficiência, além de reduzir o tempo e o custo energético necessário para a finalização do processo (Junqueira *et al*., 2018; Ramallo; Hubinger; Mascheroni 2013).

A aplicação do pulso de vácuo é usualmente chamada de desidratação osmótica com pulso de vácuo (PVOD) o que implica uma redução na pressão do sistema no início do processo, para a retirada de parte dos gases presentes no interior dos poros do alimento. Em seguida, ao restaurar a pressão atmosférica, ocorre a penetração da solução osmótica pela estrutura porosa formada, aumentando a área de contato disponível para transferência de massa devido à diferença de pressão (Ito, 2007; Corrêa et al., 2010). A Figura 5 ilustra o efeito do pulso de vácuo durante a desidratação osmótica.

Figura 5 - Representação do efeito da aplicação de pulso de vácuo na DO.



Fonte: Adaptado de Fito (1994).

No primeiro estágio (A), representado na Figura 5, o processo encontra-se sob pressão atmosférica, tendo início de aplicação do pulso de vácuo no estágio subsequente (B). Nos estágios C e D observa-se os espaços intercelulares dentro dos poros do alimento sendo expandidos por capilaridade e os gases sendo liberados. No último estágio (E) ao se restabelecer a pressão atmosférica do sistema, o líquido que se encontra em contato com o alimento penetra o interior dos poros. O aumento da área superficial entre o alimento e a solução osmótica favorece a remoção de água e a incorporação de solutos (Fito, 1994).

O estudo com aplicação de vácuo em morangos de Macedo *et al*. (2022b) relatou que houve aumento nas taxas de transferência de massa, resultando em um menor teor de umidade e atividade de água e maior ganho de sólidos, perda de água, redução de peso e encolhimento. Além disso, houve uma perda significativa de antocianinas em todos os seus tratamentos principalmente quando aplicado o processo a vácuo, o que influenciou diretamente na coloração do morango.

De Mello Jr. *et al*. (2019) em seu trabalho com figos verdes cortados transversalmente relataram que as amostras apresentam maior estabilidade após a aplicação do PVOD devido à perda de água, aumentando a qualidade das amostras e consequentemente dos futuros coprodutos, podendo ser mais eficaz quando aplicada como pré-tratamento à secagem convencional.

Comportamento semelhante também foi descrito por Corrêa *et al*. (2021) que investigaram a influência da desidratação osmótica a vácuo pulsado com sorbitol como pré-tratamento na secagem convectiva de yacon. Eles observaram que existem perspectivas adequadas para uso industrial, pois as amostras apresentaram menor atividade de água e menor retração do que a secagem convectiva sem pré-tratamento.

2.6 Revestimento comestível

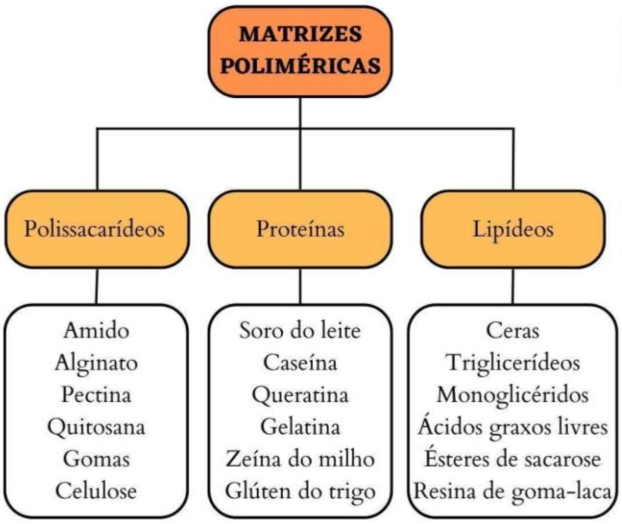
Segundo Ortiz, Vicente e Mauri (2014) os revestimentos podem ser considerados tanto uma embalagem quanto um componente alimentício, que ao longo dos séculos tiveram suas aplicações refinadas. Atualmente, a utilização de filmes e revestimentos comestíveis como uma tecnologia de preservação tem se tornado promissora como uma alternativa para minimizar as perdas, manter a qualidade sensorial e prolongar a vida útil de frutas e vegetais, tanto *in natura* (inteiros) como minimamente processados, durante o período pós-colheita.

Embora, revestimentos e filmes comestíveis sejam termos amplamente empregados na área de alimentos para descrever a adição ou substituição das coberturas cerosas de frutas, ambos têm conotações específicas. O termo revestimento (ou cobertura) consiste em uma fina camada de material comestível aplicada diretamente à superfície de um alimento que após secagem leva à formação de um filme. Enquanto, o termo filme é uma película formada pela secagem da solução do biopolímero preparada previamente que em seguida é sobreposta ao produto alimentício (Barboza *et al*., 2022.).

Os revestimentos podem ser aplicados por imersão ou pulverização da solução na superfície do alimento, portanto, precisam ser naturais e seguros para consumo. Os principais componentes utilizados com base para o seu desenvolvimento são os polissacarídeos, proteínas e lipídeos (Nottagh *et al*., 2020), conforme representado na Figura 6.

Polissacarídeos são materiais que devido à sua natureza hidrofílica, apresentam elevada afinidade por água, o que está associado a predominância de grupos amino ou hidroxila e carboxila em suas estruturas. Os grupos amino ocorrem por ligações covalentes (R-N-H), onde a eletronegatividade das ligações gera sítios de elevada polaridade. Essa característica da estrutura química favorece o rearranjo e o acúmulo de moléculas de água em torno desses sítios. Os componentes hidrofílicos geralmente são uma boa barreira contra CO_2 e O_2 e podem efetivamente diminuir a taxa de respiração dos frutos climatéricos e a oxidação dos frutos oleosos. Além disso, apresenta eficientes propriedades mecânicas de água, favorecendo uma melhor dispersão do soluto e uma formação mais homogênea do filme (Assis; Britto, 2014; Chiumarelli; Hubinger, 2014).

Figura 6 - Resumo dos principais componentes de filmes e revestimentos comestíveis.



Fonte: Adaptado de Salgado *et al*. (2015).

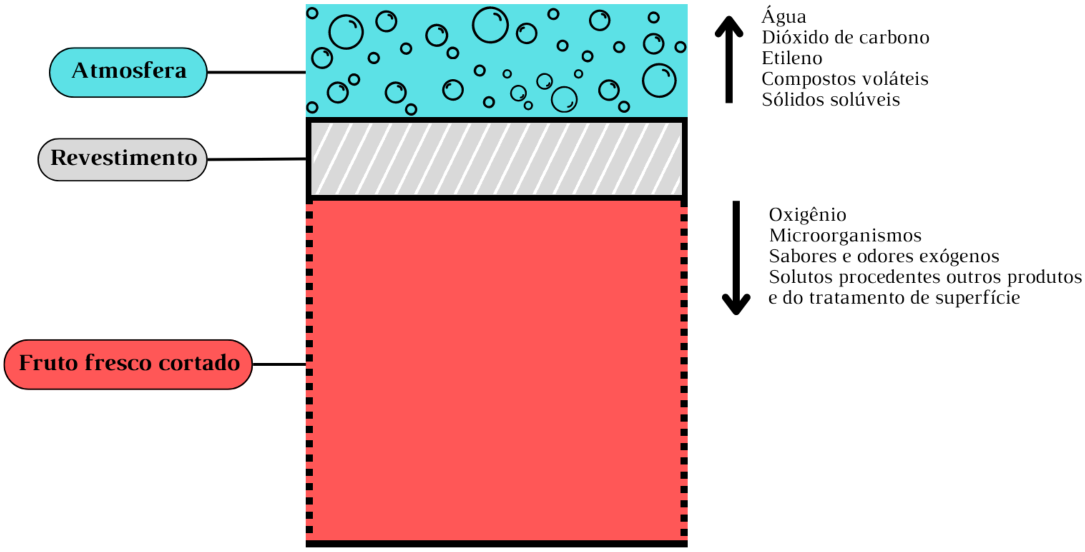
Por outro lado, os filmes à base de lipídios ou proteínas agem como barreiras efetivas para o vapor de água, umidade, oxigênio, dióxido de carbono, óleos e demais compostos voláteis, atuando eficientemente contra a deterioração natural. Porém, há quase sempre a necessidade da adição de plastificantes por não apresentarem resistência estrutural e durabilidade quando utilizadas isoladamente. Estes materiais na presença de água tendem a se aglomerar e excluir as moléculas polares de sua volta, isso ocorre devido à presença de estruturas dos grupos alquilas e aromáticos cujas ligações tendem a ser eletricamente neutras, caracterizando-se como regiões apolares (Carrasco; Gandra; Chim, 2019).

As soluções filmogênicas hidrofílicas ou hidrofóbicas podem ser adicionadas de aditivos alimentares para modificarem as propriedades físico-químicas ou outras funcionalidades dos revestimentos. Um exemplo são os plastificantes, como glicerol, são substâncias não voláteis de baixo peso molecular que afetam a capacidade do sistema de proteínas plastificadas atrair água e também de reduzir as ligações de hidrogênio internas entre as cadeias poliméricas (Sharifimehr; Soltanizadeh; Goli, 2019).

Além disso, os plastificantes de acordo com sua composição, tamanho e forma podem atuar como facilitadores no processo de obtenção do filme menos frágil e mais flexível, aumentando o espaçamento intermolecular e reduzindo as escamações e rachaduras. Por outro lado, influenciam no aumento da permeabilidade do filme ao oxigênio e à transmissão de umidade, ocasionando a maior permeabilidade à água (Zhang *et al.*, 2022).

Conforme Grande-Tovar *et al*. (2018) esses materiais devem ser escolhidos de acordo com a espessura, permeabilidade e homogeneidade dos filmes produzidos e devem atender a alguns requisitos específicos: alta barreira contra gases ou vapores, não toxicidade, estabilidade microbiana e fornecer proteção estrutural para evitar danos mecânicos, bioquímicos, físico-químicas durante o transporte, manuseio e exposição. Também deve ter bons atributos sensoriais e uma tecnologia simples e baixo custo de matéria-prima e processamento. Essas funções mais comuns dos filmes e coberturas comestíveis são descritas na Figura 7.

Figura 7 - Fenômenos de transporte entre superfícies frescas e o ambiente externo.



Fonte: Adaptado de Ferreira (2008).

Na Figura 7 é representado um fruto fresco cortado e recoberto por uma cutícula constituída de material lipídico em formato de camadas. Na camada externa existe a presença de microporos que podem ser permeáveis com a aplicação de revestimentos e também existem aberturas maiores, como estômatos e lenticelas, que permitem uma maior troca gasosa com o ambiente, caracterizando assim a respiração (trocas gasosas) e a transpiração (transferência de umidade), afetando os fenômenos de transporte entre a superfície fresca dos frutos e hortaliças e o ambiente externo (Assis; Britto, 2014).

Estudos têm sido desenvolvidos a fim de investigar a aplicação de coberturas de alimentos com um pré-tratamento para a secagem com objetivo de proteger contra a oxidação dos compostos ativos e preservar as propriedades sensoriais e nutricionais do produto final. A influência de dois revestimentos comestíveis um com isolado de proteína de soro de leite (WPI)

+ goma de alfarroba (LBG) e outro com pectina foram estudados por Silva *et al*. (2015) no processo de secagem em ar quente a 60 e 70 °C de fatias de abacaxi. Os resultados mostraram que o pré-tratamento com revestimentos de pectina e WPI-LBG não afetaram o comportamento de secagem das amostras e ambos os revestimentos foram eficazes na retenção de vitamina C durante a secagem com ar quente.

Também tem se revelado efetivo para impedir a absorção de sólidos durante a desidratação osmótica sem afetar a remoção de água quanto para neutralizar o amolecimento dos tecidos causado pela pressão osmótica excessiva. Esse comportamento foi investigado por Etemadi, Alizadeh e Sirousazar (2020) no seu estudo com goma de semente de manjericão como revestimento em rodelas de maçã no processo de desidratação osmótica com sacarose em diferentes concentrações e temperaturas de solução. Nesta pesquisa, as amostras revestidas com solução de goma de semente de manjericão a 0,3% em peso indicaram os melhores resultados com absorção de sacarose 18% menor em comparação com as maçãs não revestidas.

No trabalho realizado por Haneef *et al*. (2022) as fatias de manga foram previamente revestidas por uma solução de aloe-pectina e desidratados osmoticamente por imersão em solução de sacarose para realização de uma secagem final com ar quente. Os resultados concluíram que durante o armazenamento de 4 meses, as amostras revestidas mantiveram melhores parâmetros de microestrutura, textura e cor em comparação com as amostras de controle. Sendo assim, o revestimento de aloe-pectina definiu-se como uma boa barreira de evaporação de umidade dentro das amostras durante o armazenamento e resultou em textura comparativamente mais macia.

3 CONSIDERAÇÕES GERAIS

O mamão é um fruto com alta perecibilidade que exige o uso de métodos de processamento, visando prolongar sua vida útil e também preservar os parâmetros qualitativos do produto. A secagem é uma alternativa eficiente para a conservação, bem como para a disponibilidade de alimentos em períodos de entressafra. Porém, este processo é, usualmente, acompanhado de degradações físicas, químicas e nutricionais com relação ao produto fresco. Para a minimização destas perdas, devem-se buscar novas alternativas, como o uso de um revestimento comestível que atua como uma barreira ao oxigênio e ao dióxido de carbono, mas uma barreira pobre à água e, assim, ajuda a reter o aroma e o sabor dos alimentos, fortalecendo a integridade celular para suportar a pressão osmótica excessiva.

Neste mesmo contexto, a desidratação osmótica pode ser utilizada para ajudar a manter a integridade celular, reduzir a perda de compostos sensíveis ao calor, cor e sabor das frutas. Portanto, leva a uma melhor qualidade dos produtos de frutas secas. O soluto mais utilizado para a preparação desta solução é a sacarose. No entanto, algumas características indesejáveis estão ligadas a este soluto. A isomaltulose surge como alternativa à sacarose, por ser um carboidrato de baixo índice glicêmico e ação cariogênica. Sendo a desidratação osmótica com pulso de vácuo uma forma de acelerar a transferência de massa e aumentar a área interfacial sólido/líquido, além de reduzir o gasto energético.

Além disso, a utilização de um solvente de baixo custo e atóxico, como o etanol também pode ser uma alternativa viável como pré-tratamento baseado na sua capacidade de dissolver componentes da parede celular, resultando em alterações na estrutura do material, aumentando sua permeabilidade. Consequentemente, podendo reduzir significativamente o tempo de secagem, aprimorar a qualidade dos produtos finais e garantir menor consumo de energia.

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ARTICLE 1 - OSMOTICALLY DEHYDRATED FORMOSA PAPAYA WITH ISOMALTULOSE: INFLUENCE OF VACUUM USE AND ALGINATE COATING ON MASS TRANSFER

Matheus de Souza Cruz[1*], Jefferson Luiz Gomes Corrêa[1], Leandro Levate Macedo[2], Amanda Aparecida de Lima Santos[1], Jhenifer Cristina Carvalho Santos[1], Guilherme Mathias Lopes[3], Paula Giarolla Silveira[1]

[1] Department of Food Science, Federal University of Lavras, Lavras, Minas Gerais, Brazil
[2] Federal Institute of Espírito Santo, Venda Nova do Imigrante Campus, Venda Nova do Imigrante, Espírito Santo, Brazil
[3] Department of Agricultural Engineering, Federal University of Lavras, Lavras, Minas Gerais, Brazil

*Corresponding author: matheusnetsouza15@gmail.com

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ABSTRACT

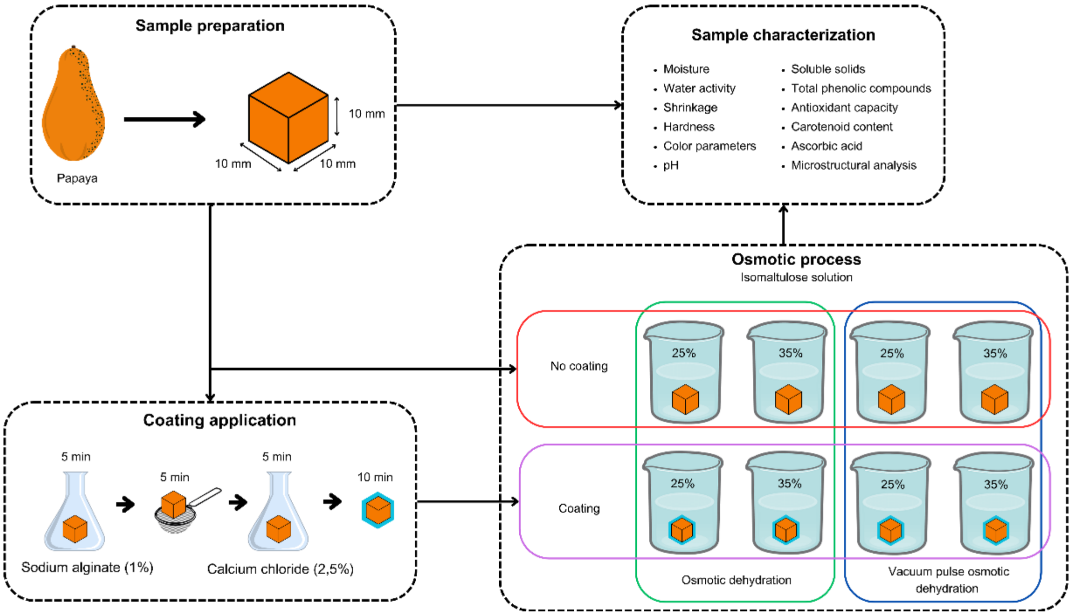
In osmotic dehydration (OD), the goal is to use healthier agents and reduce solute incorporation. Based on this, isomaltulose was used as the osmotic agent and sodium alginate as the coating in this study. Coated and uncoated Formosa papaya cubes were subjected to OD with isomaltulose (25% and 35% w/w), with and without vacuum application (80 kPa for the first 20 minutes). The OD kinetics were evaluated up to 300 minutes at 25°C. The application of the coating reduced solid gain by up to 26% while maintaining water loss, and the condition with the least solute incorporation included the simultaneous use of coating and vacuum. Additionally, the coated samples showed lower water activity and higher preservation of phenolic compounds. Solutions with higher concentrations of isomaltulose resulted in greater solid gain, water loss, weight reduction and shrinkage, and up to a 17% reduction in moisture content. Vacuum application preserved antioxidant capacity and resulted in less browning and morphological deformation of the samples.

Keywords: vacuum pulse osmotic dehydration; food enrichment; palatinose.

PRACTICAL APPLICATIONS

The processing of papayas as dehydrated products is a potential area to be explored to minimize post-harvest losses. However, growing health concerns have led consumers to seek alternatives to sucrose, which is traditionally used in osmotic solutions. This research explored the influence of isomaltulose at different concentrations and the use of vacuum at the beginning of the papaya osmotic dehydration process. Additionally, an innovative approach was taken to reduce solute impregnation during the mass transfer process by applying a coating. The investigation revealed that using sodium alginate was effective, as the coating acted as a semipermeable membrane, preventing excessive sugar absorption and allowing water to exit the food. Therefore, this comprehensive study aims to elucidate current practices for dehydrated papayas, highlighting their potential benefits and limitations.

GRAPHICAL ABSTRACT



1 INTRODUCTION

Papaya (*Carica papaya* L.) is one of the most consumed fruits worldwide, playing a significant role in the economy of tropical countries and in human nutrition and health. It is an important raw material in the processing industry due to its composition of vitamins, minerals, fibers, carotenoids, and phenolic compounds, which act as antioxidants. However, being a highly perishable fruit, its rapid ripening complicates handling, transportation, storage, and commercialization, leading to significant post-harvest losses (Braga et al., 2020; Chandra et al., 2021; Macedo et al., 2023a).

Osmotic dehydration (OD) involves immersing fruits and vegetables in hypertonic solutions, resulting in the diffusion of moisture from the cellular tissue to the solution and the solute from the solution into the food (Jiménez-Hernández et al., 2017; Rascón et al., 2018; Abrahão & Corrêa, 2023; Rodrigues et al., 2006). Vacuum pulse osmotic dehydration (PVOD) involves reducing the pressure in the first minutes of OD followed by a return to atmospheric pressure. By removing occluded gases in intercellular spaces and filling these spaces with the osmotic solution, PVOD typically leads to greater mass transfer compared to ordinary OD (Vieira, Pereira & Hubinger, 2012; Araújo & Pena, 2023; Corrêa et al., 2010; Corrêa, Ernesto & De Mendonça, 2016; Junqueira; Corrêa & De Mendonça, 2017; Macedo et al., 2021a; 2022a; 2022b).

Sucrose is the most commonly used osmotic agent in OD due to its low cost and availability. However, it results in products with high sweetness and high caloric value (Abrahão & Corrêa, 2023; Junqueira et al., 2017; Rodrigues, Cunha, & Hubinger, 2003). Isomaltulose (6-O-D-glucopyranosyl-D-fructose), also known by the commercial name Palatinose®, is a natural disaccharide found in sources such as honey, sugarcane, and molasses, and can be produced through microbial enzymatic conversion of sucrose. It has half the sweetness and a similar caloric value to sucrose (Carmo et al., 2022a; 2022b; Rubio-Arraez et al., 2015; Sawale et al., 2017). Few studies on OD with isomaltulose have been published.

In OD processes, the aim is to reduce solid gain, regardless of the osmotic agent used (Hissham et al., 2022; Rodriguez, Soteras & Campañone, 2021; Gulzar et al., 2018). The application of edible coatings can reduce solid gain in OD. These coatings are thin layers of edible material that cover the surface of the food. Sodium alginate is one of the most commonly used materials in coatings due to its film-forming ability (Chiumarelli & Hubinger, 2014; Kotovicz et al., 2014; Sakooei-Vayghan et al., 2020; Matuska, Lenart & Lazarides, 2006;

Alharaty & Ramaswamy, 2023). However, there are no reports in the literature of its use as a pre-treatment for OD and PVOD of papaya.

The objective of this study was to investigate the influence of isomaltulose solution concentration, vacuum time, and the use of coating on mass transfer parameters in the osmotic dehydration of Formosa papaya cubes, as well as quality aspects of the fruit such as moisture, water activity, shrinkage, hardness, color, soluble solids, pH, total phenolic compounds, antioxidant capacity, carotenoid content, ascorbic acid content, and microstructural analysis.

2 MATERIALS AND METHODS

2.1 Raw material

Papaya fruits (*Carica papaya* L.), cultivar Formosa, were acquired from the local market (Lavras, Minas Gerais, Brazil). The fruits were selected based on skin color (between 50-75% predominantly yellow, stage 4), ripeness (10.73 ± 1.01 °Brix), mass (1426.23 ± 307.60 g), length (26.46 ± 2.82 cm), and integrity (absence of lesions).

2.2 Sample preparation

The papayas were washed under running water, sanitized with a sodium hypochlorite solution (200 ppm for 15 min), rinsed, drained with absorbent paper, and stored under refrigeration at 4 °C for up to 2 days. The fruits were then sliced longitudinally, and using a stainless steel mold, papaya pulp samples with an edge of 11.0 ± 0.5 mm, corresponding to 1.67 ± 0.10 g each, were obtained. The samples showed a moisture content of 89.29 ± 1.25 (kg of water per 100 kg of sample), water activity of 0.980 ± 0.002, pH of 5.38 ± 0.08, and hardness of 2.952 ± 0.206 N.

2.3 Coating preparation and application

The coating solution was prepared according to the procedure presented by Hissham et al. (2022) and Rodriguez, Soteras, and Campañone (2021) with modifications. The 1% (w/v) sodium alginate solution (Sigma-Aldrich, Steinheim, Germany) was obtained by dissolving the alginate powder in distilled water for 12 hours at room temperature (27 ºC) to obtain a clear solution. The 2.5% (w/v) calcium chloride solution (Vetec, Duque de Caxias, Brazil) was prepared by dissolving the $CaCl_2$ powder in distilled water and stirring at room temperature.

The samples were immersed in the sodium alginate solution for 5 min without agitation. They were then removed from the solution and placed on a nylon mesh sieve (10 cm in diameter) for 5 min to remove excess coating. After this period, the cubes were immersed in the $CaCl_2$ solution for a cross-linking time of 5 min. After removal from the $CaCl_2$ solution, the samples were kept at room temperature for 10 min to allow further cross-linking. The samples were then drained with absorbent paper to remove any excess cross-linking agent.

2.4 Osmotic dehydration (OD) and vacuum pulse osmotic dehydration (PVOD)

The osmotic solutions were prepared using distilled water and isomaltulose (Beneo-Palatinit, Mannheim, Germany) in concentrations of 25 and 35 (kg of solute per 100 kg of solution), with respective water activities of 0.952 ± 0.004 and 0.938 ± 0.003.

OD and PVOD experiments were performed by individually immersing the samples in the isomaltulose solution at 25ºC under controlled temperature (Eletrolab EL111/4, São Paulo, Brazil). The fruit to osmotic solution ratio was 1:10 (w/w) to avoid significant medium dilution (Junqueira et al., 2018; Tiroutchelvame, Maran & Pragalyaashree, 2019). OD was conducted under atmospheric pressure (101.2 kPa). PVOD had a vacuum pressure of 80 kPa for the first 20 min, with atmospheric pressure resumed after this period. The total osmotic processing time was 300 min, with samples taken at 20, 40, 60, 90, 120, 180, 240, and 300 min (Corrêa et al. 2010; Carmo et al., 2022b; Grzelak-Blaszczyk et al., 2020; Macedo et al., 2022a). Samples removed from the solution were immediately immersed in ice water for 10 s to stop dehydration and remove any remaining osmotic solution on the surface. The surfaces of the samples were then drained with absorbent paper to remove excess surface water (Macedo et al., 2022a).

2.5 Mass transfer parameters

In osmotic processes, water loss (WL), solid gain (SG), and weight reduction (WR) were used to evaluate mass transfer and were calculated according to Equations 1, 2, and 3, respectively (Corrêa, Ernesto & De Mendonça, 2016).

$$WL(\%) = \frac{W_0 M_0 - W_f M_f}{W_0} \times 100 \quad (1)$$

$$SG(\%) = \frac{W_f (1 - M_f) - W_0 (1 - M_0)}{W_0} \times 100 \quad (2)$$

$$WR(\%) = \frac{W_0 - W_f}{W_0} \times 100 \quad (3)$$

where W is the weight of the sample (kg); M is the moisture content of the sample (kg of water per 100 kg of sample); and the subscripts “0” and “f” indicate the initial and final samples, respectively.

2.6 Sample characterization

Fresh and osmotic dehydrated samples were characterized for moisture content, water activity, shrinkage, hardness, color, soluble solids, pH, total phenolic compounds, antioxidant capacity, carotenoid content, ascorbic acid content, and microstructural analysis, as determined by the methods described below.

2.6.1 Moisture content

The moisture content of the samples was determined gravimetrically in a vacuum oven (Solab SL104/40, Piracicaba, Brazil) at 70°C until constant weight (AOAC, 2019), according to method 934.06. All measurements were conducted triplicate.

2.6.2 Water activity (a_w)

Water activity was determined in triplicate using a hygrometer (Aqualab, model 3-TE, Washington, USA) at 25 °C.

2.6.3 Shrinkage

The shrinkage of fresh and osmotically dehydrated samples was calculated according to Equation 4. The dimensions of each axis (x, y, and z) of the papaya cube were determined using a digital caliper (± 0.01 mm) (Western, model DC-60, Zhejiang, China). The volume of the samples was calculated by the product of the average of five measurements of each dimension. (Junqueira et al., 2018).

$$\text{Shrinkage} = 1 - \frac{V}{V_o} \tag{4}$$

where V e V_0 are the volumes (m^3) before and after the osmotic process, respectively.

2.6.4 Hardness

Hardness was measured using a texturometer (Stable Micro Systems, model TA-X2T, Surrey, England), equipped with a 50 kg load cell, a 6 mm diameter probe, a penetration distance of 3 mm, and a speed of 2 mm/s (Macedo et al., 2023a). The response was expressed in Newton (N), based on the average of five replications.

2.6.5 Color parameters

Color determination was obtained from the emission of a light beam from the lens of the electronic colorimeter (Shenzhen Linshang Technology Co., Ltd., model LS173, Shenzhen, China). All measurements were conducted in five replications and expressed according to the CIELAB coordinates including L*, a*, b*, C*, and ºh, where L* is a measure of the brightness of an object ranging from 0 (black) to 100 (white), a* is a measure of red (positive a*) or green (negative a*), and b* is a measure of yellow (positive b*) or blue (negative b*). Chroma (C*), defining the intensity of the sample's color, and hue (°h), related to the tone, were also evaluated. The total color difference (ΔE) was calculated according to Equation 5.

$$\Delta E = \sqrt{(L^* - L_0^*)^2 + (a^* - a_0^*)^2 + (b^* - b_0^*)^2} \tag{5}$$

considering the control as the fresh sample, represented by the subscript “0”.

2.6.6 pH

The pH reading was performed using a digital bench pH meter (Tecnal®, model TEC-4MP, Piracicaba, Brazil), calibrated with pH 4.0 and 7.0 solutions. All measurements were conducted triplicate.

2.6.7 Soluble solids

Soluble solids content was determined using a portable digital refractometer (Hanna Instruments, model HI 96801, Cluj-Napoca, Romania). The material was mashed, and two drops were transferred to the refractometer prism, discarding large pulp particles. All measurements were conducted triplicate and the results were expressed in °Brix.

2.6.8 Total phenolic compounds and antioxidant capacity

Extracts for phenolic compound and antioxidant capacity were extracted with 50% methanol and 70% acetone. Approximately 3.0 g of the sample were mashed with 30 mL of 50% methanol, stirred at room temperature for 30 minutes, and then subjected to 30 minutes in an ultrasonic bath. The extract was filtered through qualitative filter paper, reserving the filtered extract. The residue was subjected to a new extraction with 30 mL of 70% acetone, stirred for 30 minutes, and filtered. The methanolic and acetonic filtrates were transferred to a 50 mL volumetric flask, which was filled with distilled water. The extracts were coded and stored under refrigeration in sealed and light-protected vials.

2.6.8.1 Total phenolic compounds - Fast Blue method

The total phenolic content assays were determined using the Fast Blue BB reagent according to the sequential method described by Medina (2011). Initially, an aliquot of 0.8 mL of the extract was transferred to a test tube, followed by the addition of 0.2 mL of distilled water and 0.1 mL of Fast Blue BB solution, with subsequent homogenization. Then, 0.1 mL of NaOH solution was added, and the samples were shaken for 1 minute and kept in a dark environment for 90 minutes. The same procedure was performed by replacing the sample with the solvent to obtain the blank. Aliquots (300 µL) were transferred to microtitration plates, and the absorbance reading was performed in a spectrophotometer at 420 nm. The phenolic content was determined using the equation of the standard curve of gallic acid. All measurements were conducted triplicate and the results were expressed in milligrams of gallic acid equivalents (GAE)/100g of sample on a dry basis.

2.6.8.2 Antioxidant capacity - ABTS+ method

The assay evaluates the ability of the extracts to scavenge the free radical (ABTS+), performed according to the method of Auzanneau et al. (2018). Briefly, the (ABTS+) solution was prepared by reacting 2,2'-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid) diammonium salt at a concentration of 7 mmol/L with potassium persulfate at 2.45 mmol/L. The mixture was left to stand at room temperature in the dark for 16 h. The resulting solution was then diluted with ethanol to an absorbance of 0.70±0.05 at 734 nm. In a 96-well microplate, 3 µL of each extract was pipetted in triplicate, and 297 µL of the radical solution was added to each well and homogenized. The microplate was left for 6 minutes in the dark before reading the absorbance at 734 nm in a spectrophotometer (Biochrom, model BIO EZ READ 2000, Cambridge, United Kingdom). All measurements were conducted triplicate and the results were expressed as % ABTS reduction according to Equation 6.

$$\%\ \text{ABTS reduction} = \left(1 - \frac{A_c - A_s}{A_c}\right) \times 100 \tag{6}$$

where Ac is the absorbance of the control (free radical + solvent without sample) and As is the absorbance of the sample.

2.6.9 Carotenoid content

The carotenoids from 2 g of sample were extracted with 20 mL of acetone P.A. by maceration, followed by shaking for 20 min. Then, the extract was filtered into an Erlenmeyer flask using filter paper, washed with acetone until the residue turned white. The filtrate was transferred to a separatory funnel in a dark environment and 15 mL of petroleum ether and 35 mL of distilled water were added. This procedure was repeated 3 times to completely remove the acetone. After the washes, the separation of the extract (upper phase) and water (lower phase) occurred in the separatory funnel, and the water phase was discarded. The extract was transferred to a 50 mL volumetric flask and the volume was completed with petroleum ether. The content was again filtered and stored in a dark bottle under refrigeration until reading. The carotenoid content was then calculated according to Equation 7 and expressed in µg/g of sample (dry basis). All measurements were conducted triplicate. (Rodriguez-Amaya, 2001).

$$\text{Carotenoid content} = \frac{A \times V \times 10^6}{A_{1cm}^{1\%} \times M \times 100} \quad (7)$$

where: A = absorbance of the solution at 450 nm for beta-carotene; V = final volume of the solution in mL; $A_{1cm}^{1\%}$ = molar absorptivity coefficient of a pigment in a specific solvent (2592 for beta-carotene); M = mass of the sample taken for analysis in g.

2.6.10 Ascorbic acid

The ascorbic acid analysis was performed according to the methodology described by Barcia et al. (2010), with some modifications. For extract preparation, approximately 1.0 g of the sample was weighed and 10 mL of metaphosphoric acid solution (4.5%) in ultrapure water was added, allowing it to stand for 1 h in an amber flask. Then, the sample was filtered using filter paper, and the supernatant was centrifuged at 7,000 rpm for 10 min and transferred to a 1.5 mL flask. This was placed in an ultrasonic bath (Unique, model USC 2850 A, Indaiatuba, Brazil) for 30 minutes and kept refrigerated until quantification. To determine the ascorbic acid content, the method of Vinci et al. (1995) with modifications was used, and quantification was performed using a high-performance liquid chromatograph (HPLC, Shimadzu, LC-20AT) equipped with a UV detector (Shimadzu, SPD-20A). Separation was performed on a Phenomenex C18 column with 5 μm particles (250 x 4.6 mm), thermostated at 30 °C. The mobile phase was an aqueous acetic acid solution at 0.15% (v/v) with a flow rate of 1.0 mL/min. Detection was done at 245 nm. The identification of the ascorbic acid peak was made according to the retention time compared to standard solutions. The analytical curve was obtained from the chromatogram of the standards, measuring the areas of the ascorbic acid peaks under the same separation conditions applied to the samples. The standard concentrations of ascorbic acid ranged from 1 to 100 mg/L. All measurements were conducted triplicate and the results were expressed as mg/100g of sample on a dry basis.

2.6.11 Microstructural analysis

Scanning electron microscopy (SEM) was used to analyze the internal structure of fresh fruit and after osmotic processing. Initially, all samples were sectioned and fixed with a modified Karnovsky solution (2.5% glutaraldehyde, 2.5% formaldehyde in 0.05M sodium cacodylate buffer, pH 7.2, 0.001M $CaCl_2$), refrigerated for 24 h. These samples were immersed in a cryoprotective solution (30% glycerol in water) for 30 min, immersed in liquid nitrogen, and fractured on a metal surface cooled with liquid nitrogen using a scalpel. These fragments were rinsed in distilled water and then dehydrated in solutions of increasing concentrations of acetone 25%, 50%, 70%, 90%, and three times in 100%. In each of these concentrations, the samples remained immersed for 10 min. After dehydration, the samples were subjected to drying in a critical point dryer (Bal-tec, model CPD 030®, Schalksmühle, Germany). At this stage, the acetone in the sample was replaced by CO_2. Then, the samples were placed on aluminum supports and covered with an aluminum foil using double-sided carbon adhesive tape, properly identified. Finally, all samples were covered with a gold layer (20 nm) using a sputter coater (Bal-tec, model SCD 050®, Schalksmühle, Germany) and visualized with a scanning electron microscope (Tescan, model CLARA FEG-SEM, Libušina, Czech Republic) operating at 20 kV, with a working distance of 11 mm.

2.7 Statistical analysis

The experiment was conducted in a completely randomized design with three replications, totaling 8 treatments (Table 1) and 24 plots. The data were analyzed in a 2^3 factorial scheme using analysis of variance (ANOVA). Treatment comparisons were performed using Tukey's test at 5% significance, while individual comparisons between each treatment and the control sample (fresh sample) were performed using Dunnett's test, with a 95% confidence interval.

Table 1 – Exprimental conditions.

Code	**Coating**	**Concentration (%, w/w)**	**Vacuum Time (min)**
OD25	No	25	0
OD35	No	35	0
PVOD25	No	25	20
PVOD35	No	35	20
OD25-COA	Yes	25	0
OD35-COA	Yes	35	0
PVOD25-COA	Yes	25	20
PVOD35-COA	Yes	35	20

Abbreviations: OD stands for osmotic dehydration; PVOD, vacuum pulse osmotic dehydration; and COA, coating.

A multivariate analysis was conducted using principal component analysis (PCA) to correlate mass transfer responses after osmotic processes and quantitative characterization results of the samples with osmotic solution concentration (25% or 35%), vacuum pulse time (0 or 20 min), and coating use. The samples were projected in the factorial space (PC1 × PC2) to understand the grouping according to the experimental data.

Data processing and statistical analysis were performed with the assistance of Statistica 14.0.1.8 software (StatSoft Inc., Tulsa, OK).

3 RESULTS AND DISCUSSION

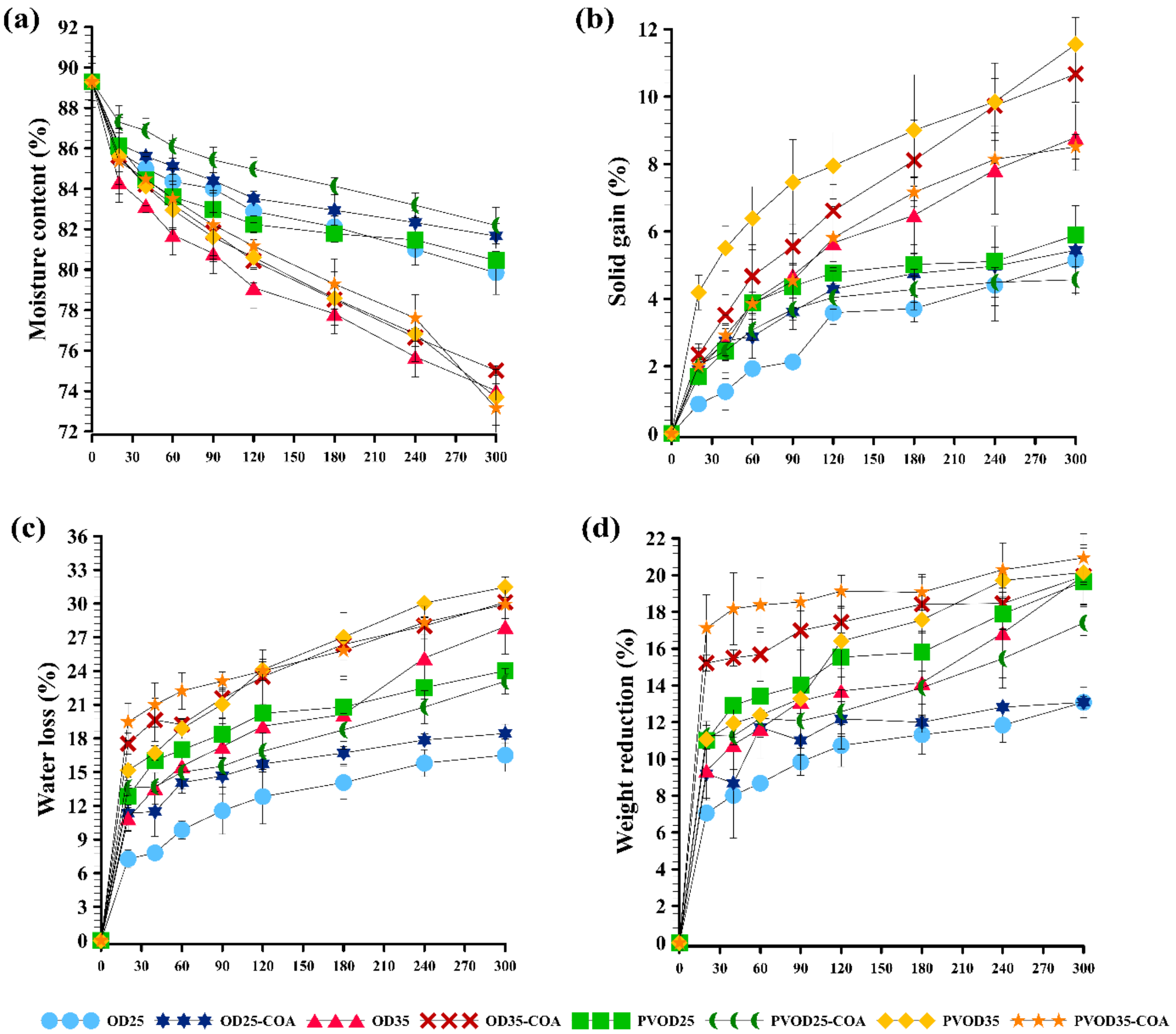
3.1 Mass transfer parameters

Figure 1 presents the mass transfer results of dehydrated papaya cubes at different immersion times at 25 ºC. Over time, a reduction in moisture content and an increase in solid gain (SG), water loss (WL), and weight reduction (WR) were observed for all treatments. The highest mass transfer rates occur at the beginning of the osmotic process, as also verified by other studies in the literature (Corrêa, Ernesto & De Mendonça, 2016; Junqueira et al., 2017; Macedo et al., 2023b). However, at 300 minutes, it is noted that mass transfers have already attenuated, indicating that the process tends towards equilibrium after this period.

Treatments with higher concentrations of isomaltulose showed higher SG, WL, and WR, and consequently lower moisture contents. In Figure 1c, it is observed that an increase in the concentration of the osmotic solution leads to increased water loss due to the increased chemical potential gradient between the solution and the food, with a consequent increase in osmotic pressure favoring mass transfer flows (Abrahão & Corrêa, 2023).

The use of vacuum for 20 minutes was applied to maximize mass transfer by increasing the contact area between the osmotic solution and the food through the removal of gases occluded in the intercellular spaces of the food (Araújo & Pena, 2023; Corrêa, Ernesto & De Mendonça, 2016). However, the treatments with vacuum pulse showed no significant difference in moisture content compared to treatments under atmospheric pressure (Figure 1a). It was also expected that the use of vacuum would lead to increased SG, WL, and WR, but this was not verified for all treatments. This behavior was also observed by Ramallo, Hubinger, & Mascheroni (2013), Viana, Corrêa, and Justus (2014), and Souza et al. (2023) working with pineapple, forage cactus, and tomato, respectively.

Figure 1 - Moisture (a), solids gain (b), water loss (c), and weight reduction (d) during the dehydration process with and without coating application.

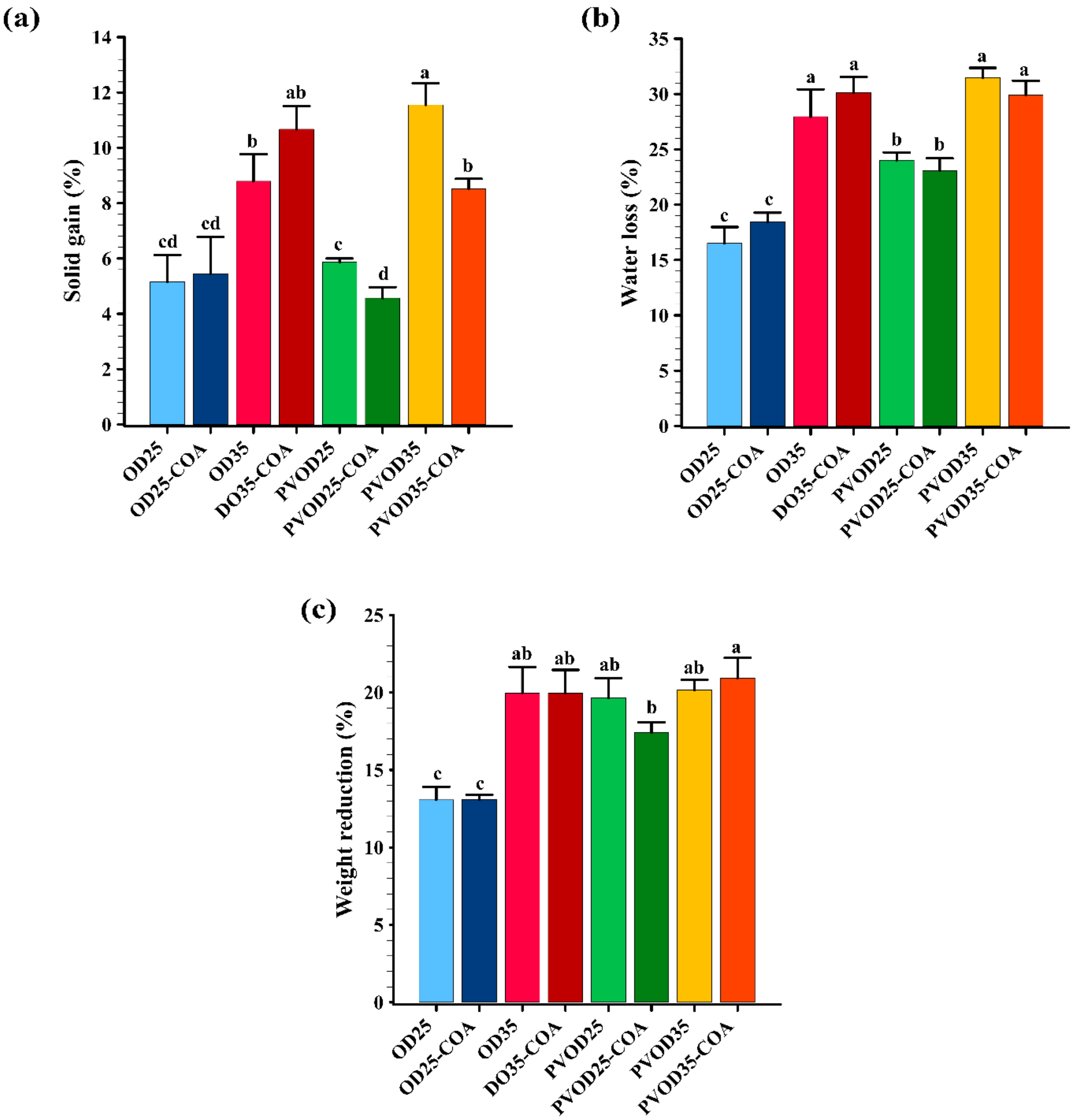


The bar represents the standard deviation.

Besides different concentrations of the osmotic agent and the use of vacuum, treatments with coating application were also evaluated and did not interfere with the osmotic process trend. However, when associated with the use of vacuum, they presented lower SG over the contact time of the fruit with the solution (Figure 1b). This can be justified as the reduction in pressure improves adhesion to the surface and penetration into microfissures, preventing the formation of uneven areas or bubbles, resulting in a more uniform and efficient coating (Senturk Parreidt et al. 2019).

The comparison between treatments for SG, WL, and WR at the final time (300 min) is shown in Figure 2.

Figure 2 – Solids gain (a), water loss (b), and weight reduction (c) after 300 minutes of dehydration.



The same letter indicates that there is no significant difference between the treatments, according to Tukey's test ($p<0.05$). The bar represents the standard deviation.

The solid gain of the treatments varied from 5.15 to 11.55%, as observed in Figure 2a. As expected, treatments with higher concentrations of the osmotic agent led to greater impregnation of isomaltulose. The treatments PVOD25-COA and PVOD35-COA showed 22% and 26% less solid incorporation, respectively, compared to similar treatments without coating. That is, the application of the coating when associated with vacuum significantly reduced solid gain. Thus, in processes using vacuum, the coating layer and the accumulation of solids on the coating surface may have acted as obstacles to SG during the osmotic process (Hissham et al., 2022). On the other hand, the use of vacuum and coating when analyzed individually had no significant influence.

In Figure 2b, it is noted that the PVOD35 treatment showed the highest water loss rate with 31.47±0.89%, but it is not statistically different from the other treatments with 35% isomaltulose. Thus, it was observed that treatments with lower concentrations of the osmotic agent resulted in lower WL percentages, ranging from 16.51 to 24.02%. However, it is noted that these treatments with 25% isomaltulose (OD25 and OD25-COA) when compared to their similar treatments with vacuum (PVOD25 and PVOD25-COA) show a significant difference among themselves. The use of vacuum did not show a change in the other treatments. The use of the coating did not influence the WL of papaya cubes, confirming that the hydrophilic nature of alginate gels allows the transfer of water molecules similar to previous studies with alginate coating applied to ginger and pumpkin (Hissham et al., 2022; Jansrimanee & Lertworasirikul, 2020; Tello et al., 2015).

Figure 2c showed the results of the weight reduction parameter, which varied from 13.07 to 20.94%. The different solute concentrations and the application of the coating showed no significant difference in WR. The use of vacuum only significantly influenced the increase in WR in treatments with 25% isomaltulose (PVOD25 and PVOD25-COA). On the other hand, treatments without vacuum OD25 and OD25-COA showed the lowest WR values, differing from the other treatments. This result was expected when analyzing the kinetic data, which demonstrated that WL is much higher than SG. For this study, these results were extremely important, as it is desired to preserve the characteristics of fresh papaya as much as possible, incorporating fewer solids.

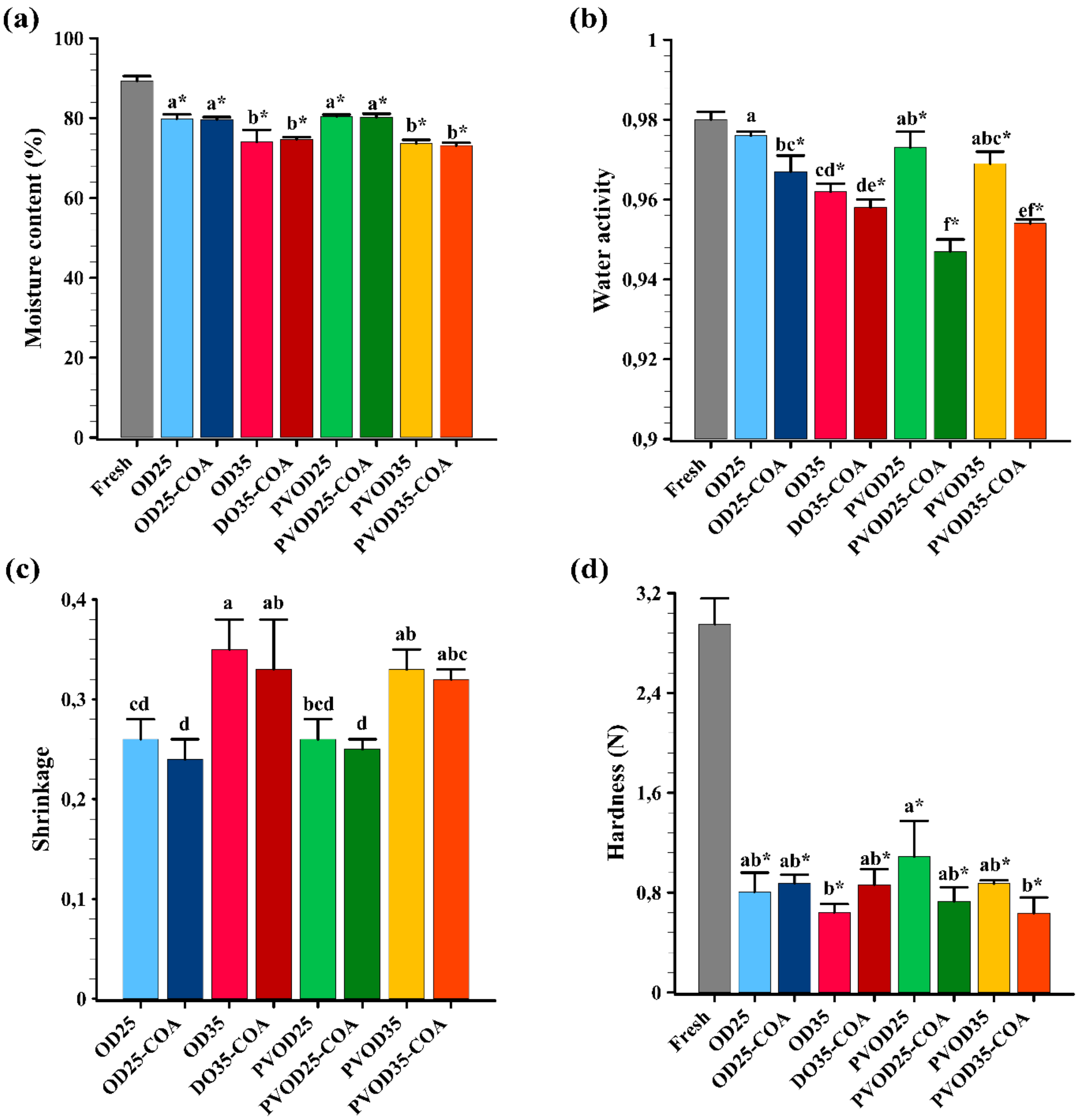
3.2 Sample characterization

3.2.1 Moisture

Figure 3a displays the moisture levels of Formosa papaya subjected to different osmotic dehydration conditions compared to fresh samples.

A significant reduction in moisture is observed across all osmotic dehydration treatments compared to the fresh samples, indicating the effectiveness of the process in removing water from the papayas. Samples treated with a 25% concentration showed less reduction compared to those with 35% isomaltulose.

Figure 3 - Moisture (a), water activity (b), shrinkage (c), and hardness (d) of fresh and dehydrated papaya cubes with and without coating application.



The same letter indicates that there is no significant difference between the treatments, according to Tukey's test ($p<0.05$). The asterisk indicates a significant difference between each treatment and the fresh sample, according to Dunnett's test ($p<0.05$). The bar represents the standard deviation.

This response is due to the mechanism of osmotic dehydration, where a higher concentration of osmotic solution creates a greater pressure gradient relative to the papayas, generating a driving force that promotes the migration of water from the papayas to the isomaltulose solution (Wang et al., 2023; Lopez, Morais & Morais, 2020; Rastogi, Raghavarao & Niranjan, 2014).

Contrary to the belief that the coated product would resist water loss, this phenomenon was not observed, as water removal was not significantly influenced ($p>0.05$) between uncoated and coated samples due to the semipermeable nature of the alginate coating. The use of vacuum pulse also did not cause significant changes between OD and PVOD, with similar responses in water removal under the same solution concentrations. Similar results were obtained by Macedo et al. (2022a) with strawberries and Ito et al. (2007) in studies with mangoes.

3.2.2 Water activity

Fresh fruits generally exhibit high water activity levels, with papaya showing values close to 0.98, indicating a highly perishable product due to the large amount of available water for microbial actions and chemical and enzymatic reactions (Macedo et al., 2023a).

The results in Figure 3b show significant reductions in water activity ($p<0.05$), with the average water activity of osmotically dehydrated samples ranging from 0.947 to 0.973, except for the OD25 treatment, which had 0.976 ± 0.001. This reduction is associated with water loss and solid gain factors during the osmotic dehydration process (Chandra et al., 2023; Ito et al., 2007).

As reported in previous studies (Macedo et al., 2023a; Corrêa et al., 2016; Chandra et al., 2023), osmotic processes alone are insufficient to ensure microbiological stability, recommending storage of products with indices below 0.6. To achieve these values, preservation methods such as drying, refrigeration, or pasteurization are necessary, with drying being the most commonly used method to reduce moisture levels (Macedo et al., 2021b; Abrahão & Corrêa, 2023).

It is understood that the vacuum applied in the first few minutes removes gases trapped in the materials, increasing the contact area. Thus, when atmospheric pressure is restored, the osmotic solution fills these additional spaces to perform mass exchanges (González-Pérez, Ramírez-Corona & López, 2021; Macedo et al., 2023b).

However, samples subjected to the 20-minute vacuum pulse (PVOD) did not experience significant influence ($p>0.05$) in reducing water activity levels. Similar findings were reported by Macedo et al. (2023a), who observed that for calcium lactate osmotic solutions, the vacuum was inert. The exception was the PVOD25-COA sample, which reached significantly lower values (0.947 ± 0.003) compared to OD25-COA.

Regarding different solute concentrations, treatments with 35% isomaltulose were responsible for greater reductions in water activity, but significantly only in non-vacuum treatments. On the other hand, the use of coating proved effective in decreasing water activity, with all treatments showing significant reductions ($p<0.05$) in this parameter.

3.2.3 Shrinkage

Figure 3c shows that the shrinkage value ranged from 0.22 to 0.35. According to Junqueira et al. (2017, 2018), the decrease in moisture content resulting from osmotic dehydration reduces the pressure exerted by the liquid against the cell wall. This phenomenon can cause a pressure imbalance between the interior and exterior of the cell, potentially generating contraction tension and consequently inducing shrinkage.

Both OD and PVOD treatments caused shrinkage in the papaya samples (Macedo et al., 2023a). The greatest shrinkage was observed in the OD35 treatment (0.35±0.03), but it did not differ from other samples subjected to a 35% concentration. Therefore, treatments with lower isomaltulose concentrations showed less shrinkage, consistent with Macedo et al. (2022a).

The application of coating and the use of vacuum did not show any action to minimize sample shrinkage during the osmotic process.

3.2.4 Hardness

Figure 3d shows that fresh papaya had a low hardness value (2.956 ± 0.206 N) due to its advanced ripening stage. The softening of the pulp occurs due to the high respiration rate and increased ethylene production, making it difficult to commercialize and highlighting its physical fragility (Braga et al., 2020).

It is also noted that there was a significant reduction in the hardness of all dehydrated treatments compared to the fresh material, as reported by Junqueira et al. (2018) and Chandra et al. (2021). This occurs due to changes in the texture of the material subjected to the osmotic process, related to moisture extraction and physical and chemical changes resulting from solute incorporation and degradation of the middle lamella. These transformations cause turgor loss, resulting in tissue softening (Junqueira et al., 2018).

The hardness of the dehydrated samples ranged from 0.636 to 1.089 N. However, when compared among themselves, the different concentrations of osmotic agent, vacuum use, and coating application did not show any isolated influence on the food's hardness. This may be due to the long osmotic process time, with similar results found by Macedo et al. (2023a), where the 20-minute vacuum use also did not significantly influence the hardness of dehydrated papaya cubes.

3.2.5 Color parameters

Table 2 presents the average values and standard deviation of the luminosity (L), red/green (a), yellow/blue (b), saturation (C), hue (°h), and total color difference (ΔE) parameters observed for papaya cubes (fresh, osmotically dehydrated, and coated). The papaya cubes subjected to OD and PVOD showed a significant reduction ($p<0.05$) in L values, indicating a darkening of the samples when compared to fresh samples. Comparing the treatments among themselves, it is noted that the use of vacuum resulted in significant differences compared to other treatments, indicating that the use of PVOD may be responsible for less darkening of the samples. This can be justified by the absence of occluded gases, as observed by Junqueira et al. (2018) during the dehydration of carrots.

Table 2 - Analysis of colorimetry parameters of fresh and osmotically dehydrated papaya cubes.

Code	**L***	**a***	**b***	**C***	**°h**	ΔE
Fresh	51,50±0,85	20,45±0,29	24,45±0,34	31,29±0,64	52,20±1,57	-
OD25	36,76±0,91 a*	23,13±1,30 a	27,60±1,17 a	37,08±0,15 a*	48,05±1,64 a*	16,23±0,56 bc
OD25-COA	37,09±1,83 a*	24,29±1,70 a*	26,98±1,64 a	36,36±1,56 a*	47,75±1,49 a*	15,94±1,30 bc
OD35	37,55±1,57 a*	21,46±1,67 ab	21,72±1,74 bc	30,71±1,75 b	45,12±1,78 a*	14,80±2,00 c
OD35-COA	37,72±1,88 a*	23,82±1,83 a*	24,21±1,86 ab	34,07±1,88 ab	45,40±2,00 a*	14,98±1,63 c
PVOD25	31,09±2,00 b*	15,64±1,91 c*	18,19±1,89 cd*	23,96±1,95 c*	49,06±1,87 a	22,07±3,05 ab
PVOD25-COA	35,46±2,00 ab*	13,26±1,91 c*	13,45±1,89 de*	18,86±1,95 d*	45,26±1,87 a*	20,67±3,42 abc
PVOD35	30,80±1,80 b*	15,19±1,70 c*	12,37±1,72 e*	19,76±1,70 cd*	39,02±1,54 b*	24,61±2,99 a
PVOD35-COA	34,14±1,80 ab*	16,58±1,70 bc*	17,27±1,72 cd*	24,11±1,70 c*	45,92±1,54 a*	19,34±2,87 abc

Values are described as the mean ± SD ($n = 5$). The same letter indicates that there is no significant difference between the treatments, according to Tukey's test ($p<0.05$). The asterisk indicates a significant difference between each treatment and the fresh sample, according to Dunnett's test ($p<0.05$).

Samples subjected exclusively to osmotic dehydration (OD25 and OD35) maintained their red coloration (a), and no significant differences were observed with the application of the coating. In contrast, samples subjected to vacuum pulse showed a decrease in this coloration. This can be justified by the fact that the vacuum pulse increases solute incorporation, impacting color changes (Macedo et al., 2022c). The osmotically dehydrated papayas had lower °h values than fresh papayas, indicating a higher red hue (0° or 360°). This is due to the higher concentration of pigments, making it redder than the fresh papaya cube.

According to Macedo et al. (2022c), high C values represent the high color intensity of samples perceived by humans. Fresh papaya had a higher C value than osmotically dehydrated papayas. This is the result of various chemical reactions, including pigment destruction.

The ΔE values ranged between 14.80 ± 2.00 and 24.61 ± 2.99, indicating that osmotically dehydrated papayas showed a high color difference compared to fresh papaya (Pathare et al., 2013). This high distinction between the colors of the dehydrated and fresh samples is due to a series of changes caused by osmotic dehydration, including both the concentration and degradation of natural fruit pigments, as well as the formation of other pigments. However, no significant influence ($p<0.05$) was observed regarding the application of coating and different osmotic concentrations on the evaluated color parameters.

Color is the main element that influences the appearance of food since it constitutes the first quality criterion evaluated by the consumer, determining whether they will be attracted to purchase the product or not. Thus, it is an essential characteristic to be controlled in dehydrated foods (Silveira et al., 2024).

3.2.6 pH and soluble solids

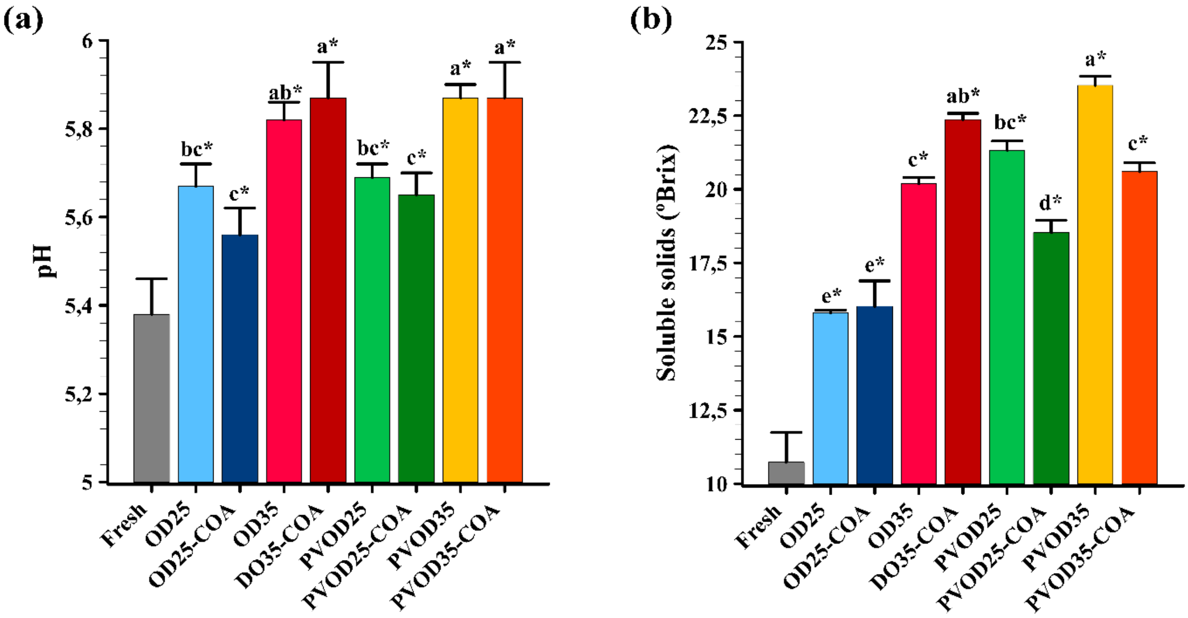
Changes in the total soluble solids content and pH values of fresh and osmotically dehydrated samples are presented in Figure 4.

Fresh papayas had a pH and soluble solids content of 5.38 ± 0.08 and 10.73 ± 1.01 °Brix, respectively. These results are consistent with the values reported by other researchers (Braga et al., 2020; Lovera; Ramallo & Salvadori, 2018).

Dehydrated samples showed a significant difference compared to fresh samples, due to an increase in pH values ranging from 5.65 to 5.87 (Figure 4a). These changes can be associated with the increase in dry matter content and the leaching flow of natural fruit minerals into the osmotic solution. This occurs due to the GS and PA processes, which, during dehydration, reduce the concentrations of hydrogen ions and organic acids, leaching these substances from the material to the osmotic solutions, thereby reducing the concentrations of hydrogen ions and acids (Junqueira et al., 2017; Macedo et al., 2022a).

When comparing the treatments with the osmotic process, it was possible to observe that treatments with higher isomaltulose concentration that used coating and/or vacuum were responsible for the highest pH values. However, the application of vacuum and the use of coating did not show a significant influence on pH values.

Figure 4 - Comparison of pH (a) and soluble solids (b) of fresh and osmotically dehydrated papaya cubes.



The same letter indicates that there is no significant difference between the treatments, according to Tukey's test ($p<0.05$). The asterisk indicates a significant difference between each treatment and the fresh sample, according to Dunnett's test ($p<0.05$). The bar represents the standard deviation.

According to Silva et al. (2015), the total soluble solids content is a characteristic of interest for food products, as the consumer market prefers sweet fruits. The osmotic dehydration process caused an increase in soluble solids content compared to the fresh pulps. Soluble solids results ranged from 15.80 to 23.53 °Brix for the product dehydrated with isomaltulose (Figure 4b).

The fresh sample differed from all treatments as the solute impregnation during the osmotic process increased the SS of the treatments. The increase in soluble solids content was a consequence of the moisture loss from foods during dehydration, which causes the concentration of naturally present sugars in the pulps and the incorporation process of isomaltulose present in the osmotic solution (Abrahão & Corrêa, 2023).

As expected, the higher the concentration, the higher the SS of the treatments, regardless of the use of coating or vacuum time. This effect of the SST content was also observed by Valera et al. (2005) in the osmotic dehydration of mango.

The use of vacuum increased the soluble solids content, except for treatments PVOD35-COA and PVOD25-COA, showing that the use of coating was effective in these treatments. This reduction is important, as in other studies, such as that conducted by Rodriguez, Soteras, and Campañone (2021), osmotically dehydrated and coated samples were sensorially preferred by tasters regarding sweetness, being the samples with the lowest soluble solids content.

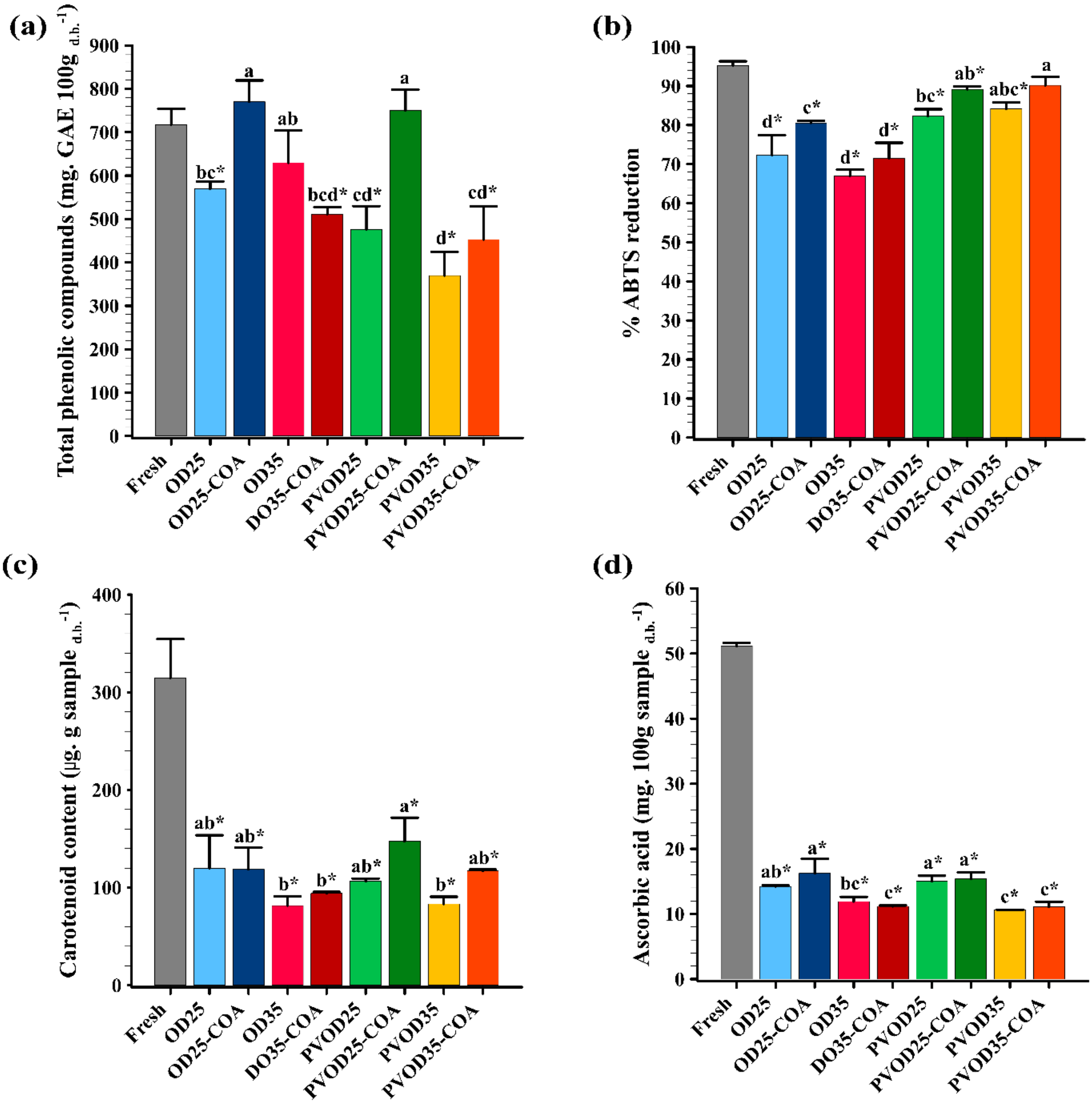
3.2.7 Total phenolic compounds

The phenolic compounds of fresh and osmo-dehydrated papayas are shown in Figure 5a. Fresh papayas showed a significant TPC (717.50 ± 36.51 mg of gallic acid equivalent per g of papaya, on a dry basis). Fresh papayas had lower TPC than the osmo-dehydrated treatments (OD35) and with coating (OD25-COA and PVOD25-COA), but without statistically significant differences ($p < 0.05$). In this scenario, the treatment that stood out the most in preserving phenolic compounds was the OD25-COA treatment, showing a concentration equal to 769.99 ± 49.40 mg of gallic acid equivalent per g of papaya, on a dry basis.

However, it is important to note that osmotic processes can cause losses of phenolic compounds. Phenolics are water-soluble compounds, facilitating their loss by leaching during osmotic dehydration (Abrahão & Corrêa, 2023). Additionally, these compounds are thermosensitive and are therefore easily degraded when the material is heated (Macedo et al., 2021b). Nevertheless, the use of coating provided preservation of these compounds, corroborating the hypothesis that the use of coating would maintain nutritional value.

Other treatments, regardless of isomaltulose concentration or vacuum usage, impacted the degradation of phenolic compounds, with significant differences compared to fresh papaya, as highlighted by Abrahão and Corrêa (2023), osmotic dehydration can result in a decrease in phenolic compounds, which are water-soluble, making their loss more prone to leaching.

Figure 5 - Graphical representation of the analyses of total phenolic compounds (a), antioxidant activity (b), carotenoid content (c), and ascorbic acid (d) in fresh and osmotically dehydrated papaya cubes.



The same letter indicates that there is no significant difference between the treatments, according to Tukey's test ($p<0.05$). The asterisk indicates a significant difference between each treatment and the fresh sample, according to Dunnett's test ($p<0.05$). The bar represents the standard deviation.

3.2.8 Antioxidant capacity

Through Figure 5b, it is noted that fresh papaya showed a 95% ABTS reduction, thus presenting the highest antioxidant activity. Samples subjected to different osmotic dehydration treatments showed a reduction in the range of 66 to 90%.

The use of different concentrations of isomaltulose did not show an influence on the results, as the OD25, OD35, and OD35-COA treatments showed lower reduction values, without significant differences among them, therefore, these were the treatments that showed the greatest degradation of antioxidant activity.

The PVOD treatments compared to similar DO treatments showed significant differences, indicating that the use of vacuum had a positive effect, preserving the antioxidant action of papaya cubes. On the other hand, the use of coating did not show a change in free radical reduction values, except for the PVOD25-COA treatment, which increased antioxidant activity by approximately 8% compared to the treatment without coating.

The reduction in antioxidant activity after the osmotic process in fruits was expected, according to the literature (Chandra et al., 2021; Macedo et al., 2022a). Only the PVOD35-COA treatment did not show a significant difference compared to the fresh sample, thus, for maintaining the antioxidant activity of papaya, this is the most recommended treatment.

3.2.9 Carotenoid content

The fresh sample showed a carotenoid content of 314.606 ± 39.854 µg/g of sample on a dry basis (Figure 5c). The other treatments showed a significant difference compared to the fresh fruit, as its value was twice as high as the PVOD25-COA treatment with 147.262 ± 24.323 µg/g of sample on a dry basis, being the highest amount of carotenoids among the dehydrated samples.

According to Rivera-Lopez et al. (2005), the degradation of carotenoids during processing may be due to exposure to oxygen, as beta-carotene is oxidized when exposed to light, heat, and oxygen. Thus, it is understood that the long exposure time of the fruit associated with mass transfer conditions was determinant for this expressive reduction in carotenoid values of the dehydrated treatments.

When the dehydrated treatments were compared among themselves, it was noted that the use of solutions with lower concentrations of isomaltulose and the application of alginate coating with or without the use of vacuum did not influence the carotenoid contents of the samples. Although their treatments showed higher carotenoid values, statistically their difference was not observed.

Thus, it is evident that the carotenoid content was influenced by the variables, regardless of the condition studied, as the application of coating and the use of vacuum were not sufficient to prevent the pigment from undergoing isomerization and oxidation reactions. Junqueira et al.

(2018) suggested in their study with carrots that this reduction occurs due to heat and light and not the leaching flow, as these molecules are hydrophobic.

3.2.10 Ascorbic acid

Fresh papayas showed 51.167 ± 0.494 mg/100g of dry sample, characterizing it as a good source of this important vitamin. Ascorbic acid is a micronutrient recognized for its antioxidant capacity that helps protect the body against chronic diseases such as cancer, cataracts, and cardiovascular diseases. However, due to its inability to be synthesized by the human body, it is essential to obtain it through food intake (Giampieri, Alvarez-Suarez & Battino, 2014).

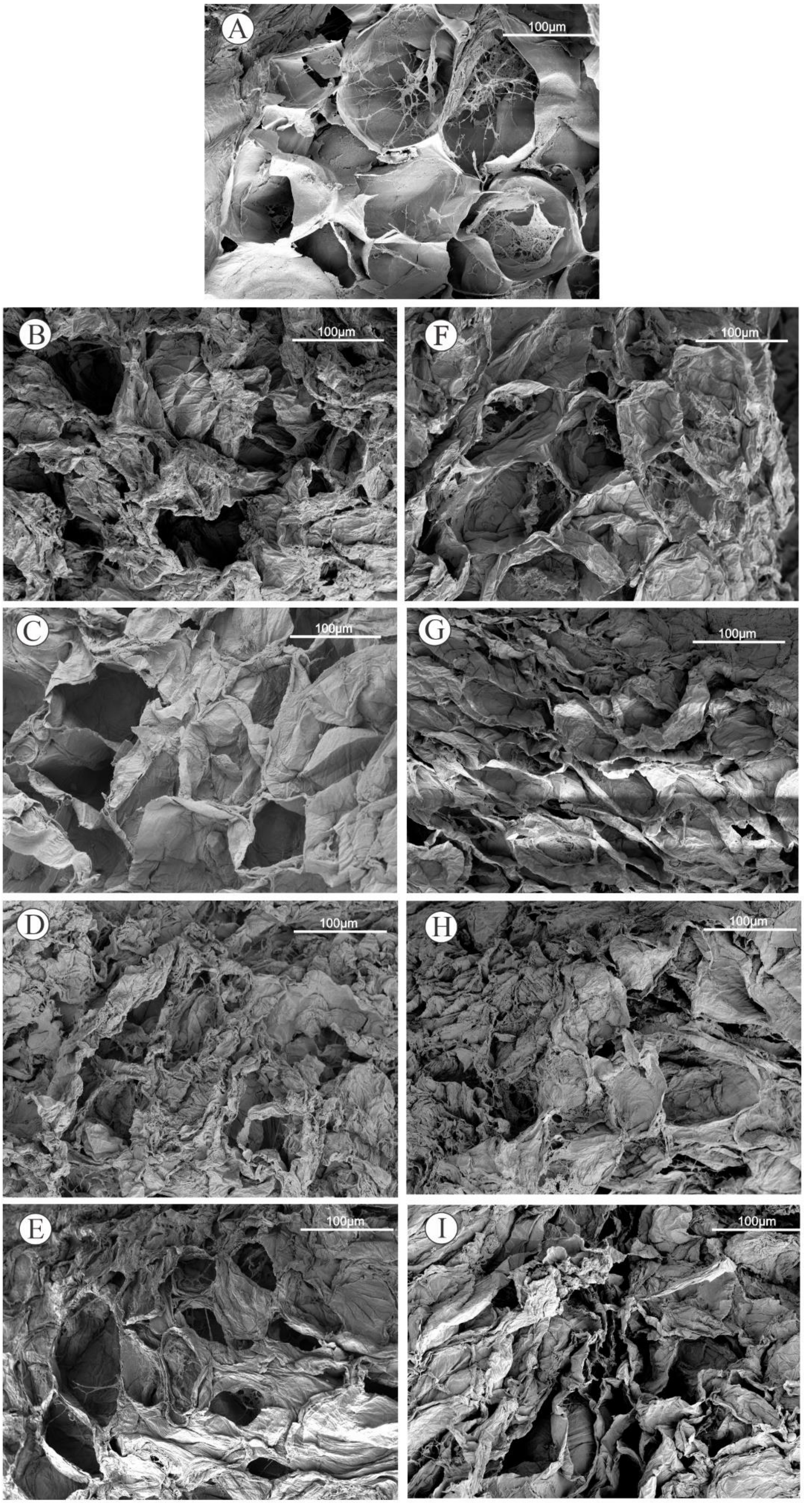
It is observed in Figure 5d that there was a significant difference between the fresh and dehydrated samples. Fresh papaya had a value three times higher than the most significant treatment (OD25-COA) with 16.224 ± 2.2262 mg/100g of dry sample. These reductions ranged from 68% to 79% and occurred as expected, as AA has high solubility, favoring the occurrence of leaching of this compound from the material to the osmotic solution (Abrahão & Corrêa, 2023).

Among the other treatments, there was no significant difference between OD25, OD25-COA, PVOD25, and PVOD25-COA, and between OD35, OD35-COA, PVOD35, and PVOD35-COA. It can be noted that the vacuum pulse and the coating did not cause a significant difference in the amount of ascorbic acid at the same concentration. However, treatments carried out with 35% isomaltulose presented significantly lower values than those carried out at 25% isomaltulose, similar to what was observed by Macedo et al. (2023b).

3.2.11 Microstructural analysis

The internal structure of fresh and dehydrated papaya cubes was analyzed using a scanning electron microscope (SEM), and the impacts caused by osmotic processing are shown in Figure 6. It can be observed that the fresh sample (Figure 6a) presents a defined and organized cell wall. Additionally, it can be characterized by its turgid, rounded, and elongated cells, as well as the presence of intracellular spaces. A similar description of fresh papaya cells was made by the authors Lovera, Ramallo, and Salvadori (2018).

Figure 6 – Scanning electron micrograph of the tissue of dehydrated papaya cubes.



A) Fresh; **B)** OD25; **C)** OD25-COA; **D)** OD35; **E)** OD35-COA; **F)** PVOD25; **G)** PVOD25-COA; **H)** PVOD35; **I)** PVOD35-COA.

Regarding the dehydrated treatments (Figures 6b-6i), significant changes in the cellular tissue can be observed. According to Junqueira et al. (2018), structural damage to the cells at a microscopic level during osmotic dehydration occurs due to mass transfer flows (gain of solids and loss of water) that are carried out through the intercellular and extracellular spaces.

It is possible to observe that the treatments with 35% isomaltulose (Figures 6d, 6e, 6h, 6i) show more distorted tissues. This was expected since the higher the concentration, the more intense the tissue collapse and the plasmolysis effect caused by the loss of water from the cytoplasm (Khin, Zhoi & Perera, 2017). However, when coated, the treatments without the use of vacuum (Figures 6c, 6e) presented more stable and preserved structures, as they underwent less cellular deformation, becoming less compact and distorted.

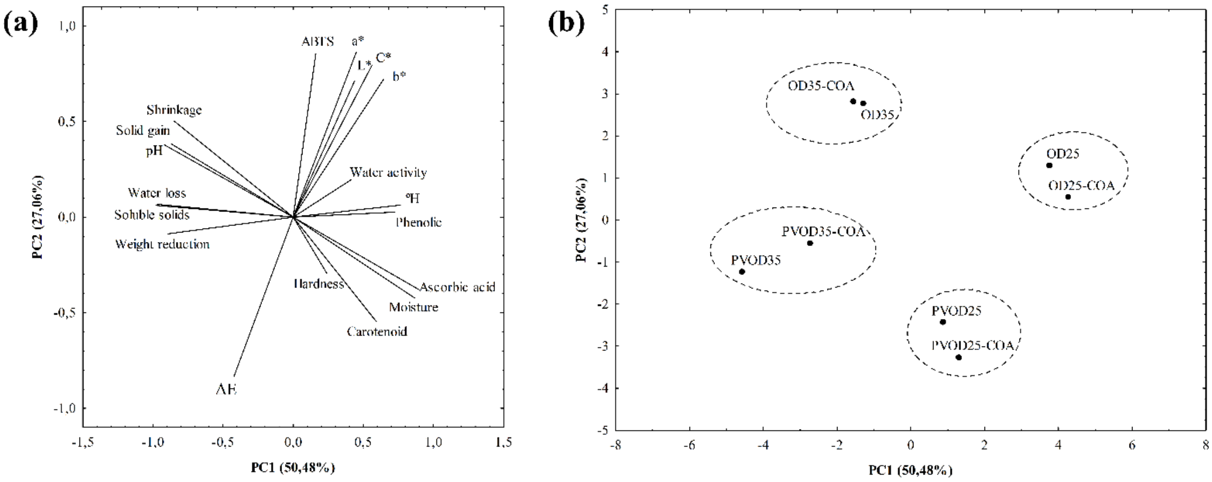
The use of vacuum, in turn, caused the treatments to generate less deformation and wrinkling of the cell walls in the uncoated samples (Figures 6f, 6h). This was not observed in the coated samples (Figures 6g, 6i), as they were more retracted and flattened. According to previous research, the presence of a hydrophilic cut surface on the sample makes adhesion extremely difficult due to low surface energy (Frabetti et al. 2021). Thus, it is understood that the use of vacuum may have aided in the impregnation of the coating, preventing the increase of intercellular space due to gas expansion, since the internal structure does not present turgid and smooth cells in the coated samples (Senturk Parreidt et al. 2019).

3.3 Principal component analysis (PCA)

The loading and score plots were created as illustrated in Figure 7, based on mass transfer responses and qualitative parameters, and were used in PCA to assist in distinguishing between treatments subjected to different osmotic dehydration conditions.

The principal components, PC1 and PC2, accounted for 50.48% and 27.06%, respectively, totaling 77.54% of the total variance of the dataset. As shown in Figure 7b, the treatments were clustered into four groups due to their similarities. The four formed groups were OD25 and OD25-COA, OD35 and OD35-COA, PVOD25 and PVOD25-COA, and PVOD35 and PVOD35-COA, where the evaluated responses were similarly influenced by the treatment within the same cluster.

Figure 7 - Graphical representation of loading (a) and score (b) based on the principal components.



The dashed-line circles represent the groups formed by cluster analysis.

It can be inferred that two factors were crucial in these groupings: the use of vacuum and the concentration of the solution in the employed methods. In other words, isomaltulose concentrations, both at 25% and 35%, along with OD and PVOD variables, emerged as primary characteristics of the obtained responses. On the other hand, it was found that the coating did not influence the observed values; uncoated treatments showed responses similar to coated ones. Such responses were observed by Macedo et al. (2022a) in their study with strawberries, which found that osmotic solution concentration and vacuum use had strong influences on the evaluated responses.

As seen in the score plot (Figure 7b), samples with 35% isomaltulose were located on the negative side of the PC1 axis, while samples with lower concentrations were on the positive side, highlighting the differences between the concentrations. When analyzing the graphical location (Figure 7a) of mass transfer responses, pH, SS, and shrinkage, it is evident that they belong to the same graphical region as treatments PVOD35 and PVOD35-COA, which corresponds with the high values found in these analyses. Conversely, treatments PVOD25 and PVOD25-COA were associated with high values of moisture, ascorbic acid, and carotenoids, and low hardness values.

The PCA concludes that the use of vacuum and higher concentration solutions are recommended when the goal is to achieve higher mass transfer values during osmotic dehydration. Additionally, it is understood that the application of coating did not influence the results when all analyses were considered together.

4 CONCLUSIONS

The application of coating before the osmotic dehydration with vacuum pulse of papaya cubes significantly reduced the solid gain and did not impair the water loss flow. Greater solid gain, water loss, weight reduction, and lower moisture content were observed with the use of the osmotic solution with a higher concentration of isomaltulose. Compared to fresh samples, the values of hardness, carotenoids, and ascorbic acid significantly decreased throughout the process for all treatments. The use of vacuum preserved the antioxidant capacity, but it was not effective in optimizing mass transfer flows. Furthermore, the use of vacuum caused less deformation in the internal structure of the papaya. PCA indicated that treatments with vacuum and 35% isomaltulose concentration showed the best results related to the osmotic process and quality. However, the application of coating is recommended for osmodehydrated products when the reduction of solid gain is desired.

AUTHOR CONTRIBUTIONS

Matheus de Souza Cruz: conceptualization, data curation, formal analysis, investigation, methodology, project administration, validation, visualization, writing, review, and editing. **Jefferson Luiz Gomes Corrêa:** conceptualization, funding acquisition, supervision, and review. **Leandro Levate Macedo:** conceptualization, investigation, methodology, project administration, supervision, review, and editing. **Amanda Aparecida de Lima Santos:** formal analysis, investigation, methodology, writing, and review. **Jhenifer Cristina Carvalho Santos:** formal analysis, investigation, methodology, writing, and review. **Guilherme Mathias Lopes:** formal analysis, investigation, methodology, writing, and review. **Paula Giarolla Silveira:** investigation, methodology, writing, and review.

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CONFLICT OF INTEREST STATEMENT

No potential conflicts of interest were reported by the authors.

DATA AVAILABILITY STATEMENT

The research data are not shared.

ORCID

Matheus de Souza Cruz: https://orcid.org/0000-0002-4125-3341
Jefferson Luiz Gomes Corrêa: https://orcid.org/0000-0002-6818-6927
Leandro Levate Macedo: https://orcid.org/0000-0003-3010-7485
Amanda Aparecida de Lima Santos: https://orcid.org/0000-0001-8662-4911
Jhenifer Cristina Carvalho Santos: https://orcid.org/0000-0002-9060-3141
Guilherme Mathias Lopes: https://orcid.org/0000-0001-8174-6645
Paula Giarolla Silveira: https://orcid.org/0000-0002-3409-8267

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ARTICLE 2 – USE OF ETHANOL IN CONVECTIVE DRYING OF COATED AND OSMOTICALLY DEHYDRATED PAPAYA WITH ISOMALTULOSE

Matheus de Souza Cruz[1*], Jefferson Luiz Gomes Corrêa[1], Leandro Levate Macedo[2], Bruna De Souza Nascimento[1], Amanda Aparecida de Lima Santos[1], Gilson Gustavo Lucinda Machado[1], Paula Giarolla Silveira[1]

[1] Department of Food Science, Federal University of Lavras, Lavras, Minas Gerais, Brazil

[2] Federal Institute of Espírito Santo, Campus Venda Nova do Imigrante, Venda Nova do Imigrante, Espírito Santo, Brazil

*Corresponding author: matheusnetsouza15@gmail.com

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ABSTRACT

Papaya is a tropical fruit with unique sensory characteristics and is an important source of bioactive compounds and antioxidants. Despite its beneficial health effects, the sale of papaya is limited due to its short shelf life and post-harvest losses. The objective of this study was to investigate the convective drying process of papaya that had been coated, osmotically dehydrated, and immersed in ethanol. The papaya cubes were coated with sodium alginate, osmotically dehydrated with isomaltulose (35% w/w; 300 minutes with vacuum application at 80 kPa for the first 20 minutes), and immersed in 95% ethanol for 2 minutes. Convective drying was then performed at 60°C until a final moisture content of 13.02 ± 1.59%. The drying process took between 240 and 340 minutes, and the kinetic behavior of all treatments was well represented by the Fick model with $R^2 > 0.95$. The use of ethanol significantly reduced drying time and consequently energy expenditure. The reduction in drying time was maximized when ethanol was used in conjunction with osmotic dehydration of both coated (COA+PVOD+ET+CD) and uncoated samples (PVOD+ET+CD), achieving a 30% reduction for a total drying time of 240 minutes. Osmotically dehydrated samples exhibited lower shrinkage, hardness, and effective diffusivity. Coating application resulted in better preservation of carotenoids, antioxidant activity, and phenolic compounds; however, leaching of these compounds, particularly ascorbic acid, was significant across all treatments. The results suggest that drying papaya using the COA+PVOD+ET+CD treatment produced a dried product with good physical and nutritional quality at a reduced cost.

Keywords: osmotic dehydration with vacuum pulse, energy consumption, drying rate, mathematical modeling.

1 INTRODUCTION

Papaya (*Carica papaya* L.) is a fruit widely consumed around the world, rich in nutrients, sugars, and vitamins. It has a characteristic flavor and aroma and is commonly found in tropical and subtropical climates. It possesses antioxidant properties as it is a source of phenolic compounds, amines, and flavonoids, and it also contains lycopene and carotenoids. These components emphasize its relevance to human nutrition and health. However, it is a climacteric fruit, highly perishable due to its high water activity (Chandra et al., 2023; Gomes et al., 2018; Monteiro et al., 2022).

Drying emerges as an alternative to mitigate post-harvest losses, extend shelf life, facilitate storage, and diversify marketing options (Chandra et al., 2023). It is one of the oldest and most widely used practices in food preservation, based on reducing water activity, thereby delaying microbial or enzymatic deterioration (Llavata et al., 2020). Convective drying is widely used due to its operational simplicity and low processing cost (Wang et al., 2019; Macedo et al., 2023a).

The quality of the final product is strongly influenced by the drying approach adopted. The application of osmotic dehydration as a pre-treatment to drying results in a partial loss of water and offers a new option for enhancing the sensory or functional properties of the final products (Llavata et al., 2020). For fruits, sucrose is the most commonly used solute to prepare the hypertonic solution. However, given consumers' growing health concerns, recent research has explored replacing sucrose with healthier or more natural sugars (Macedo et al., 2023b). Isomaltulose, known commercially as palatinose, is an alternative solute to sucrose, with low glycemic and cariogenic indices (Macedo et al., 2021). Its use has been studied in papaya (Macedo et al., 2023b), strawberry (Macedo et al., 2021), mango (Do Carmo et al., 2022), among others.

One limitation of osmotic dehydration is the excessive solids gain, which can result in a crystallized and overly sweet texture in the products (Rodriguez, Soteras & Campañone, 2021). This can also negatively impact both processing efficiency and the nutritional composition of the final products (Campañone, Soteras & Rodriguez, 2024). The application of edible coatings, thin layers of materials applied to the surface of the food before the osmotic dehydration process, offers an alternative to control the diffusion of the osmotic agent without hindering water removal from the product (Campañone, Soteras & Rodriguez, 2024; Rodriguez, Soteras & Campañone, 2021). One of the most widely used materials for this purpose is sodium alginate, due to its biodegradability, biocompatibility, low cost, and non-toxic properties.

Through the interaction of sodium alginate with polyvalent metal cations such as calcium, strong gels or biopolymers are formed (Rodriguez; Soteras; Campañone, 2021; Chiumarelli & Hubinger, 2014).

To improve the drying process, in addition to the use of pre-treatments and coatings, other technologies can be employed, such as ultrasound, pulsed electric fields, high pressure, and ethanol immersion. These approaches can significantly reduce drying time, improve the quality of final products, and ensure lower energy consumption (Llavata et al., 2020). The use of ethanol, a low-cost and non-toxic solvent, as a pre-treatment is based on its ability to dissolve cell wall components, resulting in changes to the material's structure, increasing its permeability (Santos et al., 2024; Wang et al., 2019). These effects are driven by the Marangoni effect and changes in vapor pressure. Thus, ethanol pre-treatment has proven effective in reducing drying time, lowering process costs, and reducing the exposure time of the material to high temperatures, thereby preserving food quality (Macedo et al., 2021; 2023a). The use of this solvent has shown beneficial effects on the drying of food materials such as yacon (Silveira et al., 2024), banana (Corrêa et al., 2012), strawberry (Macedo et al., 2021; Macedo et al., 2023a), taioba leaves (Junqueira et al., 2021), peach (Fotiou & Goula, 2024), potato (Guedes et al., 2021), papaya (De Arruda et al., 2022; Santos et al., 2023), acerola residues (Santos et al., 2024), among others.

The objective of this study was to investigate the effects of edible coatings, osmotic dehydration with a vacuum pulse, and the use of ethanol as pre-treatments for convective drying, and to understand the impacts of their combinations on mass transfer kinetics, as well as the physical, physicochemical parameters, and structures of dried papaya cubes, with the goal of preserving their quality.

2 MATERIALS AND METHODS

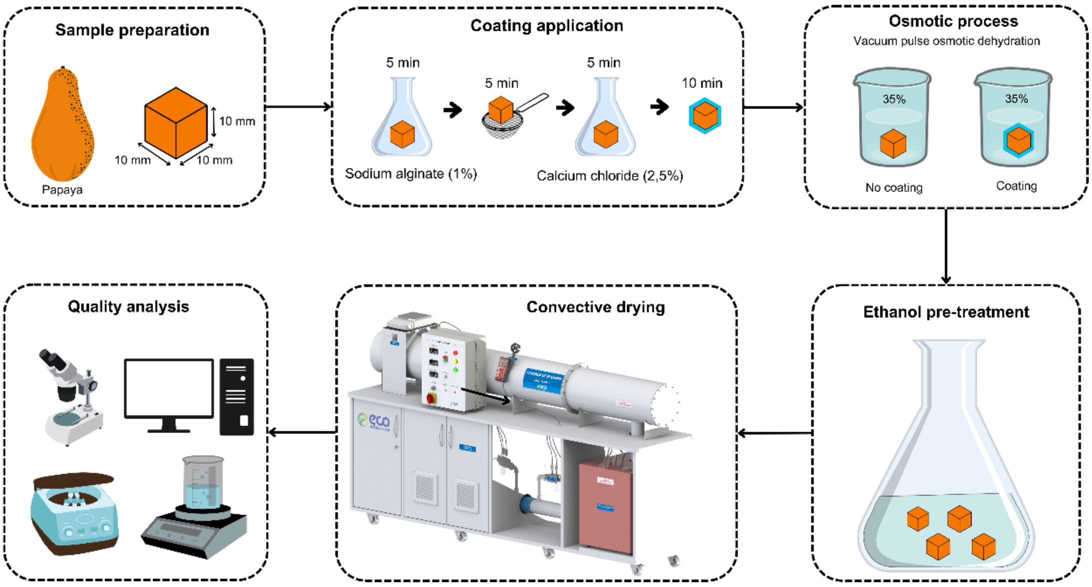
2.1 Raw material and sample preparation

Papayas (*Carica papaya* L. cv. Formosa) were purchased at a local market (Lavras, Minas Gerais, Brazil) and selected according to skin color, degree of maturity and integrity. The fruits were washed in running water and immersed in a sanitizing solution (chlorinated water at 200 ppm) for 15 min. Then, they were cut into slices lengthwise and with the help of a steel mold, 10 mm cubes of papaya pulp were obtained. The initial characteristics of the fresh cubes were as follows: moisture content of 91.03 ± 0.79 (kg of water per 100 kg of sample), water activity of 0.982 ± 0.002, pH of 5.37 ± 0.06, hardness of 3.026 ± 0.775 N and soluble solids of 10.67 ± 1.11 °Brix.

2.2 Experimental conditions

The experiments were planned with the combination of drying and pre-treatments with alginate coating, osmotic dehydration with isomaltulose and immersion in ethanol (Figure 1).

Figure 1 - Graphical representation of the experimental planning.



2.2.1 Preparation and application of the coating

The papaya cubes were immersed in a 1% (w/v) sodium alginate solution (Sigma-Aldrich, Steinheim, Germany) for 5 minutes. The samples were then removed from the solution and placed on a nylon filter mesh sieve (10 cm in diameter) for 5 minutes to remove excess coating. After this, the cubes were immersed for 5 minutes in a 2.5% (w/v) calcium chloride solution (Vetec, Duque de Caxias, Brazil), which was prepared by dissolving powdered $CaCl_2$ in distilled water and stirring at room temperature. Once removed from the $CaCl_2$ solution, the samples were kept at room temperature for 10 minutes to allow cross-linking, and were then drained using absorbent paper (Hissham et al., 2022; Rodriguez, Soteras, and Campañone, 2021).

2.2.2 Osmotic process

The osmotic solution was prepared by dissolving isomaltulose (Beneo-Palatinit, Mannheim, Germany) in distilled water to achieve a concentration of 35%. Pulse vacuum osmotic dehydration (PVOD) was performed out by immersing papaya cubes, with and without coating, in the osmotic solution at a ratio of 1:10 (w/w), at 25 °C, for 300 minutes without agitation (Macedo et al. 2022a). The PVOD process involved applying a vacuum (80 kPa) for the first 20 minutes, after which atmospheric pressure was restored until the 300-minute mark. Following the osmotic process, the samples were immersed in an ice bath for 10 seconds to halt mass transfer. The sample surfaces were then blotted with absorbent paper (Junqueira et al., 2018).

2.2.3 Use of ethanol

Ethanol treatment was performed by immersing the samples in 95% (v/v) ethanol at a 1:5 (w/v) ratio for 2 minutes at 25°C (Silveira et al., 2024).

2.2.4 Convective drying

Drying was performed in a convective tunnel dryer (Eco Engenharia Educacional, model MD018, São José, Brazil) with forced air circulation at a drying air speed of 1.5 m/s and a temperature of 60°C. Papaya samples (70.76 ± 0.40 g) were dried under the experimental conditions described in Table 1.

Table 1 – Experimental drying conditions.

Code	Coating	Osmotic process	Ethanol	Convective drying
CD	No	No	No	Yes
ET + CD	No	No	Yes	Yes
PVOD + CD	No	Yes	No	Yes
PVOD + ET + CD	No	Yes	Yes	Yes
COA + PVOD + CD	Yes	Yes	No	Yes
COA + PVOD + ET + CD	Yes	Yes	Yes	Yes

Abbreviations: CD, convective drying; ET, ethanol pretreatment; PVOD, pulse vacuum osmotic dehydration; COA, application of sodium alginate coating.

The sample holder of the dryer was coupled to an analytical balance (Marte Científica, model AD33000, Brazil) to record the mass variation of the samples during the drying process. Samples were weighed at 5-minute intervals for the first hour and then at 10-minute intervals until they reached a moisture content of 13.02 ± 1.59%. This value was established to ensure that all treatments had a water activity below 0.6 (Macedo et al., 2021).

Drying curves were generated based on the correlation between the moisture ratio (Equation 1) and drying time. Moisture content was evaluated both before and after drying (Souza et al., 2023).

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

where MR is the moisture ratio, X_t is the moisture content at a specific time, X_0 is the initial moisture content and X_e is the final moisture content of the content under previously established conditions.

The drying rate (DR) was calculated according to Equation 2 (Song et al., 2019).

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

where DR is the drying rate, X_t and $X_{t+\Delta t}$ are the moisture (kg of water per kg of dry solid) in t and t + Δt, respectively, t is the time (min) and Δt is the time difference (min).

2.3 Mathematical model

To compare the drying kinetics for different treatments, a unidirectional diffusion model based on the Fick model (Crank, 1975) was used, as represented by Equation 3.

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

where MR is the dimensionless moisture ratio, Deff represents the effective diffusivity (m^2/s), t is the time (s), i is the number of terms in the series and L is the characteristic length (half of the sample thickness) (m).

Starting from Equation 3, an equation for cubic geometry can be derived. According to Treybal (1963), solving Fick's Law for a rectangular geometry results in the product of three dimensionless terms: $[(X_t - X_e)/(X_0 - X_e)]^a$, corresponding to a half thickness a, $[(X_t - X_e)/(X_0 - X_e)]^b$, for a half thickness b and $[(X_t - X_e)/(X_0 - X_e)]^c$, for a half thickness c. In the case of a cube, where a, b and c are equal, this corresponds to applying Fick's solution for an infinite flat plate to a cube, leading to Equation 4.

$$MR = \left[\frac{8}{\Pi^2} \sum_{i=0}^{\infty} \frac{1}{(2i+1)^2} exp\left(-(2i+1)^2\, \Pi^2\, Deff\, \frac{t}{4L^2}\right)\right]^3 \quad (4)$$

where the characteristic dimension now becomes the edge of the cube (2L).

2.4 Estimation of total energy consumption

An estimate of the total energy consumption during the drying process was calculated according to Equation 5 (Corrêa et al. 2021).

$$Et = A \times v \times \rho \times t \times Cp_a \times \Delta T \quad (5)$$

where Et is the total energy consumption (kWh), A is the cross-sectional area of the container in which the sample is placed (m^2), υ is the air speed (m/s), ρ is the air density (kg/m^3), t is the operating period of the equipment (h), Cpa and the specific heat of the air (kJ/kg.K), and ΔT is the temperature difference (K). The density and specific heat of air are functions of temperature, and the values were obtained from thermodynamic tables (Smith et al., 2019).

The energy consumption required to remove 1 kg of water was calculated according to Equation 6 (Macedo et al., 2021).

$$EC = \frac{Et}{m_0 - m_f} \quad (6)$$

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

2.5 Physicochemical and microscopic characterization of dried papayas

The samples were characterized regarding moisture content, water activity, shrinkage, hardness, color parameters, carotenoid content, ascorbic acid, antioxidant capacity, total phenolic compounds, and the microstructural analysis of the papaya cubes.

2.5.1 Moisture content and water activity (a_w)

The moisture content of the samples was determined gravimetrically in a vacuum oven (Solab SL104/40, Piracicaba, Brazil) at 70°C until constant weight (AOAC, 2010). Water activity was determined using a hygrometer (Aqualab, model 3-TE, Washington, United States), at 25 ºC. Measurements were performed in triplicate.

2.5.2 Shrinkage

Sample shrinkage was determined by the displacement method using toluene for volume calculations, based on five replications according to Equation 7 (Gamboa-Santos et al., 2014).

$$Encolhimento\ (\%) = \left(\frac{1-V}{V_0}\right) \times 100 \tag{7}$$

where V and V_0 are the volumes (m3) before and after the drying process, respectively.

2.5.3 Hardness

Hardness was measured in quintuplicate using a texture analyzer (Stable Micro Systems, model TA-X2T, Surrey, England). A 50 kg cell load with 6 mm diameter cylindrical probe was used for measurement. The equipment was configured to automatically fire at a speed of 2 mm/s and a distance of 3 mm to guarantee the penetration of fresh and dry papaya samples. Hardness was obtained through the force peak in the force-deformation curve and expressed in Newton (Macedo et al. 2023a).

2.5.4 Color parameters

The colorimetric parameters (L*, a*, b*, C* and ºh) of the fresh and dried cubes were obtained in quintuplicate using a colorimeter (Shenzhen Linshang Technology Co., Ltd., model LS173, Shenzhen, China). The total color difference (ΔE) of the dry cubes was calculated according to Equation 8, taking the fresh cube as a reference, whose parameters are represented by the subscript “0”.

$$\Delta E = \sqrt{(L^* - L_0^*)^2 + (a^* - a_0^*)^2 + (b^* - b_0^*)^2} \tag{8}$$

2.5.5 Carotenoid content

The carotenoid content was determined for papaya according to the method described by Rodriguez-Amaya (2001), with modifications where 2.0 g of sample was used. The carotenoids were thoroughly extracted with cold acetone until the residue turned white. This residue was washed 3 times with 15 mL of petroleum ether and 35 mL of distilled water using a separation funnel in a dark environment. After washing, the aqueous phase formed in the lower part of the funnel was discarded and the upper phase containing the extract was transferred to a 50 mL volumetric flask and the volume was completed with petroleum ether. The absorbance of the solutions was measured by spectrophotometry with a wavelength of 450 nm, which corresponds to the determination of β-carotene. This is the most abundant carotenoid found in papayas. The carotenoid content was determined based on three replications and expressed in µg/g of sample (dry basis), according to Equation 9.

$$Teor\ de\ carotenoides = \frac{A \times V \times 10^6}{A_{1cm}^{1\%} \times M \times 100} \tag{9}$$

where: A = absorbance of the solution at a wavelength of 450 nm for beta-carotene; V = final volume of the solution in mL; = molar absorptivity coefficient of a pigment in a specific solvent (2592 for beta-carotene); M = mass of the sample taken for analysis in g.$A_{1cm}^{1\%}$

2.5.6 Ascorbic acid

Extract preparation and ascorbic acid quantification were performed according to Barcia et al. (2010) and Vinci et al. (1995), with minor modifications. About 1.0 g of sample was added to 10 mL of aqueous solution of metaphosphoric acid (4.5%). The solution was left to rest for 1 h in an amber glass environment and then centrifuged at 7,000 rpm for 10 min. The supernatant was filtered through a hydrophilic nylon filter, porosity 0.45 mm and diameter 25 mm. The filtrate was transferred to a 1.5 mL amber bottle, followed by an ultrasonic bath (Unique, model USC 2850 A, Indaiatuba, Brazil) for 30 min and kept under refrigeration until quantification. For quantification, high performance liquid chromatography (HPLC, Shimadzu, LC-20AT) equipped with a UV detector (Shimadzu, SPD-20A). A Phenomenex C18 column (250 x 4.6 mm) was used for separation at 30 °C. An aqueous solution of 0.15% (v/v) acetic acid with a flow rate of 1.0 mL/min was used as the mobile phase. Detection was performed at 245 nm. The identification of the ascorbic acid peak was performed out according to the retention time compared to standard solutions. The analytical curve was obtained from standard chromatograms that measure the ascorbic acid peak under the same separation conditions applied to the samples. Standard ascorbic acid concentrations ranged from 1 to 100 mg/L and results from triplicate measurements were expressed as mg/100g of sample (on a dry basis).

2.5.7 Antioxidant capacity and total phenolic compounds

The extract was prepared according to the methodology described by Medina (2011). For this, 3.0 g of the sample was added to the test tubes together with 30 mL of methanol (50% v/v), macerated and stirred for 30 min at room temperature. It was then subjected to 30 min in the ultrasonic bath and the supernatant was collected. Subsequently, 30 mL of acetone (70% v/v) was added to the residue at room temperature and stirred for 30 min. The supernatant was removed and added to the first. The final volume was made up to 50 mL with distilled water. The extract was used to determine the content of phenolic compounds and the antioxidant capacity by capturing the free radical ABTS.

2.5.7.1 Antioxidant capacity

The solution (ABTS+) was prepared by reacting the diammonium salt 2,2'-azinobis (3-ethylbenzothiazoline-6-sulfonic acid) at a concentration of 7 mmol/L with 2.45 mmol/L potassium persulfate. The mixture was left to rest at room temperature in the absence of light for 16 h. The obtained solution was then diluted with ethanol to an absorbance of 0.70±0.05 at 734 nm. The solutions with 3 µL of each extract and 297 µL of the radical solution were homogenized, kept protected from light with a stabilization time of 6 minutes. Then, the reading was performed out using a spectrophotometer (Biochrom, model BIO EZ READ 2000, Cambridge, United Kingdom) using a wavelength of 734 nm and the results of triplicate measurements were expressed as % ABTS reduction, according to Equation 10 (Auzanneau et al. 2018).

$$\%\ de\ redução\ de\ ABTS\ =\ (1\ -\ \frac{A_C - A_S}{A_C})\ \times\ 100 \qquad (10)$$

where Ac is the absorbance of the control and As is the absorbance of the sample.

2.5.7.2 Total phenolic content

The total phenolic compound content assays were determined using the Fast Blue BB reagent according to the sequential method described by Medina (2011). Initially, an aliquot of 0.8 mL of the extract was transferred to a test tube, adding in sequence 0.2 mL of distilled water and 0.1 mL of Fast Blue BB solution followed by homogenization. Then, 0.1 mL of NaOH solution was added, followed by the samples being shaken for 1 minute and kept in a dark environment for 90 minutes. The same procedure was performed out by replacing the sample with the solvent, to obtain the blank. Aliquots (300 µL) were transferred to microtiter plates and the absorbance reading was taken on a spectrophotometer at 420 nm and the phenolic content was determined from the straight line equation obtained from the gallic acid standard curve. The results of triplicate measurements were expressed as milligrams of gallic acid equivalent (GAE)/100g of sample on a dry basis.

2.5.8 Microstructural analysis

Scanning electron microscopy (SEM) was used to analyze the internal structure of the fruit after convective drying. The samples were immersed in liquid nitrogen and fractionated on a metal surface cooled with liquid nitrogen, using a scalpel. Then, these fragments were placed on aluminum supports and covered with a film of aluminum foil using double-sided carbon adhesive tape, duly identified. Finally, all samples were covered with a layer of gold (20 nm) using a spray coater (Bal-tec, model SCD 050®, Schalksmühle, Germany) and viewed with a scanning electron microscope (Tescan, model CLARA FEG- SEM, Libušina, Czech Republic) operating at 20 kV, with a working distance of 11 mm.

2.6 Statistical analysis

The experiments were performed out in triplicate, and the results of the analyses were evaluated by one-way analysis of variance (ANOVA) at a 95% probability level using Statistica 14.0.1.8 (StatSoft Inc., Tulsa, OK, USA). In cases of significant effects ($p \leq 0.05$), means were compared using the Tukey test, while individual comparisons between each treatment and the control sample (fresh sample) were performed using the Dunnett test.

A multivariate analysis was conducted using principal component analysis (PCA) on drying time, energy consumption, water activity, shrinkage, hardness, color parameters, carotenoid content, ascorbic acid, antioxidant activity, and phenolic compounds to correlate these variables with coating application, osmotic process, and the use of ethanol as pre-treatments. Loading and score plots were constructed to evaluate the similarity between treatments based on the analysis responses.

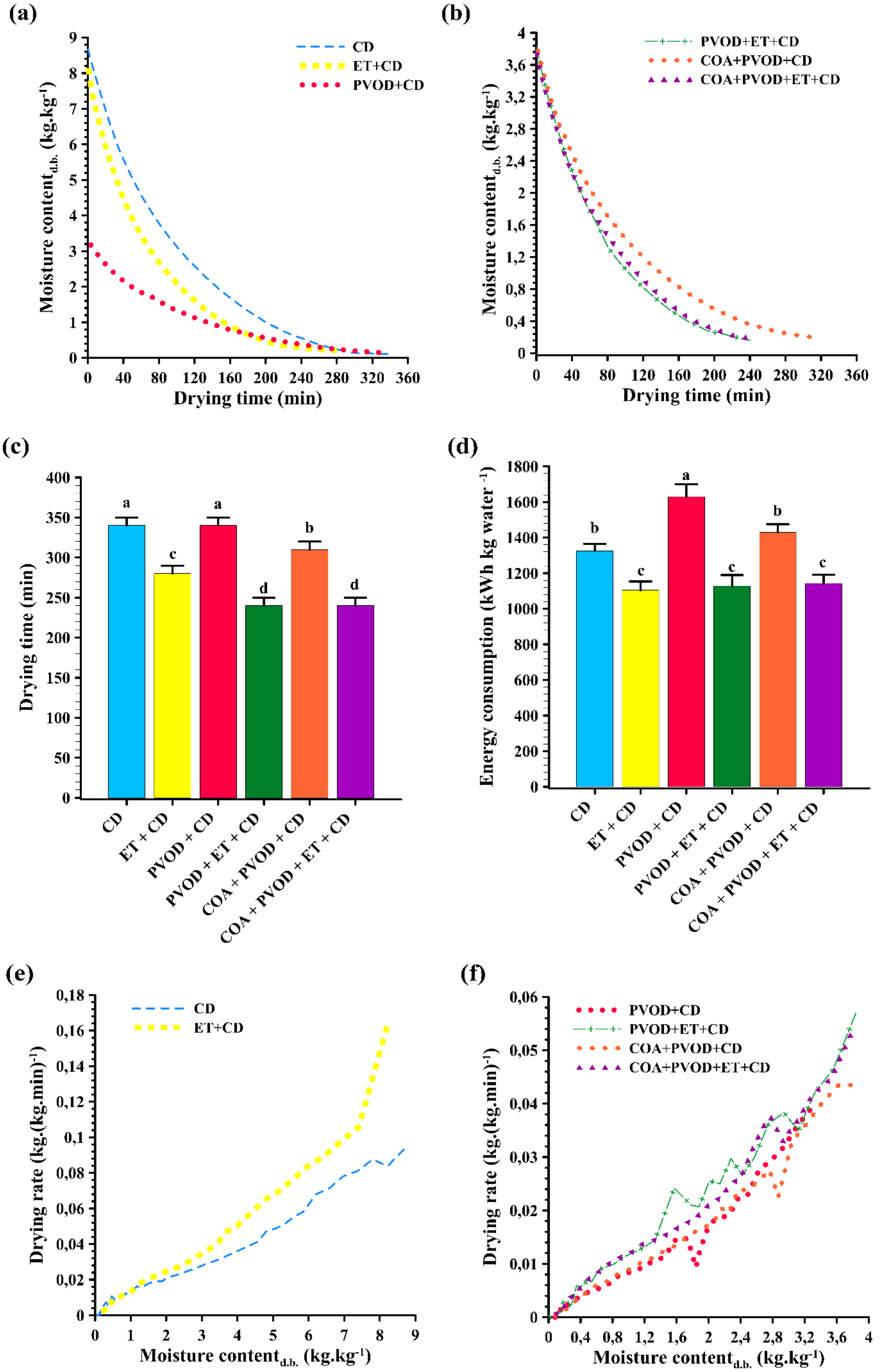
3 RESULTS AND DISCUSSION

3.1 Convective drying

The influence of pre-treatments on the drying characteristics of papaya cubes is shown in Figure 2. Fresh papaya had a moisture content of 91.03 ± 0.79 kg of water per 100 kg of sample, indicating that water is the main component of papayas, as also reported in other studies (Chandra et al., 2023). The osmodehydrated samples had an initial moisture content of 75.42 ± 1.29 kg of water per 100 kg of sample. After drying, a moisture content of 13.02 ± 1.59 kg of water per 100 kg of sample was achieved in a period ranging from 240 ± 10 minutes to 340 ± 10 minutes.

Figures 2 (c-d) show the results regarding drying time and energy consumption for each treatment. It is observed that the reduction in drying time contributed to a decrease in energy consumption, revealing significant differences between treatments ($p<0.05$) without the use of ethanol.

Figure 2 – Drying kinetics (a-b), drying time (c), estimated energy consumption (d) and drying rate (e-f).



The same letter indicates that there is no significant difference between the treatments, according to Tukey's test ($p<0.05$). The bar represents the standard deviation.

The use of ethanol as a pre-treatment resulted in a reduction of up to 30% in drying time. This can be explained by two factors: the Marangoni effect and changes in cell wall thickness (Silveira et al., 2024). The Marangoni effect arises from the difference in surface tension between water and ethanol, which facilitates the evaporation of water molecules. Changes in cell wall thickness reduce the resistance to mass transfer, thereby increasing drying rates (Araújo et al., 2020; Macedo et al., 2021).

It is important to emphasize that the ethanol application was performed using a simple and economically viable methodology, resulting in a significant reduction in the time required to dry the samples. This, in turn, can lead to reduced labor, lower energy consumption, minimized equipment wear, and limited exposure of food to drying conditions, particularly high temperatures, in industrial-scale operations (Maisnam et al., 2015; Macedo et al., 2023a; Rojas, Silveira & Augusto, 2020).

The primary objective of applying osmotic dehydration as a preliminary step in drying processes is to reduce operating time by decreasing the moisture content in osmodehydrated samples compared to fresh samples (Turkiewicz et al., 2020; Bchir et al., 2020). However, in this study, the implementation of osmotic dehydration resulted in a 22% increase in energy consumption due to the extended drying time, consistent with previous findings by Ferreira et al. (2020), Macedo et al. (2023a), and Araya et al. (2022).

This increase in drying time occurs when the solute in the osmotic solution penetrates the cells or pores of the food material, leading to a stronger interaction between water and the product matrix. This solute impregnation increases resistance to mass transfer during convective drying, hindering water evaporation (Vega-Galvéz et al., 2021a; Ferreira et al., 2020; Macedo et al., 2021).

Although osmotic dehydration raised the cost of the drying process, the presence of isomaltulose impregnated in the papaya in this study provides beneficial health properties. Unlike sucrose, which is typically used in the osmotic dehydration of fruits, isomaltulose is a non-cariogenic carbohydrate characterized by low glycemic and insulinemic indices. In this context, isomaltulose can be used in the osmotic dehydration of fruits and vegetables to enrich the final product with a healthier nutritional profile, adding value (Sawale et al., 2017; Lopez et al., 2020; Do Carmo et al., 2022).

Regarding the coated samples, it was found that the application of the alginate coating did not affect the drying behavior of the fruit, as the kinetic curves of coated and uncoated osmodehydrated papaya cubes were nearly identical, as shown in Figure 2 (a-b). Similar behavior was observed in the works of Garcia et al. (2014) and Canizares and Mauro (2015), who studied the effect of pectin coatings, without plasticizer addition, on the moisture content of papayas dried at 60 and 70°C.

Given that an important characteristic of polysaccharide-based edible coatings is their good oxygen barrier properties and low permeability to water vapor, these features may explain why the coating did not interfere with mass transfer during the process. Furthermore, this clarifies why the edible coating did not affect energy consumption during drying (Campañone, Soteras & Rodriguez, 2024; Rodriguez, Soteras & Campañone, 2021; Ferrari et al., 2013).

Based on the drying rate curves shown in Figures 2 (e-f), no constant-rate drying phase was identified, suggesting that the entire papaya drying process occurred during the falling-rate phase. This implies that diffusion was the main physical mechanism governing moisture transport in the samples throughout the drying process (Garcia et al., 2014).

Samples without pretreatment (CD) showed a high drying rate due to their higher moisture content and greater amount of free water, which allowed for more efficient water evaporation during drying. This behavior was amplified by ethanol immersion, as ethanol interacts with the material's components, altering its physical and structural properties. This can increase the material's permeability to mass transfer, facilitating water removal, as previously discussed (Carvalho et al., 2020; Rojas, Silveira & Augusto, 2020).

On the other hand, samples subjected to osmotic pretreatment experienced solute impregnation, which created an additional barrier to water removal, as the water molecules were more strongly bound to the solute molecules. As a result, the drying rate of osmodehydrated samples was slower compared to samples without pretreatment. This difficulty in water removal can prolong the time required to achieve the desired final moisture content and can affect the sensory quality and physical characteristics of the product (Macedo et al., 2021; Ferreira et al., 2020; Araya et al., 2022). However, coated treatments, due to lower solute impregnation during the osmotic process, increased drying rates, especially when combined with ethanol use (COA+PVOD+ET+CD).

The Fick diffusion model was fitted to the drying kinetics data, showing R^2 values above 0.95 for all fittings, indicating that the experimental data were well represented by the diffusion model. Table 2 presents the effective diffusivity (*Deff*) values. The treatments exhibited significant differences ($p<0.05$), with the ET+CD treatment being the most notable due to its Deff value ($4.81 \times 10^{-9} \pm 0.03$ m^2/s). This indicates that ethanol directly impacts the effective diffusivity by facilitating water exit mechanisms and reducing resistance to mass transfer (Silveira et al., 2024). Conversely, the osmodehydrated treatments showed the lowest diffusivity values due to isomaltulose impregnation.

Table 2 – Effective water diffusivities (*Deff*) and coefficient of determination (R^2) for papaya drying kinetics.

Code	**Deff (x10^9, m^2/s)**	**R^2**
CD	3.52 ± 0.02 ^{d}	0.9690
ET + CD	4.81 ± 0.03 ^{a}	0.9840
PVOD + CD	3.29 ± 0.01 ^{e}	0.9770
PVOD + ET + CD	4.59 ± 0.02 ^{b}	0.9662
COA + PVOD + CD	3.60 ± 0.02 ^{d}	0.9740
COA + PVOD + ET + CD	4.32 ± 0.01 ^{c}	0.9657

Mean ± standard deviation (n = 3). The same letter indicates that there is no significant difference between treatments, using the Tukey test ($p<0.05$).

Regarding coating treatments, it was observed that the osmodehydrated sample (PVOD+CD) had an increase in diffusivity when coated (COA+PVOD+CD), with no significant difference ($p<0.05$) compared to the sample without pretreatment (CD). Additionally, the interaction of the coating with ethanol (COA+PVOD+ET+CD) increased the average effective diffusivity by 20%. These results demonstrate that applying an edible coating positively influences drying kinetics, suggesting that the main resistance to drying is the diffusion of water through the fruit tissue. Similar findings were reported by Canizares and Mauro et al. (2015), Garcia et al. (2014), and Rasmussen and De Souza Silva (2019).

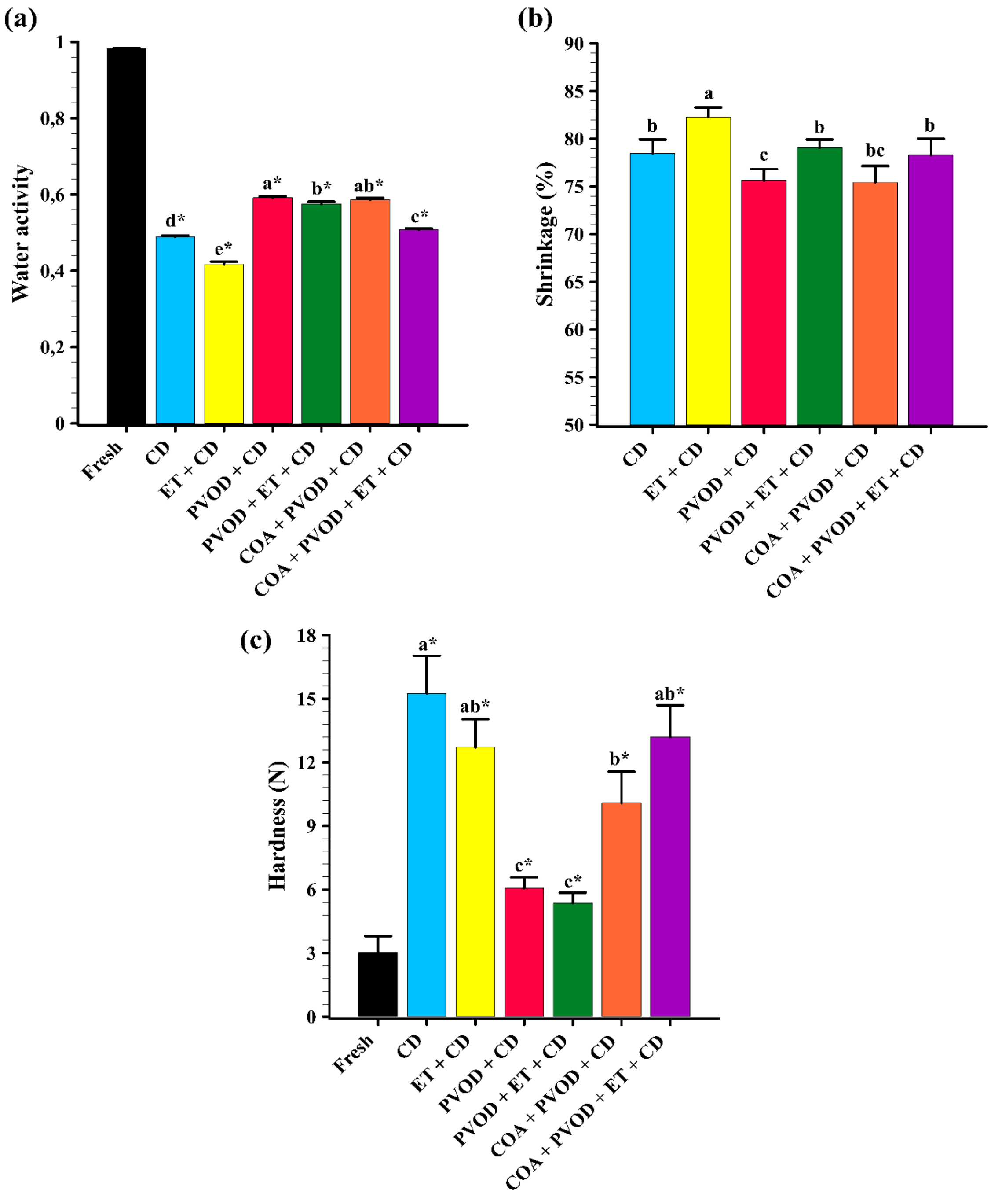
3.2 Physicochemical and microscopic characterization

3.2.1 Water activity

The water activity of fresh and dried samples is shown in Figure 3 (a). Fresh papaya had a high aw value (0.982 ± 0.002), which is characteristic of the fruit (Chandra et al., 2023; Macedo et al., 2023b). This parameter indicates that the food is highly perishable. Therefore, the use of convective drying can extend the shelf life of this food (Macedo et al., 2022b).

Among the treatments, there were significant differences ($p < 0.005$), as osmotically dehydrated papayas exhibited an increase in water activity (aw) compared to non-osmotically treated samples. The impregnation of isomaltulose during the osmotic process impedes water evaporation, as it alters the structure of the food and the interaction between water molecules and the material (Araya et al., 2022).

Figure 3 – Water activity (a), shrinkage (b) and hardness (c) of the samples.



The same letter indicates that there is no significant difference between the treatments, according to Tukey's test ($p<0.05$). The asterisk indicates a significant difference between each treatment and the fresh sample, according to Dunnett's test ($p<0.05$). The bar represents the standard deviation.

The use of ethanol significantly reduced aw, as the solvent increases the permeability of the cell wall, facilitating the removal of water (Silveira et al., 2024; Junqueira et al., 2021). The application of the coating did not influence this parameter. However, it is important to note that all treatments resulted in aw values below 0.6, indicating a minimal probability of microbial growth and chemical reactions (Macedo et al., 2022b).

3.2.2 Shrinkage

The shrinkage values of samples subjected to different treatments ranged from 75.43% to 82.29% (Figure 3b). The smallest shrinkages after drying were observed in samples subjected to PVOD and PVOD combined with coating. This result can be attributed to osmotic dehydration, which increases the solid content of the sample, thereby reducing the movement of the food's solid structure and making it behave more like a glassy state. This, in turn, limits its contraction during convective drying (Ebrahimian, Hashemiravan, & Zand, 2017; Macedo et al., 2021; Mohammadkani, Koocheki, & Mohebbi, 2024).

The use of coating alone showed a significant reduction in shrinkage when compared to the process without any pre-treatment and to those pre-treated with ethanol. The inclusion of calcium in the coating allows certain ions to penetrate the sample, strengthening the tissue structure and preventing shrinkage during the osmotic process (Campañone, Soteras, & Rodriguez, 2024), and thus also after drying.

The use of ethanol resulted in a significant increase in shrinkage compared to treatments without ethanol, as observed by Macedo et al. (2021) for strawberries. This can be explained by the rapid removal of water during the drying process, where the spaces previously occupied by water are filled by the viscoelastic matrix, resulting in material shrinkage. When water removal occurs more quickly, as with ethanol, shrinkage occurs at a higher rate (Macedo et al., 2021). Therefore, it can be concluded that the effect of ethanol predominates over other treatments, leading to increased shrinkage in all treatments.

3.2.3 Hardness

Fresh papayas had a hardness of 3.026 ± 0.775 N (Figure 3c). Samples subjected to the drying process exhibited greater hardness compared to the fresh sample, due to physical changes such as shrinkage and distortion resulting from the reduction in moisture content during drying, which leads to increased firmness of the samples (Macedo et al., 2021; Macedo et al., 2022b). The hardness values obtained for the different drying treatments (ranging from 5.363 to 15.244 N) are comparable to those reported by Chandra et al. (2023), where papaya samples underwent ultrasonic pretreatment and DO before convective drying.

Papaya samples subjected to drying pretreatments showed reduced hardness compared to samples dried without pretreatments. The application of coating significantly differed from treatments without its use, with the coating increasing hardness. This observation is consistent with findings by Ebrahimian, Hashemiravan, and Zand (2017) in pumpkin cubes coated with pectin, and by Rodriguez, Soteras, and Campañone (2021) in pear cubes coated with sodium alginate and pectin.

The coating and solids present in the sample contribute to the formation of a surface crust by enhancing cohesion between internal connections that constitute the material's structure, leading to increased hardness compared to treatments without coating (Mohammadkani, Koocheki & Mohebbi, 2024). Rodriguez, Soteras, and Campañone (2021) also note that the presence of calcium ions in the coating binds to the pectin in the material's cell wall, providing a dual protective effect. Additionally, Ebrahimian, Hashemiravan, and Zand (2017) highlight that uncoated samples, having lower resistance to solid gain during osmotic dehydration, exhibit reduced firmness.

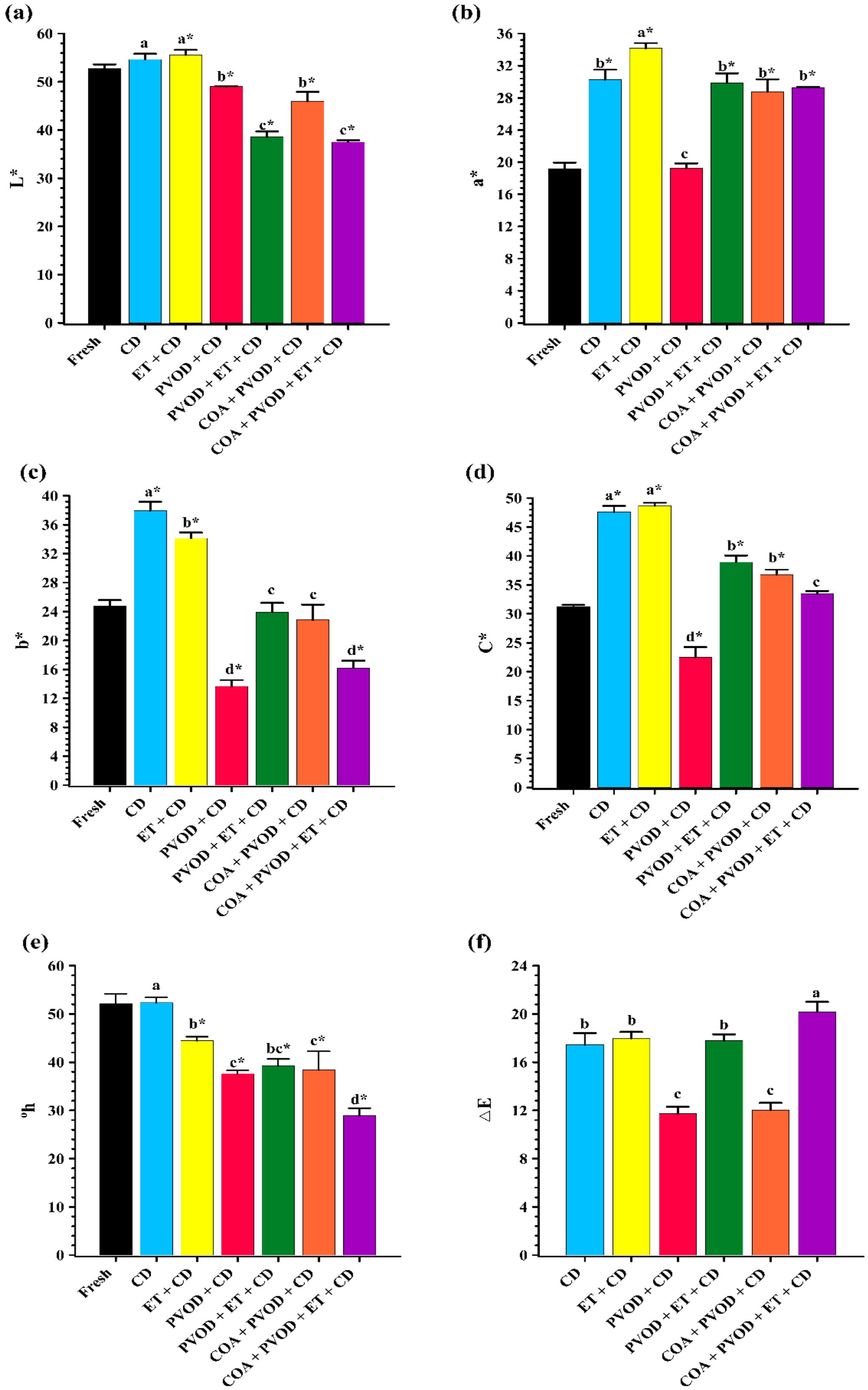
Regarding the use of ethanol, its application compared to drying without any pretreatment resulted in a significant reduction in hardness. However, the process subjected to PVOD did not show a significant difference, with PVOD proving to be the best drying treatment for reducing hardness. The combination of coating, PVOD, and ethanol led to a significant increase in hardness.

3.2.4 Color parameters

Heat treatment through enzymatic reactions, the Maillard reaction, and pigment degradation typically causes browning in fruits and vegetables (Udomkun et al. 2018). Therefore, Figure 4 summarizes the color parameters, including brightness (L*), green/red (a*), blue/yellow (b*), chroma (C*), hue angle (ºh), and color difference (ΔE), of dried papaya cubes.

The L* values for dry samples (Figure 4a) ranged from 37.52 to 55.59, showing a significant difference compared to the fresh sample (L* = 52.72 ± 0.88), with the exception of the CD treatment. Studies by Mishra et al. (2015) and Chandra et al. (2021, 2023) also reported treatments that, after drying, resulted in lower L* values than the fresh sample and showed darkening due to polyphenol oxidase enzyme activity and surface oxidation. Another possibility is the oxidation of phenolics and ascorbic acid, which can lead to the synthesis of complex brown pigments.

Figure 4 – Color parameters L* (a), a* (b), b* (c), C* (d), ◦h (e), and ΔE (f) of fresh and dried papaya.



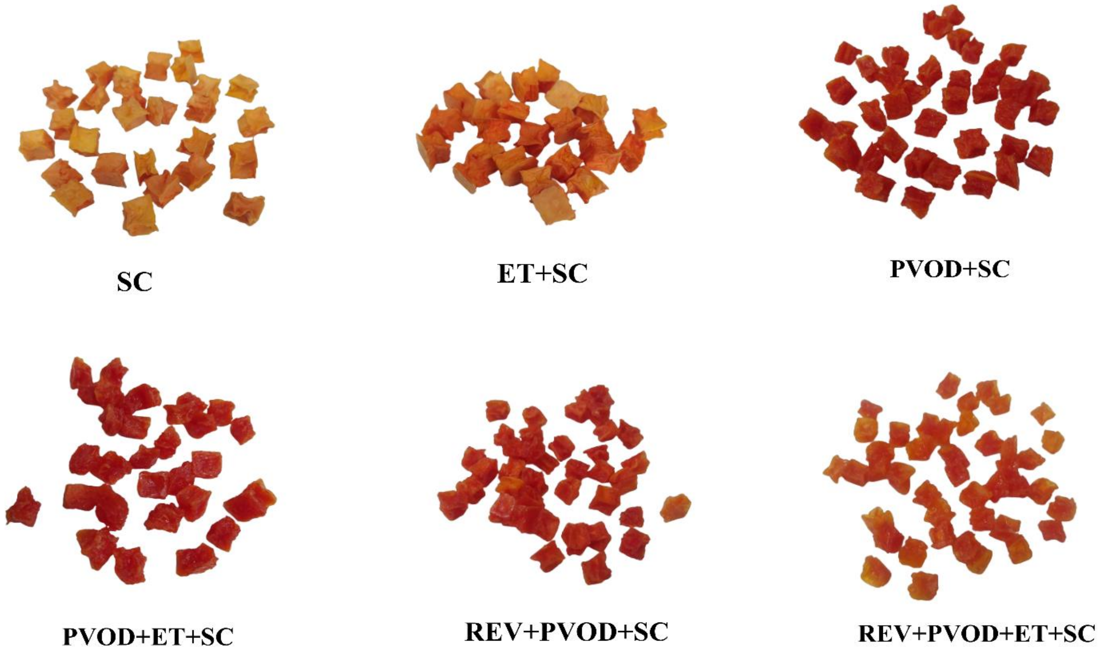
The same letter indicates that there is no significant difference between the treatments, according to Tukey's test (p<0.05). The asterisk indicates a significant difference between each treatment and the fresh sample, according to Dunnett's test (p<0.05). The bar represents the standard deviation.

The a* and b* values for dried papaya cubes varied in the ranges of 19.25–34.16 and 13.66–37.94, respectively, as shown in Figures 4 (b-c). Comparing these values to those of the fresh samples, it was found that a* > 19.19 represents an increase in redness, while b* > 24.76 corresponds to an increase in the yellowing of the dry cubes. This is associated with lycopene, which gives papaya its red color, and β-cryptoxanthin and β-carotene, which contribute to its yellow color (Da Silva Júnior et al., 2018; Chandra et al., 2021).

This study observed that high-temperature drying enhanced the color vibrancy of the papaya cubes, as only the PVOD+CD treatment had a lower value than the fresh sample. In Figure 4 (d), higher C* values are considered more desirable from the consumer's perspective, as they indicate greater color intensity (Chandra et al., 2023). The CD and ET+CD samples showed the highest C* values, 47.62 ± 1.00 and 48.69 ± 0.50, respectively. Regarding hue, the pulp of Formosa papaya has a characteristic orange tone, ranging between red (0º) and yellow (90º). The °h value of the fresh sample was 52.20 ± 1.97, which was statistically similar only to the CD treatment (Figure 4e).

In Figure 4 (f), the ΔE values ranged from 11.74 to 20.17, indicating a noticeable color change, as shown in Figure 5. According to the literature (Pathare et al., 2013), it was understood that all dry samples showed a significant difference compared to the fresh fruit, as they presented ΔE values greater than 3.0. This color change is the result of the osmotic process and convective drying, which, due to high temperatures, produced a darker, more intense orange color in the dried samples (Macedo et al., 2023a; Abrahão & Corrêa, 2023).

Figure 5 - Papaya samples after the convective drying process in a wind tunnel.



3.2.5 Content of carotenoids, ascorbic acid, antioxidant activity and phenolic compounds

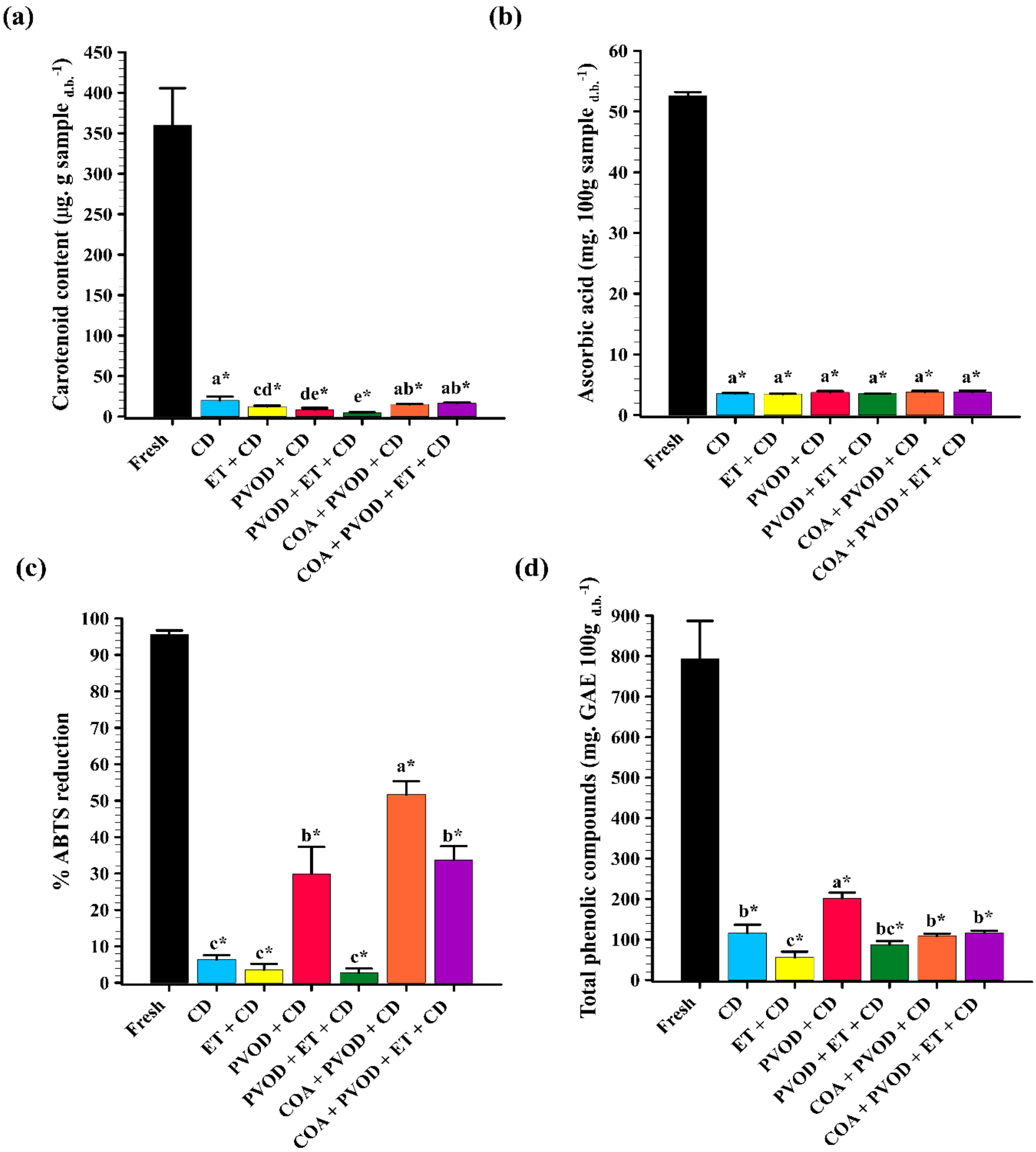
The analyses of carotenoid content, ascorbic acid, antioxidant activity, and phenolic compounds are presented in Figure 6 (a-d), respectively. Fresh papayas are a source of ascorbic acid (vitamin C) and carotenoids, which are precursors of vitamin A in the human body. Moreover, the presence of phenolic compounds with recognized antioxidant properties in papaya highlights its potential significance for human nutrition and health (Mirsha et al., 2015; Chandra et al., 2021).

The fresh samples exhibited the highest values for carotenoid content, ascorbic acid, antioxidant activity, and phenolic compounds, with values of 359.982 ± 45.603, 52.564 ± 0.641, 95.626 ± 1.08, and 794.039 ± 92.937, respectively. All treatments, when compared to the fresh samples, showed a significant reduction. This reduction is due to the drying process, which decreases moisture content and induces physical changes that favor oxidative reactions, leading to the degradation of bioactive and antioxidant compounds (Macedo et al., 2021).

Regarding the total carotenoid content presented in Figure 6(a), the treatments CD, COA+PVOD+CD, and COA+PVOD+ET+CD did not differ significantly ($p<0.05$) in this parameter, showing the highest averages of 19.886 ± 4.167, 15.203 ± 0.461, and 16.387 ± 0.983 µg/g on a dry basis, respectively. It is evident that the application of the coating was effective in maintaining carotenoid levels, serving as a barrier to the leaching process. On the other hand, PVOD significantly reduced the compound content. A similar result was reported by Chandra et al. (2023), who noted that osmotic treatment and convective drying substantially reduced the β-carotene content in papaya. Júnior et al. (2018) also observed a similar outcome, reporting a reduction in carotenoid content when subjected to vacuum drying. This is likely due to exposure to high temperatures and prolonged processing times, as these pigments are highly unstable and prone to degradation and/or isomerization (Goula & Adamopoulos, 2010). Although the use of ethanol reduced drying time, it did not influence the conservation of carotenoid levels.

Regarding ascorbic acid (Figure 6b), a reduction in vitamin C content was observed across all treatments (CD, ET+CD, PVOD+CD, PVOD+ET+CD, COA+PVOD+CD, COA+PVOD+ET+CD), with no significant differences between them, as indicated by the Tukey test ($p<0.05$). The overall average was 3.64 mg/100g, suggesting that all pre-treatments influenced the vitamin C content of the fruit. Vega-Gálvez et al. (2021b) reported similar behavior when vacuum drying papaya, observing a 27% reduction in vitamin C content. Indeed, ascorbic acid is considered a thermosensitive compound, often used as an indicator of good processing practices. However, thermal damage to the product during drying is directly proportional to the processing time (Júnior et al., 2018).

Figure 6 – Carotenoid content (a), ascorbic acid (b), antioxidant activity by ABTS (c) and total phenolic compounds (d) of the samples.



The same letter indicates that there is no significant difference between the treatments, according to Tukey's test ($p<0.05$). The asterisk indicates a significant difference between each treatment and the fresh sample, according to Dunnett's test ($p<0.05$). The bar represents the standard deviation.

Comparing the dried samples (Figure 6c), it was observed that the COA+PVOD+CD treatment showed the highest antioxidant capacity (Tukey $p<0.05$), while samples pre-treated with ethanol followed by drying exhibited lower antioxidant capacity. This suggests that treatments combining coating, drying, and osmotic dehydration are effective in retaining higher antioxidant capacity. These results differ from those reported by Bitencourt et al. (2022), who found that pre-treatment with ethanol and subsequent drying did not affect the phenolic compounds in pineapple pomace. This indicates that the effect of pre-treatment with ethanol and drying may vary depending on the food matrix.

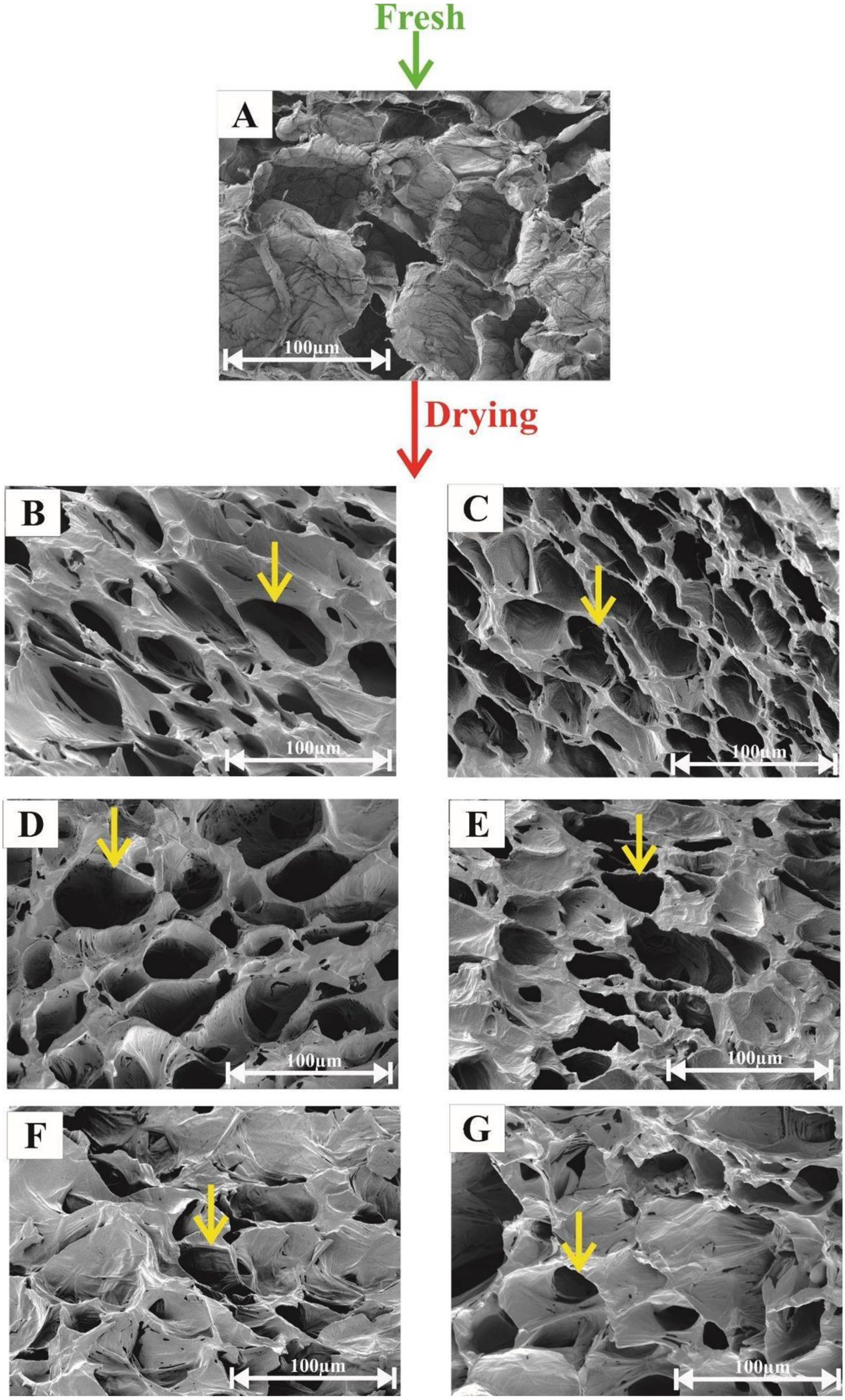
Regarding phenolic compounds (Figure 6d), samples treated with ethanol showed the lowest phenolic values. However, when combined with coating (COA+PVOD+ET+CD), there was no significant difference. The application of the coating reduced phenolic retention only when interacting with ethanol. PVOD significantly influenced phenolic compound retention, as the PVOD+CD treatment retained more phenolic compounds compared to the other treatments (Tukey $p<0.05$). This observation was also reported by Chandra et al. (2023), who found higher phenolic content in papaya treated with osmotic dehydration and convective drying. Izli, Izli, and Taskin (2018) also found that drying treatments greatly influence the total phenolic content in pineapple. According to the authors, drying treatments have a variable effect on phenolic compounds.

3.2.6 Microstructural analysis

The morphological characterization of fresh and dried papaya cubes is shown in Figure 7. From this figure, it is possible to observe that the cells in the fresh samples (Figure 7a) exhibit elongated, polyhedral shapes with well-defined cell walls. The use of ethanol (Figures 7c, 7e, and 7g) did not cause cell rupture, and the cell shape was preserved. However, a difference in cell wall thickness was observed. The use of PVOD and COA did not induce structural changes in the observed cells.

According to Silveira et al. (2024), the application of ethanol can result in the extraction of certain elements from the cell wall and membrane, which reduces their thickness but does not remove substances such as cellulose, hemicellulose, and lignin. This keeps the cell walls thinner, preventing them from collapsing.

Figure 7 – Scanning electron micrograph of the tissue of dried papaya cubes.

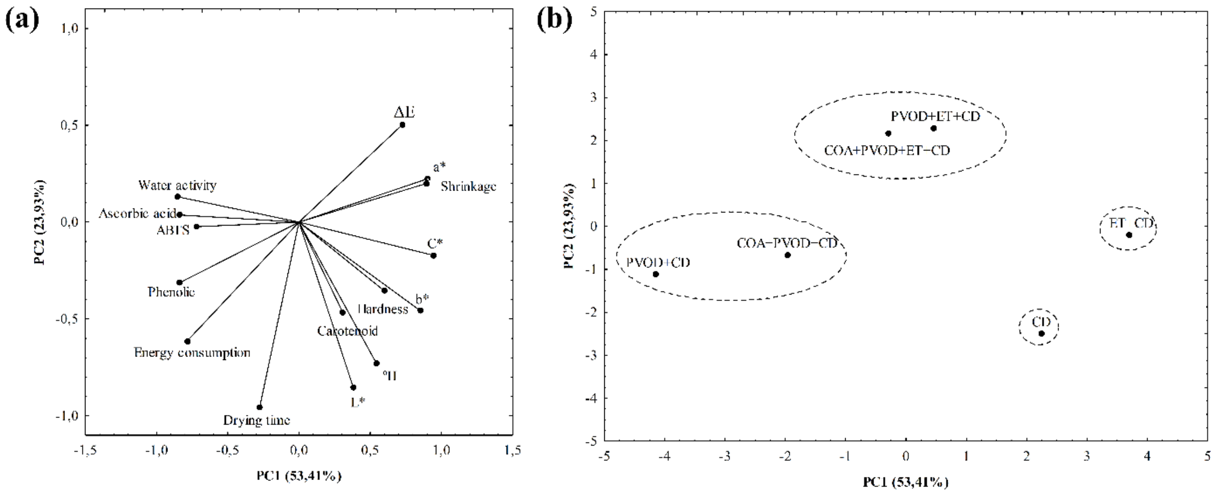


A) Fresh; **B)** CD; **C)** ET+CD; **D)** PVOD+CD; **E)** PVOD+ET+CD; **F)** COA+PVOD+CD; **G)** COA+PVOD+ET+CD

3.3 Principal component analysis (PCA)

According to the PCA results presented in Figure 8, the two main components, PC1 and PC2, explained 52.40% and 26.94% of the variation, respectively, representing a total of 79.34% of the global variability in the dataset. Based on Figure 10b, it was possible to identify through the PC2 axis that the previously dehydrated dry samples are located on the negative side, while the previously dehydrated dry samples immersed in ethanol are on the positive side, highlighting the differences in the results for the PVOD and ET combination. When analyzing the PC1 axis, it became evident that treatments not previously subjected to the osmotic process were located in the negative zone. In this way, four groups were formed: (I) PVOD+CD and COA+PVOD+CD, (II) PVOD+ET+CD and COA+PVOD+ET+CD, (III) ET+CD, and (IV) CD, all due to the similarities in the results.

Figure 8 – Graphical representation of loading (a) and score (b) based on the principal components.



The dashed-line circles represent the groups formed by cluster analysis.

The joint evaluation of Figures 8 (a-b) allows for the association of drying treatments with the maximum values of analytically determined characteristics, regardless of whether this trend is positive or negative. It was observed that treatments using ethanol resulted in shorter drying times and lower energy consumption. Previously dehydrated treatments tended to show higher levels of ascorbic acid, antioxidant activity, and phenolic compounds. Greater shrinkage and hardness were linked to the CD and ET+CD samples, along with higher levels of phenolic compounds. Therefore, in the search for isomaltulose-enriched papayas containing bioactive compounds and antioxidants, with a fast and low-cost process, dried fruits whether coated or not should be dehydrated and immersed in ethanol.

4 CONCLUSIONS

The results highlight that pre-treatment with ethanol effectively reduced drying time and energy consumption; however, it resulted in greater sample shrinkage. In contrast, osmotic dehydration using isomaltulose prolonged convective drying time and reduced effective diffusivity. Additionally, it preserved color characteristics, minimized shrinkage, and achieved higher water activity. Treatments with coating application showed better conservation of phenolic compounds, carotenoids, and antioxidant activity. From a nutritional standpoint, all treatments exhibited significant degradation of vitamin C content. The Fick model accurately described the drying behavior of papaya samples under different treatments ($R^2 > 0.95$). Considering an overall assessment of the results, the combination of coating, vacuum pulse osmotic dehydration, and ethanol as pre-treatments is recommended for drying papaya cubes due to the fast, low-cost process and preservation of high nutritional content, in comparison to other treatments.

AUTHOR CONTRIBUTIONS

Matheus de Souza Cruz: conceptualization, data curation, formal analysis, investigation, methodology, project administration, validation, visualization, writing, review, and editing. **Jefferson Luiz Gomes Corrêa:** conceptualization, funding acquisition, supervision, and review. **Leandro Levate Macedo:** conceptualization, investigation, methodology, project administration, supervision, review, and editing. **Bruna De Souza Nascimento:** conceptualization, supervision and review. **Amanda Aparecida de Lima Santos:** formal analysis, investigation, methodology, writing, and review. **Gilson Gustavo Lucinda Machado:** formal analysis, investigation, methodology, writing, and review. **Paula Giarolla Silveira:** investigation, methodology, writing, and review.

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CONFLICT OF INTEREST STATEMENT

No potential conflicts of interest were reported by the authors.

DATA AVAILABILITY STATEMENT

The research data are not shared.

ORCID

Matheus de Souza Cruz: https://orcid.org/0000-0002-4125-3341
Jefferson Luiz Gomes Corrêa: https://orcid.org/0000-0002-6818-6927
Leandro Levate Macedo: https://orcid.org/0000-0003-3010-7485
Bruna De Souza Nascimento: https://orcid.org/0000-0002-7797-8344
Amanda Aparecida de Lima Santos: https://orcid.org/0000-0001-8662-4911
Gilson Gustavo Lucinda Machado: https://orcid.org/0000-0003-3778-0357
Paula Giarolla Silveira: https://orcid.org/0000-0002-3409-8267

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