IARAMARUM DE JESUS FALCÃO

SECAGEM HÍBRIDA CONVECTIVA-INFRAVERMELHA PARA A PRODUÇÃO DE BANANA-PASSAS

LAVRAS – MG
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Dissertação apresentada à Universidade Federal de Lavras, como parte das exigências do Programa de Pós-Graduação em Engenharia de Alimentos, área de concentração em Engenharia de Alimentos, para a obtenção do título de Mestre.

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IARAMARUM DE JESUS FALCÃO

SECAGEM HÍBRIDA CONVECTIVA-INFRAVERMELHA PARA A PRODUÇÃO DE BANANA-PASSAS

HYBRID CONVECTIVE-INFRARED DRYING FOR THE PRODUCTION OF DRIED BANANA

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

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RESUMO GERAL

A produção de bananas secas pode reduzir as perdas pós-colheita e agregar valor ao produto. Este estudo investigou as cinéticas de secagem de bananas, combinando radiação infravermelha em diferentes níveis de potência (140, 160 e 180 W) e convecção de ar aquecido a diferentes temperaturas (50, 60 e 70 °C), além de três níveis de intermitência (0, 0.333 e 0.667). O teor final de umidade das amostras variou de 17% (P = 180 W e T = 70 °C, α = 0) a 57,4% b.u. (P = 160 W, T = 50 °C, α = 0.667). O consumo específico de energia (SEC) variou de 23,62 kWh/kgH2O (P = 180 W, T = 70 °C, α = 0.333) a 74,49 kWh/kgH2O (P = 140 W, T = 50 °C), enquanto as emissões de CO_2 (qCO_2) oscilaram entre 0,121 e 0,213 mgCO_2. A difusividade efetiva foi estimada entre $5{,}47 \cdot 10^{-4}$ e $1{,}37 \cdot 10^{-3}$ mm²/s, e a energia de ativação variou de 13,69 a 17,63 kJ/mol. As propriedades termodinâmicas nas secagens contínuas ΔH (11,95 a 13,41 kJ/mol), ΔS (-259,14 a -258,56 J/mol K) e ΔG (83,65 a 89,89 kJ/mol) também foram calculadas. A qualidade do produto seco foi avaliada em termos de pH (4,33 a 4,79), sólidos solúveis (28 a 83 °Brix), atividade de água (0,43 a 0,52) e dureza (2,02 a 39,77 N). A condição ótima (P = 180 W, T = 60 ºC e α = 0,389) apresentou uma desejabilidade global de 0,83, indicando um produto de alta qualidade, dentro dos limites de especificação (Mf, Aw, TSS e firmeza), maximizando o desempenho do processo (Def e SEC) e reduzindo o impacto ambiental (qCO_2).

Palavras-chave: secagem híbrida; consumo específico de energia; propriedades termodinâmicas; qualidade do produto seco; função de desejabilidade.

GENERAL ABSTRACT

The production of dried bananas can reduce post-harvest losses and add value to the product. This study investigated the drying kinetics of bananas by combining infrared radiation at different power levels (140, 160, and 180 W) and heated air convection at different temperatures (50, 60, and 70 °C), along with three intermittence levels (0, 0.333, and 0.667). The final moisture content of the samples ranged from 17% (P = 180 W and T = 70 °C, α = 0) to 57.4% w.b. (P = 160 W, T = 50 °C, α = 0.667). Specific energy consumption (SEC) varied from 23.62 kWh/kgH2O (P = 180 W, T = 70 °C, α = 0.333) to 74.49 kWh/kgH2O (P = 140 W, T = 50 °C), while CO_2 emissions (qCO_2) ranged between 0.121 and 0.213 $mgCO_2$. The effective diffusivity was estimated between $5.47\cdot10^{-4}$ and $1.37\cdot10^{-3}$ mm^2/s, and activation energy ranged from 13.69 to 17.63 kJ/mol. The thermodynamic properties in continuous drying, ΔH (11.95 to 13.41 kJ/mol), ΔS (-259.14 to -258.56 J/mol K), and ΔG (83.65 to 89.89 kJ/mol) were also calculated. The quality of the dried product was evaluated in terms of pH (4.33 to 4.79), soluble solids (28 to 83 °Brix), water activity (0.43 to 0.52), and hardness (2.02 to 39.77 N). The optimal condition (P = 180 W, T = 60 °C, and α = 0.389) achieved an overall desirability of 0.83, indicating a high-quality product within specification limits (Mf, Aw, TSS, and firmness), while maximizing process performance (Def and SEC) and reducing environmental impact (qCO_2).

Keywords: hybrid drying; specific energy consumption; thermodynamic properties; dried product quality; desirability function.

INDICADORES DE IMPACTO

Os resultados da pesquisa sobre a aplicação da secagem híbrida infravermelha-convectiva geraram impactos relevantes do ponto de vista tecnológico, econômico, ambiental e social. A principal contribuição tecnológica reside na definição de condições ótimas de operação, obtidas por meio da metodologia de superfície de resposta associada à função de desejabilidade, considerando simultaneamente o desempenho do processo, a qualidade do produto e os aspectos ambientais. A pesquisa proporcionou avanços no aproveitamento de excedentes e frutos fora do padrão comercial da banana, promovendo a redução de perdas pós-colheita e agregando valor à cadeia produtiva. Do ponto de vista econômico, os resultados indicam viabilidade na redução de custos operacionais e na melhoria da qualidade da banana-passas, aumentando sua competitividade no mercado. A tecnologia desenvolvida apresenta aplicabilidade direta para pequenos e médios produtores, que representam a maior parte da produção no estado de Minas Gerais, terceiro maior produtor nacional. A interação com produtores da região de Lavras-MG reforça o caráter extensionista do trabalho, que gerou interesse na adoção da tecnologia como alternativa para diversificação de produtos e incremento de renda. Os impactos estão alinhados aos Objetivos de Desenvolvimento Sustentável (ODS) da ONU, especialmente o ODS 2 (Fome Zero) e o ODS 12 (Consumo e Produção Responsáveis), ao contribuir para a redução de desperdícios e o uso eficiente de recursos. Além disso, os impactos se enquadram nas áreas temáticas de Tecnologia e Produção, Meio Ambiente, Trabalho e Educação, segundo a Política Nacional de Extensão, fortalecendo o potencial de aplicação da tecnologia e sua contribuição para o desenvolvimento regional sustentável.

IMPACT INDICATORS

The research on the application of hybrid infrared-convective drying has generated significant technological, economic, environmental, and social impacts. The main technological contribution lies in the definition of optimal operating conditions using the response surface methodology associated with the desirability function. This approach enables the simultaneous optimization of process performance, product quality, and environmental aspects. The results also promote advances in the utilization of surplus and off-grade bananas, contributing to the reduction of post-harvest losses and adding value to the production chain. From an economic perspective, the research demonstrates feasibility in reducing operational costs and improving the quality of dried bananas, thereby increasing their market competitiveness. The developed technology is directly applicable to small and medium-sized producers, who represent the majority of production in the state of Minas Gerais, the third-largest banana producer in Brazil. Interaction with producers in the Lavras-MG region reinforces the extension-oriented nature of the project, generating interest in adopting the technology as an alternative for product diversification and income growth. The impacts are aligned with the United Nations Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger) and SDG 12 (Responsible Consumption and Production), by contributing to waste reduction and efficient resource use. Furthermore, the research aligns with the thematic areas of Technology and Production, Environment, Labor, and Education, as defined by the National Extension Policy, strengthening its potential for application and its contribution to sustainable regional development.

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PRIMEIRA PARTE

1. INTRODUÇÃO GERAL

A banana é a fruta fresca mais exportada no mundo, tanto em quantidade quanto em valor (FAO, 2019). Estima-se que a área plantada de banana seja de 56 milhões de hectares, com uma produção anual de 114 milhões de toneladas. No Brasil, a bananicultura é praticada em quase todos os estados, tornando o país o quarto maior produtor mundial de bananas.
Apesar da grande produção, os bananicultores enfrentam um desafio na preservação dos frutos maduros, o que contribui para uma perda estimada de 40% da produção na etapa pós-colheita. As bananas possuem um teor de umidade de aproximadamente 70% em base úmida e são altamente higroscópicas, isso facilita o crescimento de micro-organismos que levam à deterioração das principais propriedades organolépticas da fruta, ocasionando a perda de valor nutricional e, consequentemente, perda de seu valor comercial (Martínez *et al*.,2023; Leite *et al*., 2007).

Grilo e Lacerda (2013) relataram que a banana tem uma vida útil muito curta devido ao seu rápido amadurecimento, processo que é percebido pelas manchas escuras que aparecem na casca da fruta. Para evitar essa degradação causada pelo amadurecimento, a fruta destinada ao armazenamento mais prolongado deve ter um teor de umidade reduzido. Para isso, é necessário que a banana seja submetida a um processo de secagem. O teor ideal é de 15% em base úmida, porém abaixo de 25%, as bananas já são estáveis contra a ação de micro-organismos que as degradam (Lima *et al*., 2000; Nunes *et al*., 2014). Além de aumentar a vida útil do produto, a secagem diminui o peso das frutas e reduz o volume de armazenamento e transporte e, consequentemente, o custo final do produto (Aral *et al*., 2016).

O produto da secagem da banana com teor mínimo de umidade de 25%, é a banana-passas e a secagem convectiva em estufa é a técnica mais usada para produzi-la. Apesar disso, o uso da secagem convectiva apresenta desvantagens como a degradação de compostos sensoriais como a cor e a textura e pelo elevado tempo de exposição ao ar aquecido e o alto gasto energético do equipamento (Fellows, 2006; Lopes,2016). Diferentes estudos vêm sendo desenvolvidos para minimizar tais desvantagens. Alguns reportam que o aumento da velocidade do ar diminui o tempo final do processo; no entanto, ainda há necessidade de novos métodos que aliem a diminuição do tempo e a conservação das propriedades nutricionais e organolépticas do produto (Lopes,2016; Queiroz *et al*.,2008).

A secagem infravermelho (IV) tem se mostrado uma tecnologia de secagem de alta eficiência e com grandes vantagens ao processo como o baixo consumo de energia e tempo de processamento reduzido e também ao produto final, que além de aumentar a vida útil, ajuda a preservar as propriedades nutricionais do mesmo. No entanto, a técnica pode levar à degradação de alguns nutrientes, como os compostos bioativos, devido à alta temperatura aplicada no material. Para minimizar esse inconveniente, vem sendo investigados métodos de secagem híbridos (Aboud *et al*., 2019; Su *et al.*, 2020).

A secagem híbrida é a junção de duas ou mais técnicas em um mesmo processo de secagem, sendo uma alternativa interessante para produtos alimentícios termos sensíveis, por permitir a redução da temperatura de secagem. Além disso, os métodos híbridos têm se provado ser mais econômicos, devido à redução do consumo energético e mais promissores em manter a maioria dos atributos de qualidade do produto (Chen *et al*., 2017).

Visando reduzir ainda mais o gasto energético nas operações de secagem tem sido cada vez mais empregado o método intermitente. A secagem intermitente é descrita como uma variação do fornecimento de energia térmica para o processo. Durante o período de têmpera, o material permanece sem contato com o ar de secagem e há migração de umidade por meio da difusão do interior do material para a sua superfície, fazendo com que se tenha uma nova distribuição de temperatura e umidade, favorecendo a transferência de massa. Assim, ao se adicionar calor novamente ao processo, a secagem se torna mais efetiva e acontece mais rapidamente, com menor tempo de exposição do material a elevadas temperaturas (Allaf *et al.,* 2015; Chua *et al*., 2005; Kumar *et al*., 2014b).

Diante do exposto, a combinação de técnicas de secagem, como a secagem convectiva e infravermelha, e a aplicação do método intermitente, emerge como uma solução promissora para os desafios enfrentados na produção de banana-passas. A busca por uma tecnologia que não apenas otimize o consumo energético, mas também preserve as propriedades sensoriais e nutricionais do produto, torna-se fundamental para a sustentabilidade da bananicultura e para a minimização de perdas na pós-colheita. Assim, o desenvolvimento de processos híbridos, com o controle de parâmetros como temperatura, potência e intermitência, tem um papel significativo para o aprimoramento das técnicas de secagem.

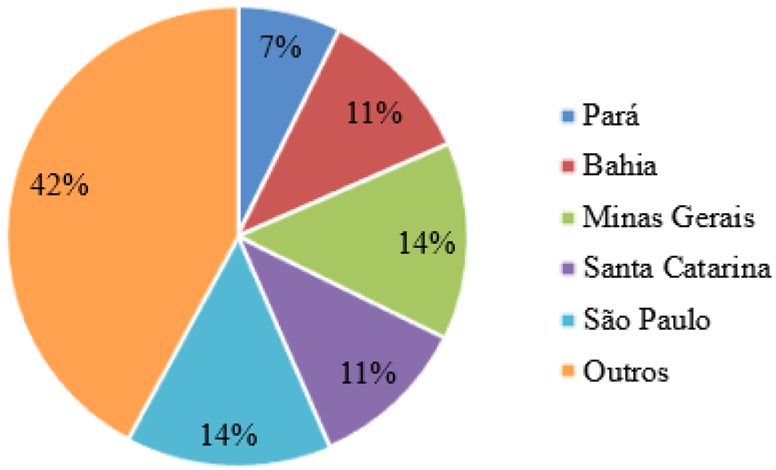
2. REFERENCIAL TEÓRICO

2.1 Banana

A banana (*Musa spp.*) é uma fruta mais consumida do mundo e de alto valor nutricional, cultivado em quase todos os países de clima tropical, sendo que no Brasil o seu consumo médio per capita chega a ser de 25 kg/ano. No mercado internacional, os maiores produtores são a Índia (26,5%), a China (9,4%), Indonésia (7%) e em quarto lugar o Brasil (5,5%). A produção de banana mundial gera mais de 500 mil empregos diretos, demonstrando assim o seu importante papel econômico no Brasil e no mundo (Embrapa, 2023; Farhaninejad *et al.*, 2017).

Em 2023, no Brasil, foram produzidas 6.825.724 toneladas de banana com uma produção igual a R$ 13.808.363 mil reais. Apenas no estado de São Paulo houve uma produção de R$ 1.986.449 (IBGE, 2023). São Paulo destaca-se como o maior arrecadação em reais de bananas do Brasil com uma participação de 14,4% na produção total, seguido por Minas Gerais (13,99%), Santa Catarina (11,2%), Bahia (11,1%) e Pará (7,3%). Os demais estados respondem por 42% da participação, conforme mostra a Figura 1.

Figura 1: Principais estados de produtores de banana no Brasil em 2023 em milhões de reais segundo o IBGE.



Fonte: Do Autor (2025).

Existem diversas variedades de banana no Brasil, porém as principais variedades que tem maior produtividade e são mais consumidas e comercializadas são as variedades do tipo

Prata, Pacova, Terra, Nanica, Maçã e Ouro, sendo que as bananas das variedades Prata e a Pacova são responsáveis por mais de 60% da área cultivada com banana no território brasileiro. A banana tem em sua composição básica água, proteínas e carboidratos. Além, disso a mesma é rica em potássio e apresenta outros componentes importantes em menor quantidade como o cálcio, magnésio, zinco, fósforo e ferro (Alves, 1999; Lima *et al.*, 2000).

Devido às suas características sensoriais e expressivo valor nutricional, a banana é uma fruta com grande aceitação. Porém propriedades nutricionais e comerciais das bananas são afetadas pelas condições de amadurecimento e armazenamento da mesma. A banana apresenta alta taxa respiratória e alta produção de etileno na etapa de pós colheita. Por ser uma fruta climatérica, que é sensível ao etileno, ou seja, amadurece sob a influência do etileno, é um alimento de alta perecibilidade. Para se evitar a perda do produto causado pela degradação, é necessário utilizar técnicas de processamento que diminuam o teor de água e consequentemente, prolonguem a vida útil do produto (Nunes *et al*., 2014).

Os principais produtos derivados do processamento de banana são o purê com 55% da produção, a bananada com 20%, a banana-passas com 13%, a banana em flocos com 10% e a banana chips com 2% da produção total. Além disso, diversos produtos podem ser obtidos a partir do processamento da banana como as frutas em calda, frutas cristalizadas, balas, farinha, pó, suco clarificado simples ou concentrado, néctar, vinho, vinagre, cerveja, aguardente, licor etc. A banana pode ainda ser utilizada como ingrediente base de diferentes produtos como tortas, bolos, biscoitos, cereais matinais, barras de frutas e cereais, alimentos infantis e dietéticos, iogurtes, sorvetes, bombons etc. (Embrapa, 2021).

2.2. Banana-passas

A banana-passas, conhecida como banana seca brasileira, é o produto obtido pelo processo de secagem natural, realizado em secador solar ou por secagem artificial em secadores à lenha, a gás ou elétricos, da banana madura inteira, em metades ou em rodelas, como pode ser observada na figura 2. O processo de produção de banana-passas dá-se da seguinte forma: as bananas com o grau de maturação adequado são lavadas, descascadas, selecionadas, cortadas ou não, opcionalmente são submetidas a um tratamento antioxidante, desidratadas em secadores até umidade final desejada, condicionadas em recipientes hermeticamente fechados para que se tenha uma uniformização da umidade final, embaladas e armazenadas (Embrapa, 2021).

Figura 2 - Banana-passas comercial obtida na cidade de Lavras – MG.

Fonte: Do Autor (2024).

A banana-passas disponível no mercado brasileiro possui sabor agradável, mas sua coloração escura, comum na maior parte da produção, compromete a percepção de qualidade do produto. Essa tonalidade escura é resultado da ação de enzimas como peroxidase, fenolase, catalase, oxidases do ácido ascórbico e invertase, que transformam a sacarose em açúcares redutores. Essas enzimas apresentam alta atividade, por isso, após o preparo da polpa, é essencial que ela seja imediatamente encaminhada ao processo de secagem (Araújo, 1985).

2.3. Secagem

A secagem é uma das mais antigas e amplamente utilizadas operações unitárias para a conservação de alimentos (Llavata *et al.*, 2020; Ratti; Mujumdar, 2020). Esse processo envolve a remoção da umidade presente nos alimentos até atingir um nível adequado, com o objetivo de inibir o crescimento microbiano e prolongar a vida útil do produto (Hnin *et al.*, 2019; Khan *et al.*, 2020). Trata-se de um processo complexo, no qual ocorrem simultaneamente os fenômenos de transferência de calor e de massa (Karim; Hawlader, 2005; Sangamithra *et al.*, 2015).

Industrialmente, a secagem da banana é realizada até que o teor de água em base úmida atinja um valor de 20 a 25% e seu controle é feito de forma prática pelo do monitoramento de cor, consistência e do teor de umidade do produto final, sendo que no Brasil o limite estabelecido pela Legislação Brasileira é de, no máximo, 25% de umidade para frutas desidratadas (Anvisa, 2022).

Um dos maiores desafios na escolha de secadores para o processo de secagem da banana é a grande variedade de equipamentos e processos de secagem para se obter um produto de qualidade e com mínimas perdas nutricionais (Anvisa, 2022). Existem atualmente dois tipos de secador amplamente utilizados para a produção de banana-passas: os secadores de bandeja e os secadores de túnel.

Os secadores de bandeja são compostos por uma câmara que contém bandejas com o produto a ser seco e um compartimento onde o ar de secagem é condicionado. Esse ar é impulsionado por um ventilador e aquecido antes de entrar em contato com a matéria-prima nas bandejas, iniciando o processo de secagem. Em contrapartida, os secadores de túnel são compostos por um túnel fechado, em que as bananas são colocadas em uma esteira e passam pelo túnel enquanto o ar quente é soprado para remover a umidade. Esse tipo de secador é recomendado para o processamento de grandes volumes de matéria-prima (Cornejo *et al*., 2003; Berk, 2018).

Alguns dos parâmetros mais importantes na secagem são a temperatura e o tempo de secagem, pois esses parâmetros influenciam, principalmente em produtos agrícolas, a coloração final do produto, que é um atributo primordial para a escolha do consumidor. Devido à sua grande importância, pesquisas vêm sendo desenvolvidas a fim de estudar os fenômenos associados à alteração de cor e, também, de textura da banana durante o processo de secagem. A secagem da banana é utilizada para fim de preservação e também esse processo é realizado a fim de aumentar o valor agregado da mesma (Jiang *et al*., 2010; Pan *et al*., 2008; Leite *et al*., 2007).

2.3.1. Secagem convectiva

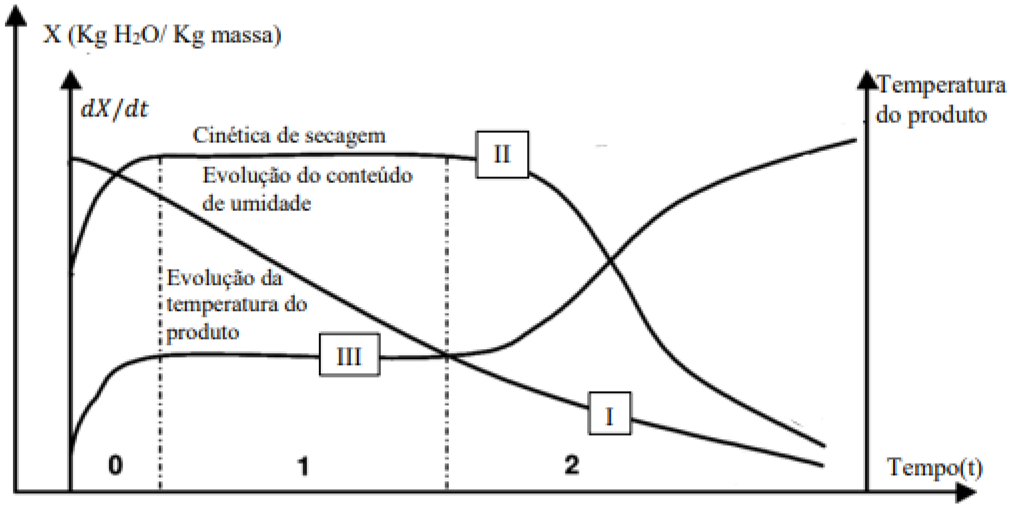
A secagem por convecção é amplamente utilizada nas indústrias alimentícias. Nesse processo, o ar de secagem transfere calor ao material e, simultaneamente, remove a água evaporada do alimento. A transferência do calor por convecção depende de fatores externos como a umidade, velocidade e a temperatura do ar de secagem. As características do produto, quando associadas às condições do ar de secagem e do meio de transferência de calor levam a diversas condições de secagem do produto final, contudo a transferência de calor e de massa entre o ar de secagem e o produto é um fenômeno comum a qualquer condição de secagem (Berk, 2018; Keey, 1972)

Sendo assim, é possível descrever o processo de secagem, baseando-se na transferência de calor e de massa. Na Figura 3, a curva I apresenta a redução de umidade em base seca (X) existente no material durante o tempo de secagem (t), a curva II mostra a taxa de secagem do material, a partir da variação de seu conteúdo de umidade em função do tempo, dX/dt, ou seja, a curva II é obtida pela diferencial da curva e a curva III representa a variação da temperatura do material durante o tempo de secagem.

O período 0 representa o início da secagem, em que ocorre um aumento gradual da temperatura do produto e da pressão de vapor d'água. Esse aumento da temperatura ocorre até que transferência de calor seja equivalente à transferência de massa. No período 1, que corresponde ao período de secagem com taxa constante, a água evaporada é a água livre e a transferência de calor e de massa são equivalentes, sendo assim a taxa de secagem se torna constante. Enquanto existir água na superfície do produto que seja suficiente para acompanhar a evaporação, a taxa de secagem será constante (Keey, 1972 ; Park *et al*., 2007).

No período 2 a taxa é decrescente, e a quantidade de água na superfície é menor, levando a redução da transferência de massa sendo assim a transferência de calor não é compensada e consequentemente, a temperatura do produto aumenta e tende a se igualar à temperatura do ar de secagem. O fator limitante desse processo é a migração interna de água. Assim, quando o produto atinge o ponto de umidade de equilíbrio em relação ao ar de secagem (X = Xeq), no qual a taxa de secagem se torna nula o processo é encerrado (Park *et al*., 2007; Keey, 1972).

Figura 3: Curvas típicas de secagem.



Fonte: Adaptado Park et al. (2007).

A umidade de equilíbrio é atingida uma vez que a massa do produto se torna constante. Essa umidade não depende apenas da natureza do produto, mas também da temperatura e da umidade relativa do ar de secagem. Além disso, a umidade de equilíbrio indica a menor umidade possível daquele produto dentro das condições de secagem utilizadas (Azevedo; Alves, 2017).

Existem diversos estudos realizados sobre a secagem convectiva de produtos agroindustriais que avaliam o efeito do processo no produto final e reportam faixas ótimas de operação. Alguns desses estudos realizados para diferentes variedades de banana estão demonstrados na Tabela 1.

Tabela 1: Estudos da secagem convectiva para diferentes variedades de banana.

Variedade da banana	Faixa de temperatura do processo	Parâmetros	Resultados principais	Referências
Prata	40, 60 e 80°C	Temperatura	As amostras secas a 80 C apresentaram maior teor de açúcar redutor, dureza, b*, C*. Sendo assim temperatura mais alta era ideal para a produção de bananas secas, apresentando o maior valor de desejabilidade global.	Macedo *et al* (2020)
Prata	40, 50, 60 e 70 °C	Temperatura e espessura	Maiores temperaturas e umidade relativa mais baixa provocaram maiores taxas de secagem, aquecimento e encolhimento na fruta e o aumento da temperatura do ar reduziu significativamente o tempo de secagem	Farias *et al.* (2020)
Prata e D'água	50 e 70 ºC	Temperatura, velocidade do ar	A secagem de bananas em quaisquer formatos foi ótima nas seguintes condições: branqueamento e secagem a 50 ºC/0,42 m/s, para banana-prata; e secagem a 70 ºC/0,42 m/s, para banana-d'água sem branqueamento.	Borges *et al*. (2010)
Pacovan	50, 60 e 70 ºC	Temperatura e espessura	A temperatura é o principal fator que afeta a secagem sendo que a taxa de secagem aumentou com a diminuição da espessura da banana. Com a espessura fixada em 5,0 mm e temperatura a 70 °C foram obtidos os menores tempos de equilíbrio na secagem.	Pires; silva; souza (2014)
Terra	40, 50 e 60 ºC	Temperatura e volume	Quanto maior a temperatura de secagem, mais rápido a banana atinge seu equilíbrio termodinâmico. A redução volumétrica é maior em menores temperaturas de secagem.	Leite *et al*. (2015)
Marmelo, ouro e maçã	65 ºC	Temperatura e umidade	O pré-tratamento com solução antioxidante resulta em um produto desidratado padronizado que mantém as características naturais. da fruta.	Mota (2005)

Fonte: Do Autor 2024.

2.3.2. Secagem infravermelho

A radiação térmica é um tipo de radiação eletromagnética emitida por objetos devido à sua temperatura absoluta. Essa emissão resulta do movimento de partículas carregadas eletricamente, que geram um campo eletromagnético variável (Deyllot, 2014; Lightfoot, 2004).

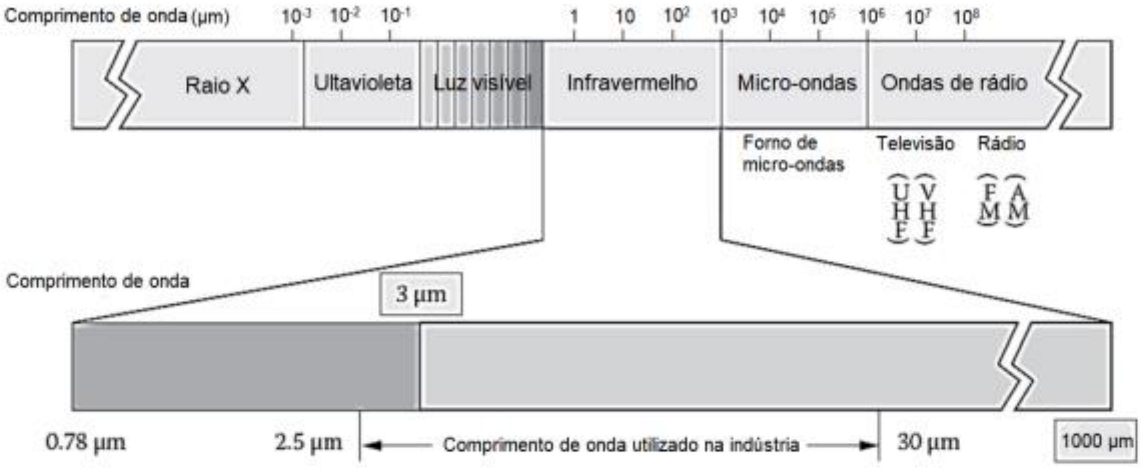
A radiação térmica é descrita pela Lei de Stefan-Boltzmann, que mostra que a quantidade de energia gerada pela radiação é proporcional à quarta potência da temperatura absoluta do objeto, como mostra a 1 Equação (1):

$$P = \sigma * A * T^4 \quad (1)$$

onde P é a potência em Watts, σ é a constante de Stefan-Boltzmann que é aproximadamente 5,67x10^{-8} ($\frac{W}{m^2 k^4}$), A é a área superficial do objeto em m^2 e T é a temperatura em K (Wasserman, 2011).

A Figura 4 ilustra o espectro eletromagnético de diferentes tipos de radiação. A radiação térmica abrange um espectro de comprimentos de onda, principalmente na região de comprimento infravermelho, e tem aplicação em operações de resfriamento, aquecimento, além de poder ser utilizada para detecção remota e fornecimento de informações sobre temperatura e composição de objetos (Deyllot, 2014; Lightfoot, 2004). A radiação infravermelha faz parte do espectro eletromagnético que se situa entre a região do visível e as micro-ondas. Em 1800, Herschel escreveu o primeiro relatório científico sobre aquecimento infravermelho reportando que a partir da exposição de lentes ao sol em direção a um papel, houve o fenômeno de combustão, levando à sua queima. Este relatório apresenta os primeiros indícios da existência da radiação infravermelha. Outro estudo utilizou um prisma para separar a luz em diferentes cores e utilizou um termômetro nas diferentes cores do espectro de energia solar. Assim, foi possível perceber que havia um forte aquecimento na região além da cor vermelha, que começava na extremidade visível do espectro (Rosental, 2012).

Figura 4: Espectro de ondas eletromagnéticas e faixas de infravermelho.



Fonte: Adaptado Aboud *et al.* (2019).

O aquecimento infravermelho tem a dependência do seu espectro, ou seja, o aquecimento depende das diferentes faixas de comprimentos de ondas dentro do espectro do infravermelho, uma vez que a energia emitida tem diferentes comprimentos de onda e parte da radiação depende da temperatura da fonte e da emissão da lâmpada. A partir do seu comprimento de onda é possível classificar o infravermelho como próximo (0,78 e 1,4 μm), médio (1,4 e 3,0 μm) e distante (3,0 e 1000,0 μm) (Aboud *et al.,* 2019).

Essa classificação influencia diretamente no aquecimento do material, uma vez que existem faixas mais apropriadas para cada componente, como por exemplo, a água que absorve o infravermelho principalmente nos comprimentos de 3, 6, 12 e 15 μm, já o açúcar tem maior absorção nos comprimentos de 3 e 7 a 10 μm, e as proteínas de 3 a 4 e 6 a 9 μm (Aboud *et al*., 2019). O fenômeno da radiação torna-se mais complexo uma vez que a quantidade de radiação incidente em qualquer superfície depende não somente do seu espectro, mas também da direção da mesma. A radiação que incide sobre um determinado objeto é convertida em calor, podendo ter a sua energia absorvida, refletida e transmitida.

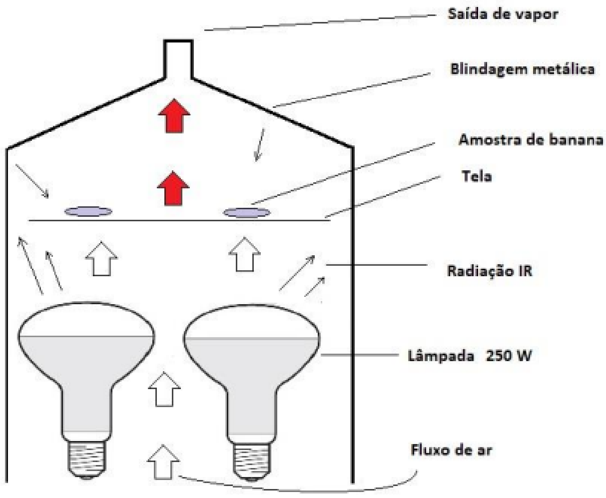
Estudos demonstram que a eficiência da secagem infravermelha depende do comprimento de onda, pois dependendo do componente presente no material a ser seco existe uma faixa ideal de absorção do mesmo, da absorção característica dos materiais, da potência, da distância e da espessura do material (Onwude *et al*., 2019; Onwude *et al*., 2018). Porém, a distribuição não padrão de temperatura que pode ocorrer durante o aquecimento infravermelho afeta significativamente a qualidade dos produtos secos e vem sendo um problema chave. Sendo assim, muitas tentativas vêm sendo realizadas na secagem no infravermelho médio e infravermelho próximo a fim de melhorar a uniformidade de aquecimento, utilizando diferentes métodos como pré-tratamento e a tecnologia de barreiras que é a utilização de diferentes camadas (podendo ser físicas ou químicas) a fim de proteger o material de trocas indesejadas (Aboud *et al*., 2019; Alaei; Chayjan, 2015; Chayjan; Fealekari, 2017; Doymaz, 2018; Sadin *et al*., 2014; Samani *et al*., 2018).

O processo de secagem infravermelho (IV) demonstra ser mais rápido que os processos de convecção forçada, uma vez que nele a energia é transferida diretamente da fonte IV para a superfície do material convertendo-a em calor, sem que haja a necessidade de transporte de calor por meio de ar aquecido, isso faz com que se tenha uma transferência de energia mais rápida e eficiente, resultando em uma aceleração no tempo de secagem. Sendo assim, o ar em contato com a superfície do alimento não se aquece como nos processos de convecção forçada, o que leva a redução de custos energéticos do processo (Rabello *et al*., 2021).

Estudos recentes demonstraram que o uso da radiação infravermelha reduz de forma significativa o tempo de secagem de bananas, quando comparado ao processo de secagem por ar quente. Shi *et al.* (2020) relataram que, ao associar a radiação infravermelha a temperaturas mais elevadas durante o processamento, o tempo de secagem foi reduzido em até 59%. Adicionalmente, observou-se que a utilização dessa técnica promoveu a formação de uma estrutura mais porosa nas amostras, com a presença de micro canais na superfície do material desidratado.

De maneira similar, Rabello (2021), ao empregar um secador infravermelho para a secagem de bananas, também constatou uma redução do tempo de secagem em comparação com o processo de convecção forçada, sem a ocorrência de pontos de queima ("hotspots") nas bananas desidratadas. O autor sugere, ainda, que futuras pesquisas devam investigar os efeitos da radiação infravermelha sobre a qualidade final do produto desidratado. Na Figura 5 é possível ver o protótipo do secador desenvolvido por Rabello.

Figura 5: Secador infravermelho.



Fonte: Rabello (2021).

Além da redução de tempo, existem outras vantagens da secagem IV como: boas condições de controle dos parâmetros de aquecimento e fácil integração com processos de secagem convectivos, condutivos, por micro-ondas, por vibração, congelamento e vácuo. Porém, apesar das vantagens promissoras sobre o aquecimento convencional, parâmetros apropriados para secagem infravermelha precisam ser estabelecidos para melhorar o processo de secagem e a eficiência geral do processo (Riadh *et al*., 2015).

Apesar da secagem infravermelha apresentar grandes vantagens, um fator muito importante a ser analisado é a temperatura da fonte de calor, uma vez que altas temperaturas apesar de proporcionarem uma secagem mais rápida, podem modificar significativamente a superfície do produto, levando a caraterísticas não desejadas de cor e textura. Dessa forma, é necessário um controle do processo e o desenvolvimento de técnicas a fim de assegura a qualidade final do produto (Glouannec, 2008; Santos, 2009).

2.3.3. Secagem hibrida

Técnicas de secagem híbridas vem sendo amplamente utilizada na atualidade, que nada mais são a combinação de duas ou mais técnicas de secagem entre si, em diferentes arranjos a fim de minimizar possíveis desvantagens das técnicas aplicadas. Estudos demonstram que os métodos híbridos de secagem são mais promissores e econômicos para produtos alimentícios por fornecer um efeito sinérgico, resultando em menor tempo de secagem e, consequentemente, menor necessidade de energia, e mantendo a maioria dos atributos de qualidade no produto desidratado (Chen *et al*., 2017).

Técnicas como a combinação da secagem por radiação infravermelha e convecção vem sendo estudadas e tem se mostrado efetiva uma vez que mostram ser mais eficiente do que o uso isolado dessas técnicas. É possível realizar essa análise em estudos como o de Nalawade *et al*. (2019) que compararam quatro métodos de secagem da hortelã (Mentha spicata L.): ar quente e infravermelho, ar quente com radiofrequência, ar de baixa umidade e ar quente convencional é obtiveram melhores resultados na utilização da técnica utilizando ar quente e infravermelho

Puangsuwan *et al*. (2021) também utilizaram a secagem hibrida em seus estudos com auxílio de secador híbrido para a secagem de bananas da variedade Pisang-Awak. O protótipo de secador desenvolvido possui fornecimento de ar quente e uma fonte IV, conforme mostrado na Figura 6, e foi utilizado na avaliação da cinética de secagem do produto durante a secagem híbrida e para as duas técnicas separadamente. Como resultado, o melhor modo de secagem para a banana foi a combinação de secagem por convecção com ar quente a 60 °C (1,5 m/s) com a secagem infravermelho. Sendo que a técnica híbrida levou a uma redução no tempo de até 100 min em relação às técnicas individuais. Além desses, outros trabalhos demonstram a efetividade da secagem híbrida e, particularmente, combinando convecção e radiação IV como é demonstrado na tabela 2.

Figura 6*:* Protótipo de secador híbrido com secagem convectiva com ar quente e infravermelha.

Fonte: Adaptado de Puangsuwan *et al.* (2021).

Tabela 2: Aplicação combinada da secagem infravermelho com convecção com ar quente para alguns alimentos em diferentes condições.

Produto	P_{IV}, V_{ar} e T_{ar}	Resultados Principais	Referências
Amora	$P_{IV:}$ 500-1500 W, $v_{ar:}$ 0,4-1,6 m/s $T_{ar:}$ 40-70 °C	A secagem hibrida demonstrou bons resultados sendo suas condições ótima para otimização do processo igual a 70 °C, a uma velocidade do ar de 0,4 m/s com uma potência de 1464,57 W.	Golpour *et al*. (2020)
Cúrcuma	$P_{IV:}$ 3,02 W cm^2 $v_{ar:}$ 2 m/s $T_{ar:}$ 50-70 °C	A secagem híbrida reduziu o tempo de secagem e aumentou a taxa de secagem em relação às secagens isoladas	Jeevarathin M *et al.* (2021)
Morango	$P_{IV:}$ 100-300 W, $v_{ar:}$ 1-2 m/s $T_{ar:}$ 60-100 °C	A secagem híbrida foi mais eficaz para garantir alta qualidade de nutrientes e presença de compostos bioativos, além da melhor aceitação do consumidor de morangos secos. Recomenda-se a operação nas faixas de $P_{IV:}$ 200–300 W, $v_{ar:}$ 1–1,5 m/s e $T_{ar:}$ 60 ºC–100 ºC para retenção de compostos bioativos e nutrientes.	Adak; Heybeli; Ertekin (2017)
Maçã	$P_{IV:}$ 2000 W/m^2, $v_{ar:}$ 0,6 m/s $T_{ar:}$ 30-60 °C	A secagem híbrida foi mais rápida e teve menor gasto energético que as demais. Além disso, produziu um produto com menor encolhimento, maior taxa de reidratação e melhor retenção de cor.	El-mesery; Mwithiga (2015)
Laranja	P_{IV}: 250 W, $v_{ar:}$ 0,4 - 1,0 m/s, $T_{ar:}$ 42 -49 °C	Maiores temperaturas decorrentes da maior potência IV levaram à diminuição do tempo de secagem. O aumento da velocidade do ar diminuiu o tempo de secagem tanto para os ensaios com ar aquecido quanto com ar ambiente.	Andrade; Prado; Marques (2019)

Do Autor (2024).

2.3.4. Secagem intermitente

A secagem intermitente é um método de secagem no qual o material a ser seco é submetido a ciclos alternados a partir do controle de fornecimento de energia térmica para o material. A forma mais comum da utilização desse método é a estratégia liga/desliga, em que se desliga a fonte de calor em um tempo determinado e, em seguida, volta-se a ligar a mesma. Diversos estudos demonstraram que a utilização da intermitência pode resultar em melhoras nas características organolépticas dos produtos, também levam à redução do consumo energético do processo (Putranto *et al*., 2011).

Para atingir a intermitência pode-se ter a variação a partir do modo de entrada de energia (por exemplo, convecção, condução, radiação ou micro-ondas). Esse método é usado quando é necessário remover a umidade de um material de forma controlada e gradual, e buscando um melhor aspecto nutricional e visual da amostra (Kumar *et al*., 2014).

De acordo com Zeki (2009), fornecer a mesma quantidade de energia durante todo o processo de secagem leva a uma degradação da qualidade e danos na superfície do produto, além de desperdício de energia térmica. Isso acontece principalmente porque a taxa de secagem tende a diminuir em estágios posteriores da secagem devido à escassez de umidade na superfície do material. A intermitência fornece tempo hábil para que a umidade se distribua do centro para a superfície da amostra, levando à diminuição dos danos causados pela exposição ao calor (como superaquecimento e ressecamento da camada superficial do material) e ao aumento da qualidade do produto final. Por fim o uso da intermitência leva à redução do consumo energético do método de secagem utilizado.

Soysal *et al*. (2009) verificaram que aspectos sensoriais como cor, aparência e textura do produto final foram melhores quando utilizado o método intermitente para a secagem de pimentas vermelhas. Outros estudos demonstraram que, quando comparados com métodos convencionais, a secagem intermitente demonstrou ser mais efetiva para a preservação de compostos bioativos como os compostos fenólicos e os flavonoides (Pan *et al*., 1999; Chua *et al*., 2000; Zhao *et al*., 2014; Allaf *et al*. 2015).

Estudos demonstram ainda a efetividade da aplicação da intermitência para a secagem de bananas. Rodrigues *et al*. (2015) realizaram a secagem de banana nanica de maneira contínua e intermitente onde secagem intermitente apresentou a diminuição do número de Biot, ou seja, a secagem ocorreu mais rapidamente, validando ainda mais os benefícios da aplicação da intermitência, em específico, na banana.

Pham (2022) e Borah (2023) utilizaram a técnica de secagem que combina a secagem por micro-ondas intermitente com a secagem convectiva na secagem de mamão e caqui respectivamente. Ambos os estudos demonstraram a efetividade da secagem intermitente mostrando efeitos significativos melhora da cor da amostra seca e na diminuição do gasto energético do processo.

Ademais a junção das técnicas convectiva e infravermelha tem se mostrado eficaz tanto na otimização do consumo energético quanto na preservação das características sensoriais do produto final, como cor, textura e conteúdo nutricional. Além disso, a aplicação da secagem intermitente, que alterna períodos de fornecimento de energia térmica, surge como uma abordagem complementar que melhora ainda mais a eficiência do processo, reduzindo o tempo de secagem e os custos energéticos. Assim, a combinação dessas estratégias representa uma solução viável na produção de banana-passas de alta qualidade além de oferecer métodos que ajudam a minimizar perdas pós-colheita e agregar valor à cadeia produtiva da bananicultura.

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SEGUNDA PARTE – ARTIGOS

(Versão preliminar do manuscrito, preparada em conformidade com as diretrizes do periódico *Journal of Food Engineering*. O conteúdo está sujeito a modificações, conforme orientações que possam ser fornecidas pelo periódico)

ARTIGO 1 - Multi-objective optimization of the infrared radiation-hot air banana drying considering process performance, environmental impact, and product quality

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Abstract: The production of dried bananas can reduce postharvest losses and enhance the added value of the fruit. This study investigated the drying kinetics of bananas by combining infrared radiation at different power levels (140, 160, and 180 W) and heated air convection at various temperatures (50, 60, and 70 °C). The final moisture content of the samples ranged from 17% (at P = 180 W and T = 70 °C) to 22% w.b. (at P = 140 W and T = 50 °C). Under these conditions, the specific energy consumption (SEC) and CO_2 emissions (qCO_2) varied significantly, with the minimum observed at 41.00 kWh/kg H_2O and $1.71{\cdot}10^{-4}$ tCO_2e, and the maximum at 74.49 kWh/kg H_2O and $3.01\ 10^{-4}$ tCO_2e. Effective diffusivity was estimated between $5.47{\cdot}10^{-4}$ and $1.12{\cdot}10^{-3}$ mm^2/s. The quality of the dry product was assessed based on pH (4.33 to 4.71), soluble solids content (40 to 83 °brix), water activity (0.43 to 0.52), and hardness (20.66 to 39.77 N). The optimal conditions, which were identified as 180 W and 59 °C, achieved an overall desirability score of 0.60. This indicates that the product meets acceptable quality standards (M_f, A_w, TSS and Firmness values) while maximizing process performance (D_{ef} and SEC values) and minimizing environmental impact (qCO_2).

Keywords: hybrid drying; specific energy consumption; effective diffusivity; dried product quality; desirability function.

1. Introduction

Bananas are the most widely produced fruit in the world, playing a significant role in the global agro-industrial sector, which generates annual revenues of approximately US$ 25 billion. However, producers face challenges in the post-harvest period due to the high moisture content of the fruit (70%), which leads to losses of up to 40% of production. Banana processing can minimize these losses by increasing shelf life and adding value to the chain (Filipenco, 2023; Martínez et al., 2023).

Dried bananas result from the natural or artificial drying of ripe bananas (whole, halved, or sliced). Their market is quite promising, given their excellent sensory acceptance, making them popular for both direct consumption as a dehydrated fruit and as an ingredient in various formulations (Jesus et al., 2005; Matsuura and Matsuura, 2021). Typically, dried bananas are made using conventional convective dryers, which are favored for their simplicity. However, these dryer have low thermal efficiency and require long drying times, which can negatively impact product quality and lead to high energy costs (Souza et al., 2024).

Hybrid drying techniques, particularly the combination of infrared (IR) and hot air drying (HA), have shown promise for heat-sensitive products like bananas. This approach takes advantage of a synergistic effect that helps maintain product quality while reducing energy consumption. Puangsuwan et al. (2021) compared several drying methods for whole Pisang-Awak bananas, including convective hot air drying at two different air speeds (1.5 m/s and 2.5 m/s), pure IR drying, and the combined use of hot air flow (Hy) at both 1.5 m/s and 2.5 m/s, along with IR heating at various temperatures (50, 60, and 70 ºC) in terms of process kinetics, specific energy consumption (SEC), and sample shrinkage. The authors concluded that the combined drying method using Hy at 1.5 m/s with a temperature of 60 ºC was the most effective technique, as it resulted in the lowest SEC value while achieving the best quality of the dried product.

Drying is an energy-intensive operation due to the high latent heat of water and the need to supply sufficient heat to remove water from the material. As a result, researchers have focused on minimizing process inefficiencies and enhancing energy performance. In this context, mathematical modelling is a valuable tool for designing, optimizing, and simulating the drying process. To the best of our knowledge, further research is needed on the drying kinetics, the effects of various operating conditions of infrared-hot air (IR-HA) dryers on product quality, and the identification of optimal process conditions to make this hybrid technique viable for banana processing. Only a few studies have successfully integrated energy efficiency, environmental impact, and product quality, such as those by Zhang et al. (2022) on milk dried by spray drying, Souza et el. (2022) and Moreira et al. (2025) on banana slices and bananas halves cut lengthwise, respectively, dried using combined infrared-convective drying with unheated air. In this sense, this work offers a comprehensive analysis of the impact of infrared radiation power and air temperature on the performance of the banana dehydration process. The effective moisture diffusivity, specific energy consumption, CO_2 emissions were determined for the process under different operating conditions. It also examines product quality attributes such as final moisture content, water activity, color, texture, pH, and soluble solids content, and the optimal operating condition was identified by response surface methodology using the desirability function approach considering parameters related to these three key areas. These findings provide an essential theoretical reference for producing dried bananas using the IR-HA technique and have the potential to support its application in the dehydration of other agro-industrial materials.

2. Materials and Methods

2.1 Materials

Bananas of the Prata variety (Musa paradisiaca L.) used in this study were sourced from local retailers in Lavras, MG. They were selected at ripeness stage C6 of the Von Loesecke subjective ripeness scale, characterized by fruits with yellow skin and no brown spots (PBMH & PIF, 2006). The bananas were cleaned, peeled, and sliced into uniform pieces, each approximately 1 cm thick. Twelve slices were then arranged on a tray with a diameter of 21 cm. The fresh banana's average moisture content was 73.6 ± 1.4% (w.b.).

2.2 Drying process

The drying experiments were performed in a hybrid dryer that combines IR radiation and forced convection with heated air (Figure 1). The drying chamber (60.0 x 39.0 cm) has carbon steel outer walls, stainless steel inner walls, and insulation made of glass wool. An IR lamp (250 W) was positioned 19 cm above the center of the tray containing the samples. The power output of the lamp was adjusted using a clamp meter (KRAD01, Kript).

The drying air was supplied by a fan and heated by passing through an electrical resistance (1400 W). The temperature of the drying air was controlled by a digital controller (Novus, N1030). The experiments were carried out under various drying air temperature conditions (50, 60, and 70 °C) with a fixed air velocity (4.5 m/s), and different IR powers levels (140, 160, and 180 W), based on a 3^2 factorial design. The air's relative humidity was measured using a thermo-hygrometer (IP-780, Impac), yielding an average value of 54 ± 7% throughout the tests.

Figure 1

The moisture reduction in each test was evaluated by gravimetry in intermittent mode. The sample was removed from the drying chamber for a few seconds, and its weight was measured on an electronic scale (AD4200, Marte) every 10 minutes in the first 100 minutes of drying and, subsequently, every 20 minutes until the mass stabilized. The final moisture content was determined by drying in an oven (SL102, Solab) at 105 ± 3 °C for 24 h (IAL, 2008). The surface temperature of the bananas was monitored throughout the entire drying process using a pyrometer (Mt-320b, Minipa) by measuring the temperature of the banana slice that was in the center of the tray.

The moisture ratio (MR) was calculated according to Eq. (1) (Pal et al., 2023):

$$\mathrm{MR} = \frac{M_t}{M_0} \tag{1}$$

where M_t is the moisture content at time t and M_0 is the initial moisture content of bananas (g water/g dry matter, dry basis, d.b.).

The equilibrium moisture was disregarded (Eq. (1)) due to the high value of the Fourier number (> 0.2).

Drying rate (DR) was estimated as follows:

$$DR = -\frac{M_{t+\Delta t} - M_t}{\Delta t} \tag{2}$$

where M_t is the moisture content at time t, $M_{t+\Delta t}$ is the moisture content at time $t+\Delta t$, all in g water/g dry matter, and Δt is the time increment between two determinations, in min.

2.3 Diffusive model

The first term of the analytical solution for Fick's second law of diffusion in rectangular geometry, assuming one-dimensional moisture transfer with negligible shrinkage, an isothermal process with uniform initial moisture distribution, and equilibrium conditions prevailing at the material surface, was used to calculate the banana's effective diffusivity, according to Eq. (3) (Kumar et al., 2023):

$$\mathrm{MR} = \frac{8}{\pi^2} \exp\left(-\frac{\pi^2 D_{ef}}{L_0^2} \mathrm{t}\right) \tag{3}$$

where L_o is the thickness of the banana slice (mm), D_{ef} is the effective diffusivity (mm^2/s) and t is the drying time (s).

The Solver tool of the Excel software was used to perform both adjustments. The fitting quality of the proposed models was assessed with the root mean square error (RMSE: Eq. (4)), the chi-square (χ^2: Eq. (5)) and the coefficient of determination (R^2: Eq. (6)).

$$\boldsymbol{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}\left(MR_{pre,i}-MR_{exp,i}\right)^2}{N}} \quad (4)$$

$$\boldsymbol{\chi^2} = \frac{\sum_{i=1}^{N}\left(MR_{exp,i}-MR_{pre,i}\right)^2}{N-n} \quad (5)$$

$$\boldsymbol{R^2} = 1 - \frac{\sum_{i=1}^{n}\left(MR_{pre,i}-MR_{exp,i}\right)^2}{\sum_{i=1}^{n}\left(\overline{MR}_{pre,i}-MR_{exp,i}\right)^2} \quad (6)$$

where $MR_{exp,i}$ is the ith experimental moisture ratio; $MR_{pre,i}$ is the i^{th} predicted moisture ratio; N is the number of observations, and n is the number of constants in the drying model.

The accuracy of each model was considered by the low RMSE and χ2 values, and R^2 close to unity.

2.4 Specific energy consumption and CO_2 emissions

The mains voltage (V) and currents (i) of the IR lamp, electrical resistance and axial fan were measured using a digital clamp meter (KRAD01, Kript). From these values, the total power of the system was calculated, and then the SEC (kWh/kgH_2O) for each experiment was estimated as the energy consumed to remove water from bananas from the initial moisture content to a final value of 22.0% (w.b.) according to Eq. (7).

$$SEC = \frac{(P_{IR}+P_{res}+P_{conv}) * t}{m_w} \quad (7)$$

where P_{IR}, P_{res} and P_{conv} are the power consumption of the IR lamp, the electrical resistance and axial fan (kW), respectively, t is the drying time (s), and m_w is the mass of water removed (kg).

CO_2 emissions ($q_{CO2,eq}$) under different drying conditions were calculated based on the electrical energy consumed in each experiment and the average Brazilian CO_2 emission factor for 2024 (0.0545 t_{CO2}/MWh) (MCTI, 2025).

2.5 Dried product quality attributes

2.5.1 Color parameters

A colorimeter (CR10, Konica Minolta) was used to measure the surface color of bananas both before and after drying. The L*, a*, b* parameters were obtained, where L* indicated lightness, a* indicated the presence of redness (+) or greenness (-), and b* indicated the presence of yellowness (+) or blueness (-). The total color difference (ΔE) was calculated from the collected data using the following equation (Pei et al., 2022):

$$\Delta E = (\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2})^{1/2} \quad (8)$$

where ΔL^*, Δa^* and Δb^* represent the difference between $L*$, $a*$ and $b*$ of the fresh banana and the dried samples.

A qualitative analysis of the average color of the fresh and dried banana slices was also performed using the RGB (red, green, and blue) scale, based on the method described in Moreira et al. (2025). The intensity values of the red, green and blue colors obtained by the Photoshop software (Adobe) were inserted into Microsoft Word to represent the average color of each sample.

The chroma (C*), which corresponds to the color saturation, and the hue angle (H*), which express the tonality of the color, were determined according to Eqs. (9) and (10), respectively (Borges et al., 2022):

$$C^* = \sqrt{(a^{*2} + b^{*2})} \quad (9)$$

$$H^* = arctan\left(\frac{b^*}{a^*}\right) \quad (10)$$

Since the browning index (BI) represents the purity of the brown color and is an important parameter to evaluate the type of browning that occurs during the drying of sugar-rich foods, this parameter was also assessed using Eq. (11) (Soto et al., 2021).

$$BI = 100 \cdot \left[\frac{\frac{(a^{*}+1.75L^{*})}{(5.645L^{*}+a^{*}-3.012b^{*})}-0.31}{0.172}\right] \quad (11)$$

2.5.2 Total soluble solids content, water activity and pH

Total soluble solids (TSS) were determined, in triplicate, using a refractometer (RTA-50, Instrutherm). For this, the dried samples were crushed and diluted in distilled water (1:10) and stirred until homogenized. The mean value of the three measurements, in °Brix, was reported.

The water activity (A_w) was determined in triplicate using an Aqualab model 4TE, with direct readings taken at approximately 25 °C.

The pH value of the dried banana mixture in water was measured using a pH meter (MP521, Sanxin), and the mean of three measurements was recorded (IAL, 2008).

2.5.3 Texture analysis

The dried banana samples were examined in triplicate for their textural properties under different experimental conditions using a texture analyzer (TA-XT2i, Stable Micro Systems) following the methodology proposed by Medlicott et al. (1992). The penetration/puncture test was performed using a 6 mm-diameter stainless cylindrical probe, operating at a speed of 1 mm/s. The force required for the probe to penetrate the sample was measured at three points. The average of these three measurements was used to determine the maximum force on the force-deformation curve, which was recorded as the firmness value.

2.6 Response Surface Methodology

The response surface regression was conducted using Statistica 8.0 software (Statsoft Inc.) by fitting a quadratic polynomial model according to Eq. (13), which describes the relationship between independent variables IR power and air-drying temperature and each *Y* response variable (M_f, SEC, qCO_2, A_w, Firmness, D_{ef}, and TSS) derived from experimental data obtained through the 3^2 factorial design.

$$Y = \beta_0 + \sum_{i=0}^{n} \beta_i x_i + \sum_{i=0}^{n} \beta_{ii} x_i^2 + \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \beta_{ij} x_i x_j \tag{13}$$

where *Y* represents the response function, x_i and x_j identify the independent variables in coded values, β_0 is a constant term, β_i, β_{ii} and β_{ij} are the linear, squared and interaction effect, respectively.

The statistical significance of the regression coefficients was assessed by analysis of variance (ANOVA) and the models were reduced to the statistically significant terms at a p-value of 0.05.

Desirability function was used to find the optimal operating condition for hybrid drying of banana. For this, the individual desirability (d_i) of the response variables to be minimized (M_f, SEC, qCO_2, A_w, and Firmness) and maximized (D_{ef}, and TSS) were obtained using Eq. (14) and Eq. (15), respectively. Eq. (16) was then used to determine the overall desirability (*D*) by combining individual desirabilities.

$$d_i(Y_i) = \begin{cases} 1, & Y_i < T_i \\ \left(\frac{Y_i - U_i}{T_i - U_i}\right)^{r_i}, & T_i \le Y_i \le U_i \\ 0, & Y_i > U_i \end{cases} \tag{14}$$

$$d_i(Y_i) = \begin{cases} 0, & Y_i < L_i \\ \left(\frac{Y_i - L_i}{T_i - L_i}\right), & L_i \le Y_i \le T_i \\ 1, & Y_i > T_i \end{cases} \tag{15}$$

$$D = \left(\prod_{i=1}^{7} d_i\right)^{\frac{1}{7}} \tag{16}$$

where Y_i is the response variable, T_i is the target value, U_i and L_i are the upper and lower fitted values, which are desired for response Y_i, and $r_i = 1 \; \forall \; i$, considering a linear desirability.

3. Results and Discussion

3.1 Drying kinetics curves

Fresh bananas with an average initial moisture content of 73.6 ± 1.4% (w.b.) were dried using the hybrid dryer shown in Figure 1. The moisture ratio and surface temperature of the bananas as a function of drying time, observed during the drying process, are shown in Figure 2. Increasing the air temperature contributed to faster moisture removal. For instance, at P = 160 W (see Figure 2a), a reduction in the moisture content of bananas from the initial moisture content to approximately 22% (w.b.) is achieved in 447 min with T = 50 ºC. When the temperature was raised to 60 °C, the drying time was reduced by 8%, reaching 411 minutes, and increasing it to 70 °C further shortened the time by 23%, to 346 minutes.

This observation aligns with findings reported by Andrade et al. (2019) for hybrid drying of orange pomace, as well as by Teymori-Omran et al. (2023) concerning IR drying of apples assisted by heated air convection. This is because the higher temperatures increase the temperature difference between the drying air and the surface of the banana, which enhances heat transfer. Additionally, the air at a higher temperature has a greater capacity to absorb moisture due to its lower relative humidity, thereby increasing the driving force of the drying process and favoring moisture transfer.

Figure 2b demonstrates that increasing the IR power helps reduce drying time. For a temperature of 60 °C, for instance, reaching a final moisture content of 22% (w.b.) requires less drying time as the IR power increases. Specifically, when the IR power is increased from 140 W, the drying time decreases from 536 minutes to 411 minutes at 160 W, and further drops to 354 minutes at 180 W. This indicates a reduction in drying time by approximately 23% and 34%, respectively. These findings align with the results reported by Souza et al. (2024) and Moreira et al. (2025) regarding the IR drying of bananas assisted by unheated air convection.

An increase in IR power corresponds to a greater amount of energy available for moisture vaporization, which explains the reduced drying times.

It is worth noting that similar behaviors were observed under the other experimental conditions investigated; however, the corresponding graphs are omitted here for conciseness.

Figure 2

3.2 Effect of IR power and drying air temperature

Table 1 presents the final moisture content (M_f) of the banana samples, along with the effective diffusivity (D_{ef}), SEC, and qCO_2 values observed under each experimental condition. According to RDC nº 82/00, the “dried” fruit must contain a maximum of 25 g of moisture per 100 g. Thus, all experimental conditions met the quality standard required by Brazilian regulation, with moisture content remaining below 22% (w.b.).

Table 1

The data presented in Table 1 show that the estimated effective diffusivity values ranged from $5.47 \cdot 10^{-4}$ to $1.12 \cdot 10^{-3}$ mm^2/s. These values are consistent with those reported by Pinheiro and Castro (2023) for convective drying of Cavendish bananas at 50 ºC ($2.63 \cdot 10^{-4}$ mm^2/s) and by Macedo et al. (2020) for convective drying of banana slices using temperatures between 40 ºC and 80 ºC ($5.84 \cdot 10^{-4}$ to $3.54 \cdot 10^{-3}$ mm^2/s). Overall, more than 80% of dried fruits typically exhibit effective diffusivity values between 10^{-5} mm^2/s and 10^{-2} mm^2/s (Onwude et al., 2016), suggesting that the results obtained align well with existing literature. Furthermore, the diffusive model proved to be successful in describing the kinetics of the studied process, as evidenced by high R^2 values (≥ 0.954) and low RMSE (<0.06) and χ^2 (<0.004) values.

The SEC values ranged between 41.00 kWh/kgH_2O (P=180 W and T=70 ºC) and 74.49 kWh/kgH_2O (P=140 W and T=50 ºC). Under these conditions, the CO_2 emissions varied, with a minimum of 1.71 10^{-4} tCO_2e and a maximum of 3.01 10^{-4} tCO_2e observed. The decrease in SEC values with increasing drying air temperature and IR power is attributed to the rise in sample temperature (see Figure 2), which consequently increases the drying rate and reduces the total drying time. Similar results were reported by (Sahari et al., 2023) for the IR drying of coconut assisted by convection of heated air (T=50 ºC and SEC= 83.46 kWh/kgH_2O; T=70ºC and SEC= 61.25 kWh/kgH_2O). It is also noteworthy that the SEC values found are consistent with those reported by Souza et al. (2024) (12.51 to 56.64 kWh/kgH_2O) and by Moreira et al. (2025) (17.7 to 71.2 kWh/kgH_2O) for IR drying of silver bananas assisted by convection of unheated air. The variations observed are probably due to the heating of the drying air conducted in the current study.

Prediction equations for M_f (R^2=0.919), D_{ef} (R^2 =0.977), SEC (R^2=0.582), and qCO_2 (R^2=0.987) were fitted to the experimental data shown in Table 1, and the effects of the independent variables (P and T) were quantified. These equations (17-20) are presented only with significant parameters (p<0.05), being the independent variables in the coded form.

$$\mathrm{M}_f(\%\, w.b.) = 19.69 - 1.17\mathrm{P}' + 0.53P'^2 - 1.58\mathrm{T}' \tag{17}$$

$$\mathrm{D}_{ef}(mm^2/s) = 8.83 \cdot 10^{-4} + 1.67 \cdot 10^{-4}\mathrm{P}' + 4.98 \cdot 10^{-5}P'^2 + 1.16 \cdot 10^{-4}T' \tag{18}$$

$$\mathrm{SEC\ (kWh/kgH2O)} = 58.00 - 6.81\mathrm{P}' - 7.30\mathrm{T}' \tag{19}$$

$$\mathrm{q}CO_2(\ \mathrm{tCO_2e}) = 2.19 \cdot 10^{-4} - 3.57 \cdot 10^{-5}\mathrm{P}' - 1.12 \cdot 10^{-5}P'^2 - 2.86 \cdot 10^{-5}T' + 7.48 \cdot 10^{-6}P'T' \tag{20}$$

where: $\mathrm{P}' = \frac{P(W)-160}{20}$ e $\mathrm{T}' = \frac{T(℃)-60}{10}$.

The response surfaces depicted in Figure 3 were constructed to better visualize the effects of IR power and drying air temperature. As previously mentioned, increasing both the IR power and air temperature facilitates the removal of moisture, resulting in samples with a lower final moisture content (Figure 3a). It is important to highlight the positive quadratic effect of increasing IR power (Eq. 17), which is evident from the curvature of the M_f response surface. This effect may be linked to the case hardening that occurs on the surface of the banana slices, making moisture removal more challenging. Demirel and Turhan (2003) noted that this phenomenon is expected when drying foods such as bananas, that are rich in dissolved solutes at high temperatures (T > 60ºC).

Operating the dryer at higher IR powers and air temperatures resulted in higher effective diffusivity values (Figure 3b) since greater irradiation enhances molecular vibration, resulting in a temperature increase (see Figure 2b) and elevated vapor pressure within the samples. This promotes faster moisture diffusion towards the surface (Delfiya et al., 2022). Furthermore, the rise in diffusivity with increasing air temperature supports the idea that diffusion is the primary mechanism governing moisture migration (Kumar et al., 2019).

In addition, higher IR power and air temperature conditions enhance the drying rate, resulting in lower energy consumption (Figure 3c) and consequently reduced CO_2 emissions (Figure 3d).

Figure 3

3.3 Assessment of dried product quality

Table 2 shows the results obtained for the color parameters (C*, H*, ΔE, and BI) and for the quality attributes evaluated (pH, TSS, A_w and Firmness) for fresh and dried bananas.

Table 2

Color is a key quality attribute of dried bananas, significantly influencing consumer acceptability (Olalekan, 2020). As shown in Table 2, the color of all dried banana samples was darker (39.9 ≤ L* ≤ 52.6) and more opaque (25.1 ≤ C* ≤ 36.1) compared to fresh bananas (L* = 78.3; C* = 37.0). Additionally, the dried bananas exhibited a redder hue (61.3 ≤ H* ≤ 74.1) relative to the fresh fruit, which had a hue closer to yellow (H* = 91.1). The reduction in brightness and increased redness during the convective drying of bananas has also been reported by Seyedabadi et al. (2019), who studied drying of bananas at temperatures from 80 °C to 100 °C with air velocities of 1.0 and 1.5 m/s. Moreira et al. (2025) likewise observed a reduction in H* values under all conditions investigated during IR drying combined with unheated air convection. According to the authors, this reduction was more pronounced at higher IR power levels, resulting in bananas with a more orange/red appearance. The loss of brightness may be attributed to the degradation of thermolabile pigments that develop dark compounds, while the increase in redness is likely due to the formation of brown pigments (Prachayawarakorn et al., 2008). These changes are associated with non-enzymatic browning and moisture loss. Despite this, there were no statistically significant effects IR power and air temperature on BI index and color difference (ΔE) values. This may be because, at higher temperatures, darkening reactions tend to produce more dark pigments; however, since the exposure time is shorter under these conditions, there is a compensatory effect that limits the production of dark pigments (Macedo et al., 2020). Despite these findings, a negative correlation was observed between colorimetric changes (BI: r = -0.25; ∆E: r = -0.38) and total process time, which is strongly influenced by operating conditions. This suggests that these conditions play an important role in the color changes observed.

Table 3 shows the average color of dried bananas under the different experimental conditions evaluated, as well as the average color of a commercial sample (dried fruit reference). Generally, higher IR powers and drying air temperatures resulted in darker-colored products. It is worth noting, however, that commercially available dried bananas exhibited a darker color than all samples produced in this study. Furthermore, the average color of bananas obtained by Moreira et al. (2025) under the optimal operating condition (P = 216 W and intermittency ratio of 0.289) using an IR dryer combined with unheated air convection was also darker than that observed in the present study with the hybrid dryer. This difference could have implications for the food processing industry, as the technique used in this research represents a technological advancement in the industrial processing of dried bananas.

Table 3

Table 4 shows the significant effects of drying air temperature and IR power on the physical-chemical properties of dried bananas. According to Macedo et al. (2020), acidity is a crucial factor in determining the sensory quality of bananas, as it affects the perception of both acidity and sweetness. Additionally, acidity plays a role in regulating enzymatic activity and helps preserve the fruit. The authors noted that, during the convective drying of bananas, an increase in air temperature led to a decrease in acidity (resulting in a higher pH). In this study, the dried banana had a mean pH of 4.53 (see Table 4), which was slightly higher than that of the fresh fruit (as shown in Table 2). This observation suggests that the breakdown of organic acids may have taken place during the drying process. Furthermore, an increase in IR power and air temperature was linked to a reduction in the pH of the dried product (as indicated by the negative effect in Table 4). This may be attributed to the concentration of acids resulting from the removal of water (Dereje and Abera, 2020).

Table 4

The TSS values of the dried sample were between 40º Brix and 83º Brix (Table 2). This indicates an increase of 56% to 331% compared to the levels found in the fresh fruit, contributing to a sweeter flavor in the final product and enhancing the overall acceptability of the healthy snack. Additionally, it was noted that higher IR powers and air temperatures were associated with higher TSS values, as shown in Table 4. This trend occurs because lower moisture content typically leads to a higher TSS in the product, given that TSS constitutes the primary component of dry matter (Dereje and Abera, 2020).

The water activity of dried bananas, which is a crucial factor determining their shelf life, ranges from 0.43 to 0.52 (see Table 2). This represents a significant reduction of 47% to 56% compared to fresh fruit, which has an A_w of 0.98. The decrease in water activity minimizes deterioration reactions and inhibits the growth of microorganisms, thereby extending the fruit's shelf life. A water activity level below 0.6 indicates that microorganisms cannot proliferate and that enzymatic activity is rendered inactive (Kushwah et al., 2022; Macedo et al., 2020). Studies have shown that dried bananas with such low water activity and a final moisture content below the threshold set by Brazilian regulations ($M_f < 22\%$ w.b.) remain stable for up to six months of storage, exhibiting no noticeable changes in their physical-chemical properties or microbiological contamination (Batista et al., 2014). Therefore, under all the conditions studied, the final moisture content and water activity of the product meet the industrial standards. This stability ensures the quality and safety of the product, making it suitable for commercialization. It is important to note that conditions with higher IR power and air temperature can significantly influence the water activity of dried bananas. This influence is due to the greater moisture removal achieved under these conditions, leading to dried bananas with lower A_w values.

Texture is also an essential parameter for food acceptance and quality assessment. Studies have shown that instrumentally measured hardness is strongly correlated with consumer sensory perception (Meullenet et al., 1998). Macedo et al. (2020) in their study on the convective drying of bananas highlighted that softer bananas tend to achieve higher sensory acceptance. The firmness (hardness) of dried bananas ranged from 20.66 to 39.77 N, marking a significant increase compared to the firmness of fresh fruit (2.99 N). This increase in firmness is attributed to drying-induced changes in shape, deformations in cells and intercellular spaces, transformations in physical state, and ruptures of cellular bonds – all of which contribute to a harder texture (Manjarres-Pinzon et al., 2013). Additionally, the increase in firmness reflects the rise in dry matter within the sample due to moisture removal.

Results presented in Table 4 indicate that the firmness of dried banana samples was greater when drying occurred at higher IR powers and air temperatures. This is because, during the drying process, superficial vaporization happens first, followed by the migration of internal moisture. This sequence leads to surface collapse and subsequently results in a harder texture (Pashazadeh et al., 2024). The results obtained in this study are consistent with those reported by (Boudhrioua et al., 2002), who observed an increase in the penetration resistance of Cavendish Grande naine banana slices as the drying air temperature increased.

Additionally, a Pearson correlation coefficient $r = 0.92$ indicates a very strong positive linear correlation between firmness and diffusivity values. This means that higher diffusivity values correspond to higher firmness values. This relationship suggests that increased diffusivity, which signifies a faster removal of water, can result in quicker dehydration and, consequently, greater firmness.

3.4 Multi-objective optimization

Multi-objective optimization was performed using the desirability function approach to enhance process performance, reduce environmental impact, and achieve a high-quality product. As depicted in Figure 4, the condition that yielded the maximum overall desirability (D = 0.60) was achieved with the highest IR power (P = 180 W) at an intermediate air temperature (T = 59 ºC). This desirability value, which falls within the satisfactory range on the desirability scale established by (Lazic, 2004), indicates that the product meets acceptable quality standards within the specification limits and has potential for further improvement. Under this condition, the predicted values for the response variables were as follows: moisture content M_f = 18.49% w.b., Def = $9.9 \cdot 10^{-4}$ mm^2/s, SEC = 49.60 kWh/kgH_2O, q_{CO2} = 1.90 10^{-4} tCO_2e, A_w = 0.44, TSS = 77.64 ºBrix and Firmness = 37.63 N.

Figure 4

4. Conclusions

This study evaluated the optimal conditions for producing dried bananas using IR drying assisted by forced convection with hot air. The results indicated that operating the dryer at higher IR power levels and air temperatures facilitated moisture removal due to increased effective diffusivity, which ranged from 5.47×10^{-4} to 1.12×10^{-3} mm^2/s. This led to lower SEC values, which varied between 41 kWh/kgH_2O and 74.49 kWh/kgH_2O, along with a significant reduction in CO_2 emissions, ranging from 1.71×10^{-4} tCO_2e to 3.01×10^{-4} tCO_2e.

A thorough evaluation of the quality of the dried banana was conducted based on physicochemical parameters that play a crucial role in consumers' sensory perception. All studied conditions met the industry standards for moisture content (M_f < 22% on a wet basis) and water activity (A_w < 0.52). It was observed that all drying conditions resulted in bananas that were darker and opaquer compared to fresh fruit, with a redder hue. Additionally, an increase in IR power and air temperature was associated with a decrease in the pH of the dried product (between 4.33 and 4.71) and an increase in TSS, ranging from 40° Brix to 83° Brix, as well as firmness (between 20.66 and 39.77 N). The highest sensory acceptance correlated with the highest TSS value and the lowest firmness value.

The desirability function approach was effectively utilized to identify a specific condition (P = 180 W and T = 59 °C) aimed at minimizing M_f, SEC, qCO_2, A_w, and firmness while simultaneously maximizing D_{ef} and TSS. This resulted in an overall desirability score of 0.60. These findings could significantly enhance energy efficiency, reduce environmental impact, and improve the quality attributes of products in industrial banana processing.

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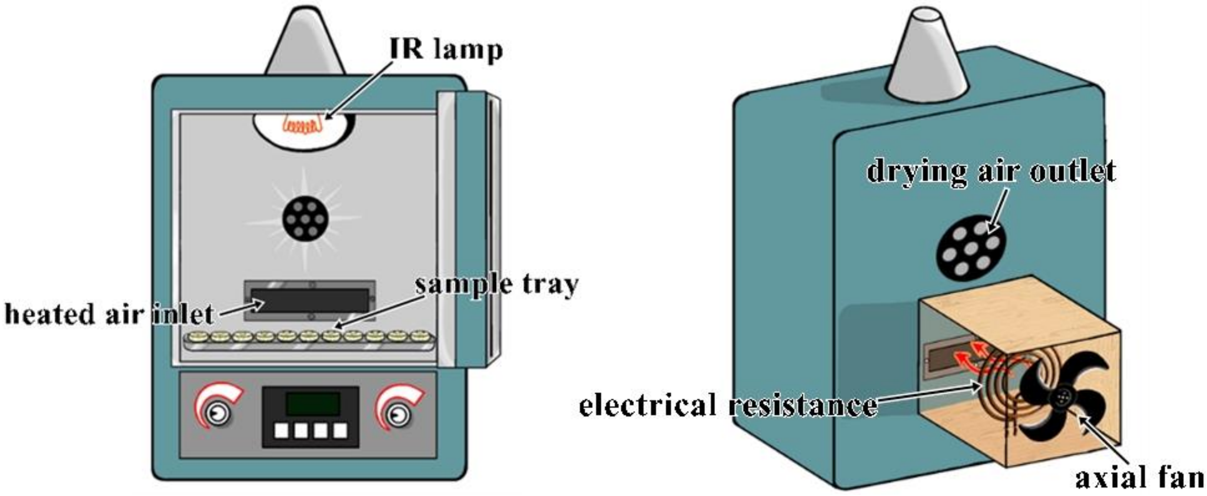
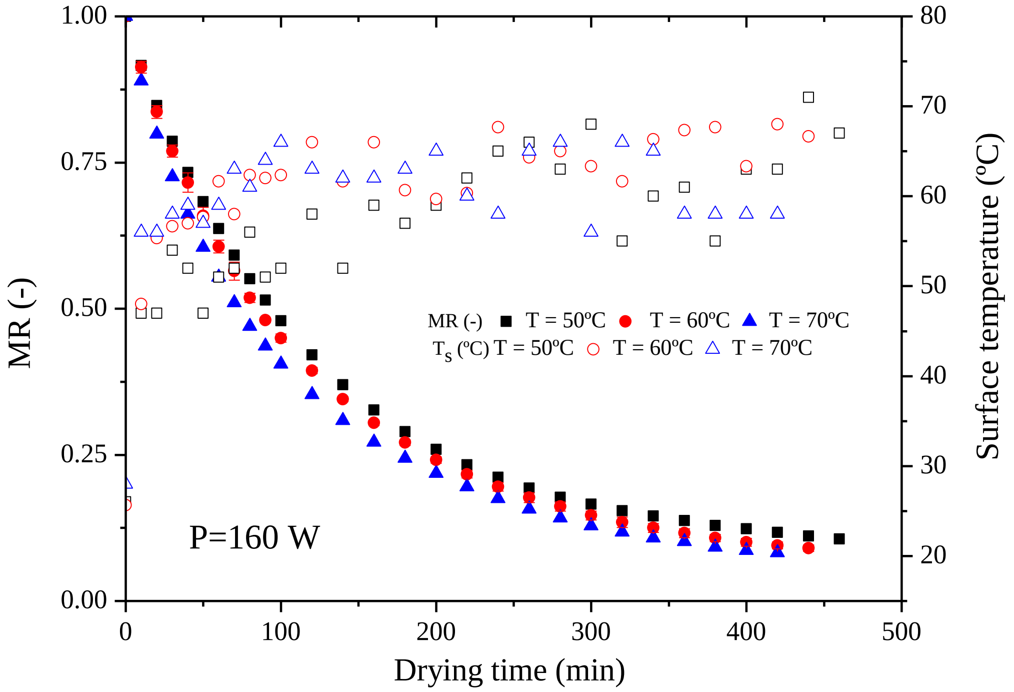
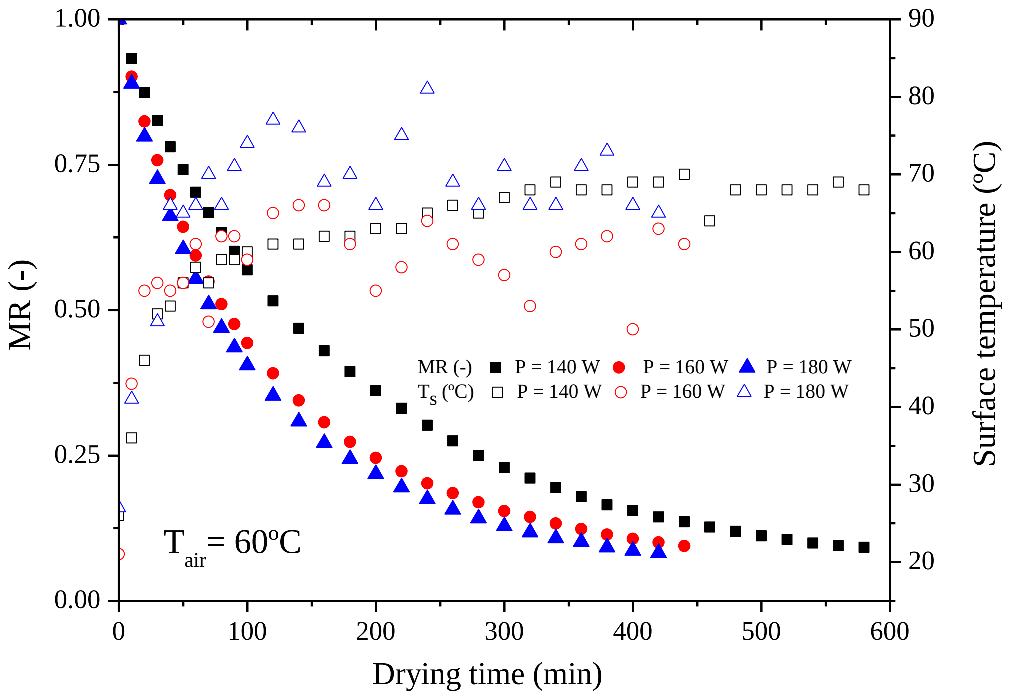


Fig. 1 Schematic sketch of the IR-HA dryer used in the experiments.



(a)



(b)

Fig. 2. Moisture ratio as a function of drying time at different temperatures with (a) P = 160W and (b) T = 60 ºC.

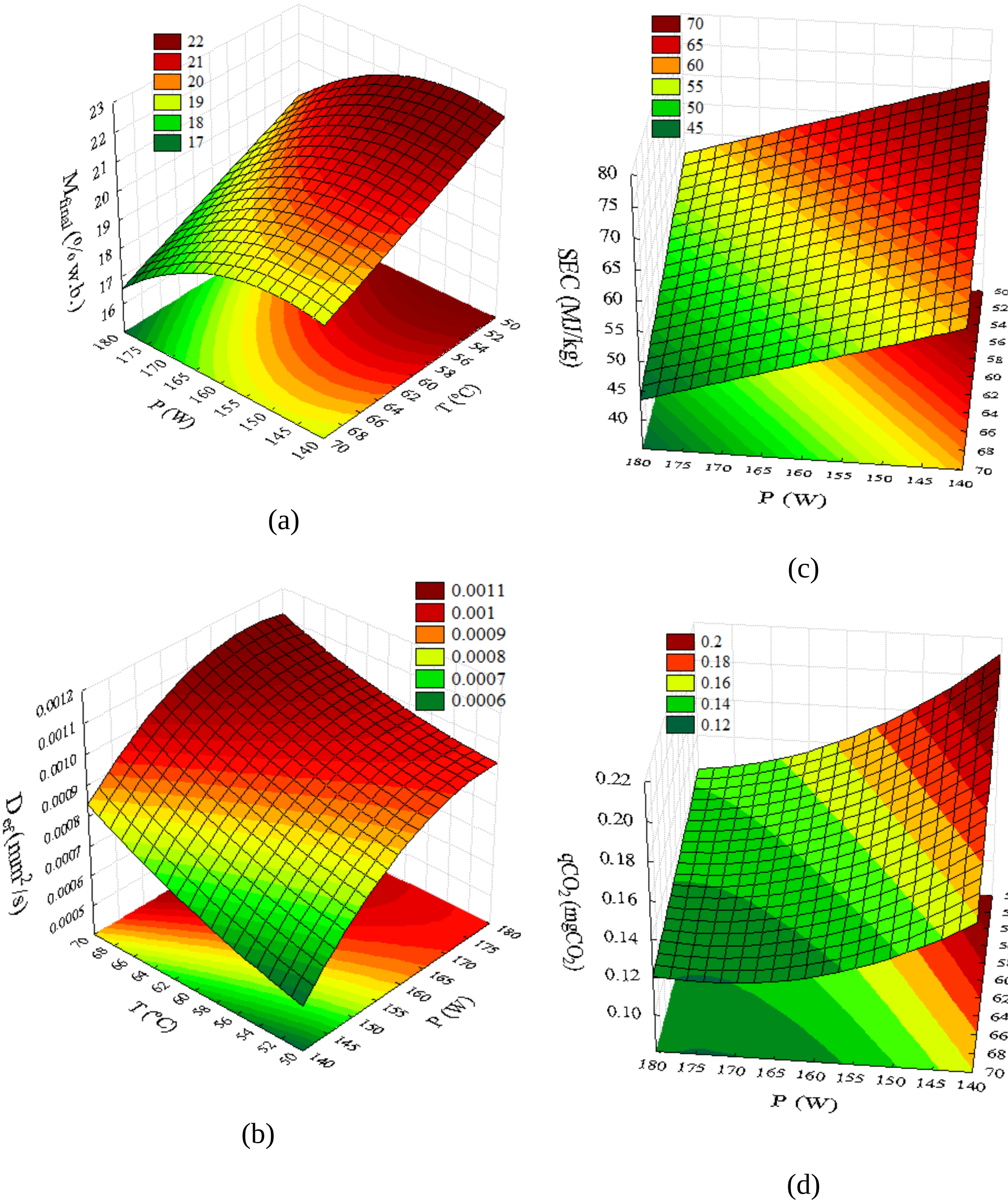


Fig. 3. Response surface plot showing the effect of IR power (P) and drying air temperature (T) and on the (a) final moisture content, (b) effective diffusivity, (c) specific energy consumption (SEC), and (d) CO_2 emissions.

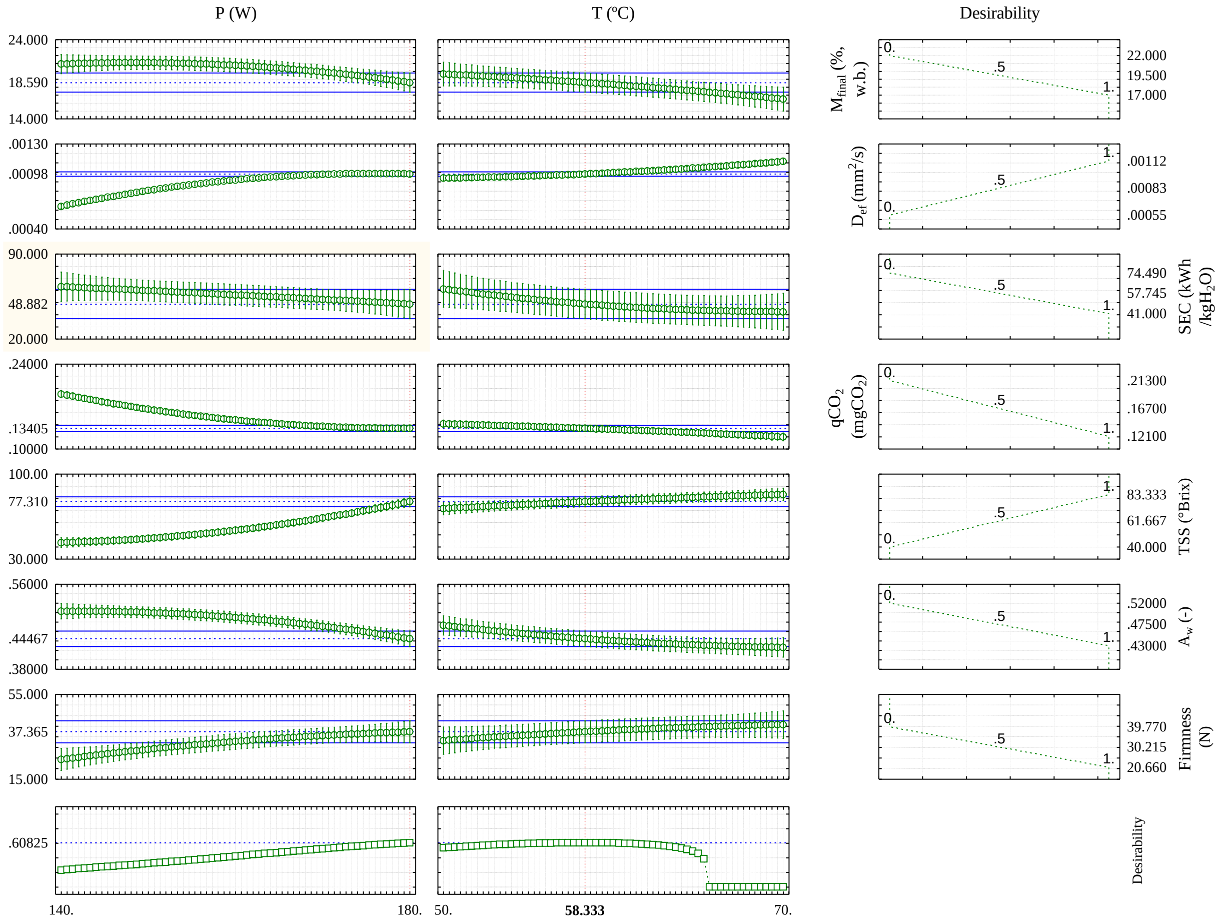


Fig. 4. Desirability function for minimize M_f, SEC, qCO_2, A_w, and Firmness and maximize D_{ef}, and TSS.

Figure captions

Fig 1. Schematic sketch of the IR-HA dryer used in the experiments

Fig 2. Moisture ratio as a function of drying time at different temperatures with (a) P = 160 W and (b) T = 60 ºC.

Fig 3. Response surface plot showing the effect of IR power (P) and drying air temperature (T) and on the (a) final moisture content, (b) effective diffusivity, (c) specific energy consumption (SEC), and (d) CO2 emissions.

Fig. 4. Desirability function for minimize Mf, SEC, qCO2, Aw, and Firmness and maximize Def, and TSS.

Table list

Table 1. Experimental results of responses (final moisture content, effective diffusivity, SEC and CO2 emissions) related to IR power and air-drying temperature.

P (W)	**T (°C)**	**M_f (% w.b.)**	**D_{ef} (mm^2 /s)**	**SEC (kWh/kgH_2O)**	**qCO_2 (10^4tCO_2e)**
140	**50**	22.0	$5.47\cdot10^{-4}$	74.49	3.01
140	**60**	20.5	$6.56\cdot10^{-4}$	62.30	2.60
140	**70**	19.0	$8.46\cdot10^{-4}$	60.06	2.26
160	**50**	21.5	$8.58\cdot10^{-4}$	57.09	2.25
160	**60**	20.5	$9.38\cdot10^{-4}$	60.64	2.07
160	**70**	18.0	$1.07\cdot10^{-3}$	58.54	1.74
180	**50**	20.0	$9.34\cdot10^{-4}$	71.79	2.17
180	**60**	17.5	$9.94\cdot10^{-4}$	43.19	1.84
180	**70**	17.0	$1.12\cdot10^{-3}$	41.00	1.71
160	**60**	21.0	$9.28\cdot10^{-4}$	54.55	2.10
160	**60**	21.0	$9.55\cdot10^{-4}$	54.35	2.05

Table 2. Colour measurements and physical-chemical properties for fresh and dehydrated banana samples.

Run	P (W)	T (ºC)	Drying Time (min)	L* (-)	C* (-)	H* (-)	ΔE (-)	BI (-)	pH	TSS (°Brix)	A_w (-)	Firmness (N)
fresh fruit reference				78.3	37.0	91.1	—	60.78	4.44	15.64	0.98	2.99
1	140	50	620	45.1	29.7	73.4	35.12	107.76	4.71	40	0.52	20.66
2	140	60	580	50.3	34.1	73.8	29.58	112.90	4.64	42	0.51	25.01
3	140	70	540	46.7	34.6	71.7	33.41	127.73	4.57	50	0.49	28.07
4	160	50	460	45.3	30.5	68.5	35.64	110.64	4.61	50	0.51	23.77
5	160	60	440	41.4	32.9	69.8	38.81	141.44	4.57	55	0.49	34.26
6	160	70	420	49.6	35.5	74.1	30.19	121.36	4.50	57	0.48	39.67
7	180	50	460	52.6	36.1	73.2	27.60	114.21	4.49	70	0.48	35.61
8	180	60	440	39.9	25.1	67.4	41.76	100.77	4.33	80	0.43	36.60
9	180	70	420	41.2	27.3	61.3	41.14	106.47	4.35	83	0.43	39.77
10	160	60	440	41.5	32.2	69.6	38.71	140.66	4.55	55	0.48	33.79
11	160	60	440	41.6	33.0	69.1	38.76	134.64	4.56	55	0.49	34.45

Table 3. Average colour of fresh and dehydrated banana samples.

T (°C)	P (W)	Color
fresh fruit reference		
140	50	
140	60	
140	70	
160	50	
160	60	
160	70	
180	50	
180	60	
180	70	
160	60	
160	60	
dried fruit reference		

Table 4. Effects of drying air temperature and IR on the physical-chemical properties.

pH (R^2 = 0.954)			
	Effect	Std.Err.	p-value
Mean	4.53	0.01	< 0.001
P	-0.25	0.02	< 0.001
P^2	0.04	0.02	0.045
T	-0.13	0.02	0.001
TSS (R^2 = 0.987)			
	Effect	Std.Err.	p-value
Mean	58.69	0.60	< 0.001
P	33.67	1.57	< 0.001
P^2	-6.43	1.16	0.001
T	10.00	1.57	< 0.001
A_w (R^2 = 0.917)			
	Effect	Std.Err.	p-value
Mean	0.48	0.00	< 0.001
P	-0.06	0.01	< 0.001
P^2	0.01	0.01	0.066
T	-0.04	0.01	0.003
Firmness (N) (R^2 = 0.863)			
	Effect	Std.Err.	p-value
Mean	31.97	0.82	< 0.001
P	12.75	2.21	< 0.001
T	9.16	2.21	0.003

ARTIGO 2 - Intermittent Hybrid Drying of Bananas: Optimizing Energy Efficiency and Physicochemical Properties Through Infrared Radiation and Hot Air

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Abstract: The use of advanced drying techniques can significantly enhance the quality of dried bananas. This study investigated the drying kinetics of bananas using three intermittence ratios (0, 0.333, and 0.667), combined with infrared radiation at different power levels (140, 160, and 180 W) and heated air convection at varying temperatures (50, 60, and 70 °C). The final moisture content of the samples ranged from 17% (at P = 180 W, T = 70 °C, and α = 0) to 57.4% w.b. (at P = 160 W, T = 50 °C, and α = 0.667). Specific energy consumption (SEC) ranged from 23.62 kWh/kgH2O (at P = 180 W, T = 70 °C, and α = 0.333) to 36.87 kWh/kgH2O (at P = 140 W, T = 50 °C, and α = 0) for an effective drying time of 140 minutes. The effective diffusivity was estimated to be between $5.47 \cdot 10^{-4}$ and $1.37 \cdot 10^{-3}$ mm²/s, with activation energy ranging from 13.69 to 17.63 kJ/mol. The quality of the dried product was evaluated in terms of pH (4.33 to 4.79), soluble solids content (28° Brix to 83° Brix), water activity (0.43 to 0.52), and hardness (2.02 to 39.77 N). The optimal condition (P = 180 W, T = 60 ºC, and α = 0.389) achieved an overall desirability of 0.83, indicating a high-quality product within specification limits (values of Mf, BI, and firmness), while simultaneously maximizing process performance (Def and SEC values).

Keywords: intermittent drying, hybrid drying, specific energy consumption; banana; desirability function.

1. Introduction

Brazil stands out as the third-largest producer and exporter of food in the world, leading the production and export of at least seven foods (FAO, 2021). Additionally, foods such as bananas have a significant impact in terms of production and export, as the country ranks as the fourth-largest producer, with an average annual revenue of approximately US$ 25 billion. However, data released by the FAO (2017) estimate that about one-third of the world's food is lost or wasted every year due to its high water content. An example is the banana, which has a high water content (70%) and can lead to a loss of up to 40% of production during the post-harvest period (Filipenco, 2023; Martínez et al., 2023; FAO, 2017).

Drying is one of the most widely used unit operations in food processing as it helps reduce water content, thereby increasing the shelf life of food. Convective drying is the most commonly used drying method in the food industry because it is a simple and highly effective process. Despite its widespread use, convective drying leads to significant nutritional losses when applied to heat-sensitive foods.

Given the new global demands for the preservation of compounds in food, new drying techniques are being developed to improve the process and increase the preservation of sensory and nutritional components in food. One of these techniques is hybrid drying, which combines two or more drying techniques (Llavata et al., 2020; Ratti; Mujumdar, 2020; Berk, 2018).

The hybrid drying (Hy) technique, such as the combination of infrared drying (IR) and hot air (HA), emerges as a promising technique for heat-sensitive foods like bananas due to its synergistic effect, which allows for improved product quality and reduced energy consumption (Souza, 2024; Puangsuwan et al., 2021). Additionally, studies show that using a heat emitter shut-off cycle can be beneficial for heat-sensitive foods. In this context, intermittent drying presents itself as an option to minimize the effects caused by the use of high temperatures and to reduce energy consumption. Intermittency has proven effective in studies on agricultural products, such as those developed by Pham (2022) and Borah (2023), who used an intermittent drying technique combining microwave drying with convective drying for papaya and persimmon fruit, respectively. Both studies showed significant effects on improving the color of the dried sample and reducing the energy consumption of the process.

Despite this, there are still no studies in the literature on the use of intermittent hybrid drying (IR-HA) for bananas. Therefore, this work focused on developing a comprehensive analysis of the intermittency ratio under different operational conditions of IR radiation power and air temperature, evaluating the performance of the banana drying process and the quality of the final product. Effective diffusivity, specific energy consumption, and CO2 emissions were determined for the process under different operating conditions. Additionally, product quality attributes such as final moisture content, water activity, color, texture, pH, and soluble solids content were evaluated. The optimal operational condition was identified through the response surface methodology, using the desirability function approach. These results serve as a key theoretical reference for the production of dried bananas using the intermittent IR-HA technique.

2. Material and Methods

2.1 Material

Bananas of the Prata variety (Musa paradisiaca L.) used in this study were sourced from local retailers in Lavras, MG. They were selected at ripeness stage C6 of the Von Loesecke subjective ripeness scale, characterized by fruits with yellow skin and no brown spots (PBMH & PIF, 2006). The bananas were cleaned, peeled, and sliced into uniform pieces, each approximately 1 cm thick. Twelve slices were then arranged on a tray with a diameter of 21 cm. The fresh banana's average moisture content was 73.6 ± 1.4% (w.b.).

2.2 Drying process

The drying experiments were performed in a hybrid dryer combining IR radiation and forced convection with heated air, and the tempering time was performed using a desiccator (Fig. 1). The drying chamber (60.0 x 39.0 cm) features carbon steel outer walls, stainless steel inner walls, and glass wool insulation. An IR lamp 90 (250 W) was positioned 19 cm above the center of the tray containing the samples. The power 91 output of the lamp was adjusted using a clamp meter (KRAD01, Kript)

The drying air is supplied by a fan,passing through an electrical heater(1400 W). The air temperature is controlled by a digital controller (Novus, N1030). The experiments were conducted varying drying air temperatures (50, 60, and 70 °C) at a constant air velocity (4.5 m/s), different IR powers levels (140, 160, and 180 W), and intermittency ratios (α) (0, 0.333, and 0.667), according to a 3^3 factorial design. The air relative humidity was measured using a thermo-hygrometer (Impac, IP-780), yielding an average value of 55 ± 10% throughout the tests.

Figure 1

In the tests with intermittency ratio α = 0, the process was characterized by continuous drying, where the sample remained inside the hybrid dryer for the entire drying process. In the tests with α = 0.333, the tempering period (toff) was 10 minutes, with the sample staying 20 minutes inside the dryer (tin = 20) and 10 minutes outside, totaling cycles of 30 minutes. For the tests with α = 0.667, the tempering period was 20 minutes, with the sample staying 10 minutes inside the dryer (tin = 10) and 20 minutes outside (toff = 20), also in cycles of 30 minutes. The values for the intermittency ratio used were adjusted based on values available in the literature (Jumah, 1995; Pan et al., 1998; Yang et al., 2013; Chin e Law, 2010).

The moisture reduction in each test was evaluated by gravimetry in intermittent mode. The samples were periodically removed from the drying chamber for brief intervals, and their weight was measured using an electronic scale (AD4200, Marte). Measures were taken every 10 minutes during the first 100 minutes of drying, and then every 20 minutes until the mass stabilized for tests conducted without intermittency. For the tests with intermittent drying cicles, measurements were recorded at the startand end of each cycle. The final moisture content was determined by oven drying (SL102, Solab) at 105 ± 3 °C for 24 hours (IAL, 2008).

The moisture ratio (MR) was calculated according to Eq. 1 (Pal et al., 2023):

$$MR = \frac{M}{M_0} \quad (1)$$

where M is the moisture content at time t and M_0 is the initial moisture content of bananas (g water/g dry matter, dry basis, d.b.).

The equilibrium moisture was disregarded (Eq. (1)) due to the high value of the Fourier number (> 0.2).

Drying rate (DR) was estimated as follows:

$$DR = -\frac{M_{t+\Delta t} - M_t}{\Delta t} \quad (2)$$

where M_t is the moisture content at time t, $M_{t+\Delta t}$ is the moisture content at time $t+\Delta t$, all in g water/g dry matter, and Δt is the time increment between two determinations, in minutes.

2.3 Diffusive model

The first term of the analytical solution for Fick's second law of diffusion in rectangular geometry, assuming one-dimensional moisture transfer with negligible shrinkage, an isothermal process with uniform initial moisture distribution, and equilibrium conditions prevailing at the material surface, was used to calculate the banana's effective diffusivity, according to Eq. (3) (Kumar et al., 2023):

$$MR = \frac{8}{\pi^2}\ exp\ (-\frac{\pi^2 D_{ef}}{L_0^2}\ t) \tag{3}$$

where L_o is the thickness of the banana slice (mm), D_{ef} is the effective diffusivity (mm^2/s) and t is the drying time (s).

The activation energy for moisture diffusion was calculated using the Arrhenius equation, according Eq. 4 (Zhang et al., 2023):

$$D_{ef}\ = D_0\ exp\ (-\frac{Ea}{RT_{m,a}}) \tag{4}$$

where D_0 is the pre-exponential factor (mm^2/s); Ea is the drying activation energy (kJ/mol); R is the molar constant of gas, $8.314 \cdot 10^{-3}$ (kJ/mol·K); and T is the drying temperature (K).

The Solver tool of the Excel software was used to make both adjustments. The fitting quality of the proposed models was assessed with the root mean square error (RMSE: Eq. (5)), the chi-square (χ^2: Eq. (6)) and the coefficient of determination (R^2: Eq. (7)).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{exp,i}\right)^2}{N}} \tag{5}$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{N-n} \tag{6}$$

$$R^2 = 1 - \frac{\sum_{i=1}^{n}\left(MR_{pre,i} - MR_{exp,i}\right)^2}{\sum_{i=1}^{n}\left(\overline{MR}_{pre,i} - MR_{exp,i}\right)^2} \tag{7}$$

where $MR_{exp,i}$ is the ith experimental moisture ratio; $MR_{pre,i}$ is the i^{th} predicted moisture ratio; N is the number of observations, and n is the number of constants in the drying model.

The accuracy of each model was considered by the low RSME and χ2 values, and R^2 close to unity.

2.4 Specific energy consumption and CO_2 emissions

The mains voltage (V) and currents (i) of the infrared lamp, electrical resistance, and axial fan were measured using a digital clamp meter (KRAD01, Kript). Based onthese values, the total power of the system was calculated, and the SEC (kWh/kgH_2O) for each experiment was estimated as the energy required to remove water from the bananas over a 140 minute period, following to Eq. (8).

$$SEC: \frac{(P_{IR}+P_{res}+P_{conv}) * t}{m_w} \quad (8)$$

where P_{IR}, P_{res} and P_{conv} are the power consumption of the infrared lamp, the electrical resistance and axial fan (kW), respectively, t is the drying time (s), and m_w is the mass of water removed (kg).

CO_2 emissions ($q_{CO2,eq}$) under different drying conditions were calculated based on the electrical energy consumption of each experiment and the average Brazilian CO_2 emission factor for 2023 (0.0385 t_{CO2}/MWh) (MCTI, 2024).

2.6 Dried product quality atributes

2.6.1 Color parameters

A colorimeter (Konica Minolta, CR10) was used to measure the surface color of bananas before and after drying. The L*, a*, b* parameters were obtained, where L* indicated lightness, a* represent redness (+) or greenness (-), and b* representsyellowness (+) or blueness (-). The total color difference (ΔE) was calculated from the collected data using the following equation (Pei et al., 2022):

$$\Delta E = (\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2})^{1/2} \quad (9)$$

where ΔL^*, Δa^* and Δb^* represent the difference between $L*$, $a*$ and $b*$ of the fresh banana and the dried samples.

The chroma (C*), which corresponds to the color saturation, and the hue angle (H*), which express the tonality of the color, were determined according to Eqs. (10) and (11), respectively (Borges et al., 2022):

$$C^* = \sqrt{(a^{*2} + b^{*2})} \tag{10}$$

$$H^* = arctan\left(\frac{b^*}{a^*}\right) \tag{11}$$

Since the browning index (BI) represents the purity of the brown color and is an important parameter to evaluate the type of browning that occurs during the drying of sugar-rich foods, this parameter was also assessed using Eq. (12) (Soto et al., 2021).

$$BI = 100 \cdot \left[\frac{\frac{(a^*+1.75L^*)}{(5.645L^*+a^*-3.012b^*)}-0.31}{0.172}\right] \tag{12}$$

2.6.2 Total soluble solids content and pH

Total soluble solids (TSS) were determined, in triplicate, using a refractometer (Instrutherm, RTA-50). For this, the dried samples were crushed and diluted in distilled water (1:10) and stirred until homogenized. The mean value of the three measurements, in °Brix, was reported.

The pH value of the dried banana mixture in water was measured using a pH meter (Sanxin, MP521). The mean value of the three measurements was taken (IAL, 2008).

2.6.3 Texture analysis

The dried banana samples under the different experimental conditions were examined in triplicate for their textural properties using a texture analyzer (Stable Micro Systems, TA-XT2i) according to the methodology proposed by Medlicott et al. (1992). The penetration/puncture test was performed with a stainless cylindrical probe of diameter 6 mm, using a speed of 1 mm/s. The force required for the probe to penetrate the sample was measured at three points. The average of the three measurements determined the maximum force of the force-deformation curve, which was taken as the firmness value.

2.7 Statistical analysis

Response surface methodology was used to investigate the effects of the independent variables IR power, intermittency ratio and air-drying temperature on the response variables (M_f, SEC, A_w, Firmness, D_{ef}, and TSS). The results were statistically analyzed using Statistica 8.0 software (Statsoft Inc.) at 95% significance level. The replicated center points allow the pure experimental error to be determined for the lack of fit test.

A quadratic polynomial regression model was used to describe the behaviour of the response surface for each *Y* response, according to Eq. (13).

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{23} x_2 x_3 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{33} x_3^2 \quad (13)$$

where *Y* represents the response function, β_0 is a constant term, β_1, β_2 and β_3 are the linear regression coefficients, β_{11}, β_{22} and β_{33} are the squared regression coefficients, and β_{12}, β_{13} and β_{23} are the regression coefficient of interaction effect, x_1, x_2 and x_3 identify the independent variables in coded values.

The statistical significance of the regression coefficients was assessed by analysis of variance (ANOVA) and the models were reduced to the statistically significant terms at a p-value of 0.05.

Desirability function was used to find the optimal operating condition for hybrid drying of banana. For this, the individual desirability (d_i) of the response variables to be minimized (M_f, SEC, A_w, and Firmness) and maximized (D_{ef}, and TSS) were obtained using Eq. (14) and Eq. (15), respectively. Eq. (16) was then used to determine the overall desirability (*D*) by combining individual desirabilities.

$$d_i(Y_i) = \{1,\ Y_i < T_i\ \left(\frac{Y_i - U_i}{T_i - U_i}\right),\ T_i \leq Y_i \leq U_i\ 0,\ Y_i > U_i \quad (14)$$

$$d_i(Y_i) = \{0,\ Y_i < L_i\ \left(\frac{Y_i - L_i}{T_i - L_i}\right),\ L_i \leq Y_i \leq T_i\ 1,\ Y_i > T_i \quad (15)$$

$$D = \left(\prod_{i=1}^{7} d_i\right)^{\frac{1}{7}} \quad (16)$$

where Y_i is the response variable, T_i is the target value, U_i is the upper fitted value, which is desired for response Y_i, and $r_i = 1\ \forall\ i$, considering a linear desirability.

3. Results and Discussion

3.1 Drying kinetics curves

The moisture ratio and surface temperature behavior of the bananas as a function of drying time obtained during the hybrid drying process are presented in Fig. 2.

From the graphs (Fig. 2) it is evidentthat intermittency plays a significant role during drying, proving to be an effective strategy for mitigating thermal impact on the product. The continuous process (α = 0), although offering a faster drying process, leads to higher surface temperatures, which compromises the final quality of the product. Intermittency with α = 0.333 achieves a notablean balance, leading to only a slight reductionin drying efficiency compared to α = 0, but without causing excessive increases in surface temperature. Conversely, the intermittency α = 0.667 resulted in the slowest drying, but it also preserved lower and more stable surface temperatures of the sample, which can be an advantage for preserving the color and texture of the final product.

The sample temperature is a direct influence on the water removal rate. It is observed that as the temperature increases, MR decreases more quickly. According to Incropera et al. (2014), this behavior is consistent with heat transfer theory, in which thermal energy promotes a higher evaporation rate of the water contained in the product, reducing the time required to reach low moisture levels. The increase in power significantly accelerates water removal, as evidenced by the rapid reduction in moisture ratio (MR). As described by Mujumdar (2006), this behavior occurs due to the higher energy density applied to the product, which intensifies water evaporation at the surface and accelerates the subsequent diffusion of water from the interior to the surface.

Figure 2

These implications are supported by the moisture and effective process time data presented in Table 1, where the continuous process demonstrated lower final moisture (M_{final}) values (17%) but was associated with longer effective process times (620 min). On the other hand, the intermittency resulted in higher final moisture values (α = 0.667, Mfinal = 57%), which is mainly related to the shorter drying process time (140 min). Additionally, the intermittency at 0.333, at the highest temperature and power (T = 70°C and P = 180 W), showed a shorter drying time compared to the continuous process (α = 0.333, t = 280 min; α = 0, t = 480 min) and achieved final moisture values (M_{final} = 23.7% wet basis) within the standards of Brazilian legislation, according to RDC nº 82/00, the "dried" fruit must contain a maximum of 25 g of moisture per 100 g.

3.2 Effect of IR power, intermittency ratio and drying air temperature

The data presented in Table 1 show that the estimated values of effective diffusivity ranged from $5.47 \cdot 10^{-4}$ to $1.37 \cdot 10^{-3}$ mm^2/s. Data analysis confirms that effective diffusivity is affected by the three parameters studied: power (P), temperature (T), and intermittence (α). The combination of high power and high temperature maximizes diffusivity, as predicted theoretically and observed in previous studies.

Table 1.

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Intermittence, in turn, modulates this effect. This is evident in the condition of 180 W and 70 °C, which presented the highest diffusivity value ($1.37 \cdot 10^{-3}$ mm²/s) with $\alpha = 0.333$, indicating an optimal condition. In this configuration, the intermittence allowed sufficient time for internal diffusion to occur, without large variations in the average temperature of the sample. According to Onwude et al. (2016), the effective diffusivity of most dried fruits ranges from 10^{-5} mm²/s to 10^{-2} mm²/s. The results obtained are consistent with these values.

Additionally, the diffusion model explains the variability of the experimental data of the process well, as it presented R^2 values of ≥ 0.810, representing 81% or more of the variation explained by the model. Although this is a good value, optimized drying models tend to have higher R^2 values (ideally close to 1.0, above 0.90). However, the RMSE values (<0.08) suggest a relatively low error between the predicted model values and the experimental data, indicating that the proposed model has good predictive capacity. The χ^2 values (<0.008) indicate minimal discrepancy between the experimental data and the proposed model, suggesting good capture of the variability of the experimental data and a proper fit in the study on banana drying using a combination of infrared radiation and heated air convection, the Arrhenius equation was employed to describe the relationship between the effective water diffusivity and the absolute drying temperature.

The values obtained for activation energy ranged from 13.69 to 17.63 kJ/mol. This variation can be attributed to different experimental conditions, such as applied power (IV), air temperature, and the intermittence ratio. For example, the power of infrared radiation influences the energy provided to the material and, therefore, the water evaporation rate. Higher power tends to reduce activation energy, as it supplies more energy for water diffusion. Similarly, higher drying temperatures generally result in lower activation energy values, requiring less energy for water molecules to diffuse. Additionally, the intermittence ratio, which involves pause periods during drying, can affect moisture redistribution within the material. This influences the diffusive behaviour and, consequently, the estimated activation energy.

The relatively constant values obtained for D_0 (between 0.20 and 0.21) indicate that intermittence did not cause significant variations in the maximum diffusivity of the drying process. This suggests that the impact of intermittence on effective diffusivity is limited. Despite the pauses in the process, the temperature conditions and drying environment allowed for a relatively consistent diffusion rate. This suggests that bananas have a diffusive capacity that is not significantly affected by small variations in the intermittence ratio, as the general drying conditions were maintained. However, the increase in E_a with increasing intermittence ratio indicates that more energy was required to initiate the water diffusion process under intermittent conditions. This occurs because, as the pause time increases, water redistributes within the banana, creating resistance to removal during the next active drying cycle. The increase in E_a reflects the need to overcome this additional resistance, as the surface rehydration process following pauses can create more difficult conditions for water diffusion.

These results indicate that, although intermittence increases the activation energy required for the drying process, it does not significantly affect the system's maximum diffusivity. In practice, this may mean that intermittence needs to be carefully adjusted to balance the benefits in terms of energy savings and product quality preservation, without making the drying process inefficient due to the increase in E_a.

The SEC values ranged from 23.17 kWh/kgH_2O to 36.87 kWh/kgH_2O, with specific energy consumption showing a decreasing trend with increasing temperature and intermittency. For example, at 180 W and 70 °C, SEC decreased from 25.21 kWh/kgH_2O for $\alpha = 0$ to 24.59 kWh/kgH_2O for $\alpha = 0.667$. This reduction is due to the increased drying rate and the shorter effective drying time (Mabasso, 2021). Lower SEC values were mostly observed in drying processes with $\alpha = 0.333$, especially when associated with higher power levels, demonstrating that intermittency can improve drying energy efficiency by reducing total energy consumption. As for CO_2 emissions, which depend on drying time, changes were observed only in relation to the studied power, remaining in the range of 0.040 to 0.052 mgCO_2 in all drying trials.

These data are consistent with the findings of Mabasso (2021), who demonstrated a 23.23% reduction in specific energy consumption in intermittent drying compared to continuous drying in maize grain. Similarly, Bissaro (2021) indicated a 46% reduction in energy consumption for intermittent operation compared to convective drying at 50 °C and a 42% reduction at 70 °C in intermittent drying of soybean seeds.

3.3 Response surface

In order to relate the parameters of IV power, air temperature, and the intermittency ratio with the final moisture content, effective diffusivity, and specific energy consumption (SEC), response surfaces were constructed (Fig. 3), presenting the effects data (Tab. 3) for these parameters.

The analysis of the response surfaces reveals that temperature (T) and intermittency (α) play critical roles in convective-infrared drying. As previously noted, increasing the temperature significantly reduces the final moisture content (Mfinal), as evidenced by the negative linear coefficient of -5.13. This behavior can be explained by the increased evaporation rate at higher temperatures, which accelerates water removal from the product. However, intermittency shows an opposite effect, with a positive coefficient of 30.04, suggesting that higher levels of intermittency result in higher final moisture content.

Additionally, power (P) shows a negative linear effect (-8.40), indicating that increasing power reduces the final moisture content, although the positive quadratic effect (4.01) suggests a reduction in drying efficiency at very high power levels. This non-linear interaction between power and final moisture content highlights the need for a balance between drying parameters to optimize the process. Finally, the significant impact of intermittency ($p < 0.001$) reinforces the importance of properly adjusting tempering cycles to control water retention and, consequently, the quality of the final product.

Figure 3

Table 2

The response surfaces 3c and 3d demonstrate the interaction between intermittency and temperature, and between intermittency and IV power, respectively. It is possible to observe an increase in effective diffusivity with rising temperature, especially at lower levels of intermittency. However, as intermittency increases, the slope of the surface decreases, indicating that the positive effect of temperature (0.00031) on diffusivity is reduced at high levels of intermittency.

Similarly, increasing power also leads to an increase in diffusivity, but the impact of power on effective diffusivity is less pronounced at higher levels of intermittency. This suggests that the longer the system spends in the tempering state, the lower the drying process efficiency, even if the power during the periods within the dryer is high.

Regarding response surfaces 3e and 3f, it is possible to observe that intermittence tends to increase SEC, particularly at lower power levels. However, the increase in SEC due to intermittence is less pronounced when associated with higher temperatures or high power, suggesting that these variables may compensate for the negative energy effects of intermittence.

Power demonstrates a negative effect (-4.68), indicating that an increase in power results in a significant decrease in SEC. The inclusion of the negative quadratic term (-1.17) indicates an additional reduction effect on SEC with increasing power, but of lesser magnitude compared to the linear term. This quadratic effect suggests that at higher power levels, the gain in energy efficiency starts to diminish, meaning the positive impact of increasing power on SEC becomes less significant.

Temperature also shows negative effects (-5.23), highlighting that an increase in temperature also significantly reduces SEC. However, the positive interaction between power and temperature (2.03) indicates that, in certain cases, the combined effect of these variables may increase SEC. Additionally, the interaction between power and intermittence presents a positive interaction (1.64), demonstrating that the use of high intermittence in conjunction with high power can increase SEC.

3.4 Assessment of intermittent mode dried product quality

Table 3 shows the results obtained for the color parameters (L*, C*, h◦, ΔE, and BI) and physical-chemical (A_w, TSS, pH and Firmness) of fresh and dried bananas.

Table 3

Based on the data presented in Table 3, it is evident that the parameters related to the color of the dried fruits exhibitsignificant variation, highlighting the influence of drying conditions, particularly the intermittence coefficient (α).

The relative lightness (L*) of the samples ranged from 39.9 to 66.0. It was observed that intermittence had a notable impact on the color of the dried fruits. The samples dried continuously (α = 0) showed a tendency for greater darkening and lower lightness compared to those subjected to higher intermittence (α = 0.333 and α = 0.667). For example, the continuously dried samples (P = 140 W) consistently showed lower lightness values (L*) and higher browning index (BI), indicating more pronounced darkening. In contrast, the samples dried with intermittence of 0.333 and 0.667 exhibited a color closer to that of fresh fruit, with less darkening and better preservation of lightness. Specifically, the samples with intermittence of 0.333 (P = 140 W, T = 50 °C and T = 60 °C) and 0.667 (P = 140 W, T = 50 °C and T = 70 °C) showed less variation in total color difference (ΔE) and a reduced browning index, demonstrating that intermittence minimizes darkening and favors color preservation of the samples.

The hue angle (h°) of the dried samples ranged from 61.3 to 89.5, indicating a color that varies from slightly yellowish to golden, with values closer to that of fresh fruit (91.1) in the samples with higher intermittence. The chroma (C*) of the dried samples was also affected by intermittence, ranging from 24.3 to 51.0, reflecting lower saturation compared to fresh fruit. These data corroborate the results found by Polat (2024), who observed L* values closer to fresh product in infrared drying with high intermittence and lower power, while the lowest L* value was recorded in continuous drying with higher power. Similarly, Jin *et al* (2020) observed reduced a* redness and b* yellowness values during intermittent drying of nuts, suggesting a better outcome compared to continuous drying. Previous studies, such as those by Viana (2017) and Souza (2024), reported high browning indices in continuous methods, highlighting that intermittent drying can be an effective strategy to reduce browning.

Considering that color is a fundamental quality attribute that directly influences consumer acceptance, the use of intermittent drying emerges as a valuable alternative to improve product acceptance. The results indicate that intermittent drying is effective in preserving the color of dried fruits, keeping it closer to that of the fresh fruit, which can significantly contribute to consumer acceptance and satisfaction (Olalekan, 2020).

Table 4

According to Macedo et al. (2020), acidity is a crucial factor for the sensory quality of bananas, as it has a direct influence on the perception of sweetness. Regarding the pH values found, dried bananas showed a variation from 4.33 to 4.79, which is consistent with previous studies on convective drying of bananas, such as Da Silva et al. (2017), who reported a pH of approximately 4.55.

Power and temperature have negative effects (see Table 4), leading to a reduction in pH. Intermittence had a positive effect on pH (0.12), suggesting an increase. The interaction between power and intermittence suggests that applying intermittence at high power levels helps mitigate the pH drop caused by high power. Furthermore, the values found are close to the pH of ripe fresh bananas (4.2 to 4.7), indicating a slightly acidic pH (Matsuura, 2021).

The values found for water activity (Aw) ranged between 0.43 and 0.94, with a reduction of up to 54% (P = 180W and T = 60ºC) during continuous drying compared to the fresh fruit. Samples that used higher intermittence showed higher Aw values, mainly due to the final moisture content of the sample and the shorter effective processing time (up to 66% less) compared to continuous drying. The analysis of the effects shows that power (-0.12) and temperature (-0.05) reduce Aw, indicating that increasing both parameters promotes more efficient drying, removing more water. However, intermittence (0.37) had the opposite effect. The interaction between power and intermittence (-0.05) showed that, even under high power conditions, intermittence can help mitigate the increase in Aw, balancing dehydration.

Samples with Aw values up to 0.6 demonstrate minimal viability for microorganism growth, and microbial spoilage in dried food is unlikely for up to 2 years. Additionally, industrially, drying is carried out until the banana reaches a maximum moisture content of 25% and a water activity of less than 0.7 (Kushwah et al., 2022; Farias, 2020; Macedo et al., 2020). All samples dried during continuous drying showed Aw values lower than 0.06, while in intermittent drying, only one sample (α = 0.333, P = 180W and T = 70ºC) had an Aw value within the range required to prevent microbial growth.

Total soluble solids (TSS) are primarily responsible for the sweetness found in dried fruits. The TSS content found in the present study ranged from 28 to 83 °Brix. These values tend to decrease with intermittence, as observed from its negative effect (-17.11). On the other hand, temperature and power have positive effects, leading to an increase in TSS content (see Table 3). The quadratic effect of power and its interaction with intermittence show that at high power levels, the TSS value tends to stabilize, mainly due to the interaction with intermittence. Additionally, lower TSS values can be attributed to higher final moisture content caused by the use of intermittence, since lower moisture levels generally result in higher TSS in the product, as moisture is the main component of dry matter (Dereje and Abera, 2020).

Texture is also an essential parameter for food acceptance and quality estimation. The firmness (hardness) of the samples ranged between 2.02 and 39.77 N. An intermittence ratio of

0.667 resulted in lower hardness values, while continuous drying presented the highest values. Samples subjected to intermittent drying showed lower hardness than those dried continuously and, in some cases, lower firmness than the fresh sample. This is mainly due to the fact that surface moisture is removed more quickly than internal moisture, leaving the interior still moist. Additionally, the concentration of sugars on the surface of the samples increases, making the outer layer more flexible.

Power and temperature have a positive effect on firmness (see table 5), indicating that increasing both leads to an increase in firmness. On the other hand, intermittence has negative effects (-26.91), demonstrating that the application of intermittence significantly reduces the product's firmness. Furthermore, the negative quadratic effect (-11.44) of intermittence reinforces the idea that intermittent drying, especially in longer cycles, has a softening effect on firmness. The interaction between power and intermittence also shows a negative effect (-5.43), preventing the application of intermittence from contributing to reducing firmness even under high-power conditions. This suggests that intermittence mitigates the increased resistance caused by high power, as the off cycles allow for a balance in the internal moisture distribution, preventing excessive hardening.

This characteristic is related to the fact that the hardness of foods is strongly influenced by drying time and temperature. The lack of interruption in the continuous process leads to higher and more stable temperatures in the samples, which contributes to the increased hardness of the product, supporting the data presented by Mujumdar (2014). However, controlling hardness during the drying process is essential, as excessively hard products may be rejected by consumers (Macedo, 2020).

3.4 Multiobjective optimization

Multi-objective optimization was performed using the desirability function approach to enhance process performance, reduce environmental impact, and achieve a high-quality product. As depicted in Fig. 4, the condition that achieved maximum overall desirability (D = 0.83) was that of the highest IR power (P = 180 W) of the highest temperature (T = 70 ºC) with an intermediate (α = 0.389). This desirability value, falling within the satisfactory range on the desirability scale presented by (Lazic, 2004), indicates a product with both acceptable and excellent quality. It represents an uncommon level of quality or performance, far exceeding that of commercially available products. For this condition, the predicted values of the response variables were M_f = 28.7% w.b., Def = $1.29 \cdot 10^{-3}$ mm^2/s, SEC = 24.07 MJ/kg, BI = 69.04 and Firmness = 10 N. It is worth noting that the optimized product does exhibit a final moisture content 14% higher than the suitable range for the commercialization of dehydrated fruits.

Figure 4

4. Conclusions

This study investigated the optimal conditions for drying bananas through intermittent drying assisted by infrared and forced convection with hot air. It reveals findings capable of optimizing the energy performance of the process, minimizing environmental impact, and improving product quality characteristics. Results indicated that operating the dryer at higher IR power and air temperatures facilitated moisture removal. Intermittent drying enabled achieving an ideal process standard by increasing effective diffusivity (ranging from $5.47 \cdot 10^{-4}$ to $1.37 \cdot 10^{-3}$ mm^2/s), with the lowest value observed under intermittent conditions. Additionally, intermittence contributed to lower specific energy consumption (SEC) values (ranging from 23.17 kWh/kgH_2O to 36.87 kWh/kgH_2O). The activation energy of the process, was estimated using the Arrhenius equation and was in the range of 13.69 to 17.63 kJ/mol, showing that high power and temperatures maximize activation energy, while intermittence helps modulate this effect.

The product quality was assessed based on physicochemical parameters critical to consumer sensory perception. Moisture content and water activity were directly affected by intermittence, with higher values were observed in intermittent drying. However, only one condition met the industrial standards (P = 180W, T = 60ºC, and $\alpha = 0.333$), while continuous drying met the industrial standards in all samples. All conditions resulted in darker ($39.9 < L^* < 60.6$) and more opaque ($19 < C^* < 47.7$) bananas compared to fresh fruit, but samples subjected to intermittent cycles showed values closer to fresh fruit with a more yellowish hue. Additionally, it was observed that increasing the IR power and air temperature caused a reduction in the pH of the dried product, while the interaction of both with intermittence helped mitigate the drop in pH (between 4.33 and 4.79) and increased the total soluble solids content (between 28° Brix and 83° Brix) and resulted in lower firmness when intermittence was applied (between 2.02 and 39.77 N). Higher sensory acceptance was related to the higher TSS value and the average firmness value. The desirability function approach was successfully employed to determine a condition (P = 180 W, T = 60 ºC, and $\alpha = 0.389$) that simultaneously improves process performance, reduces environmental impact, and achieves a high-quality product with overall desirability (D = 0.83).

Acknowledgements

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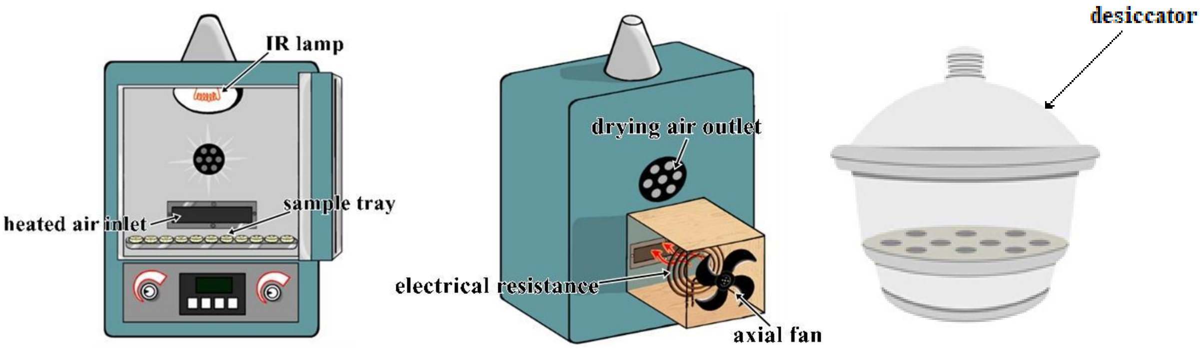
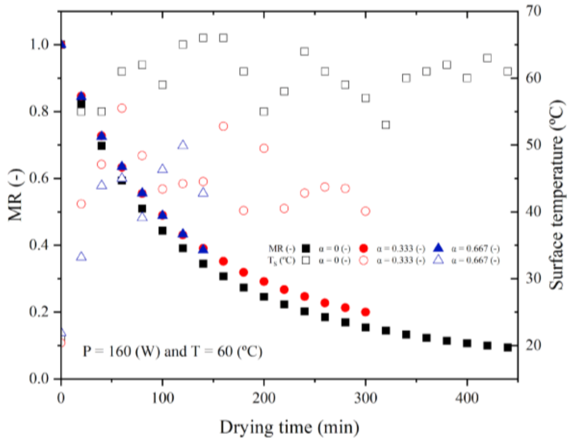
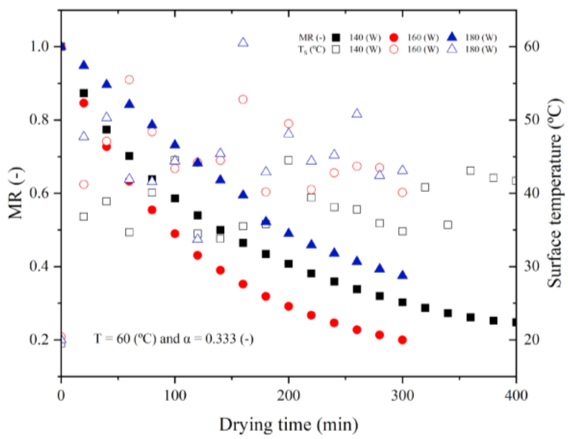


Fig. 1. Schematic sketch of the IR-HA dryer and desiccator used in the experiments.



(a)



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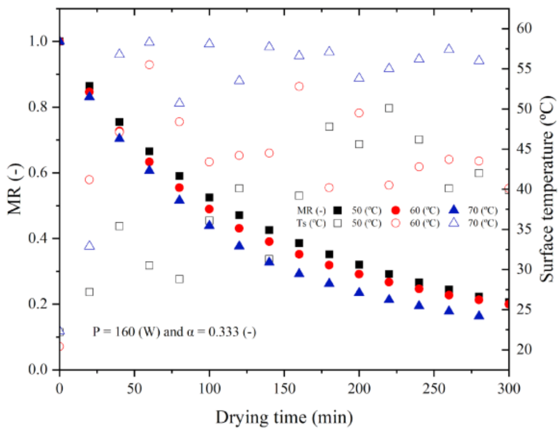
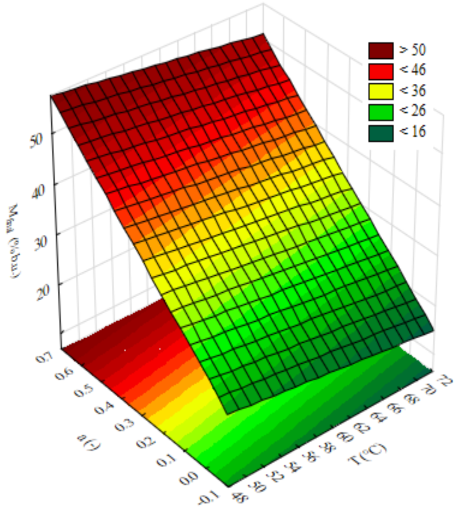


(c)

Fig. 2. Moisture ratio as a function of effective drying at different temperatures with (a) P = 160W and T = 60 ºC, (b) T = 60 ºC and α = 0.333 and (c) P = 160W and α = 0.333.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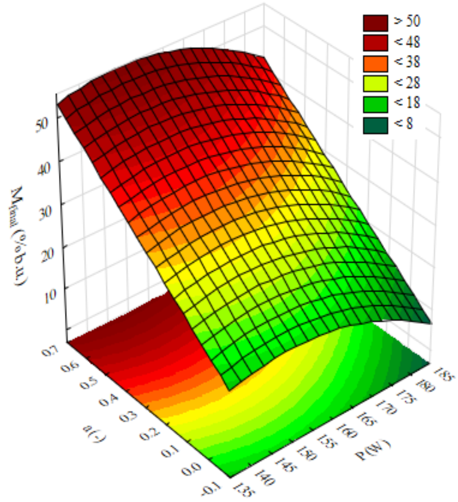
< 46
< 36
< 26
< 16
a(-)
T(°C)

(a)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< 48
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< 28
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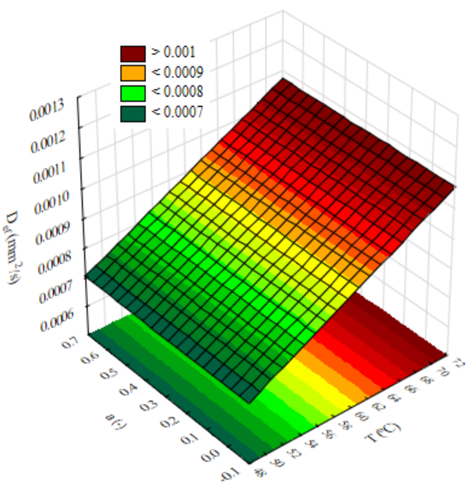
< 8
a(-)
P(W)

(b)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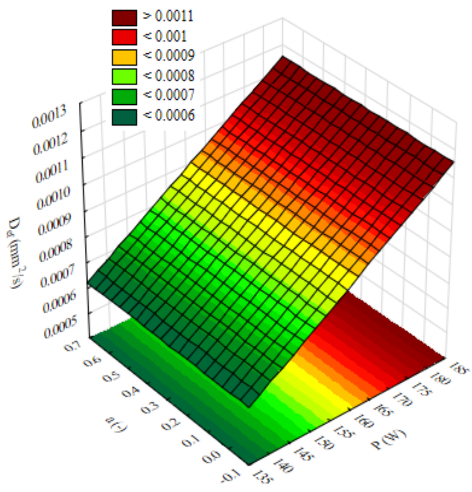
< 0.0007
a(-)
T(°C)

(c)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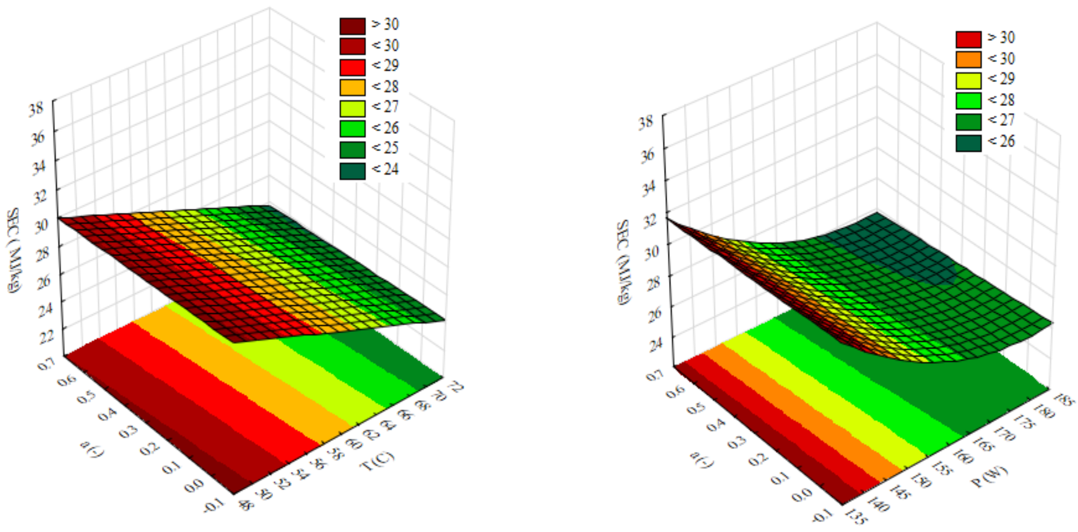
< 0.0007
< 0.0006
a(-)
P(W)

(d)



(e) (f)

Fig. 3. Response surface plot showing the effect of IR power (P), intermittency (α) and drying air temperature (T) and on the (a) final moisture content, (b) effective diffusivity, (c) specific energy consumption (SEC).

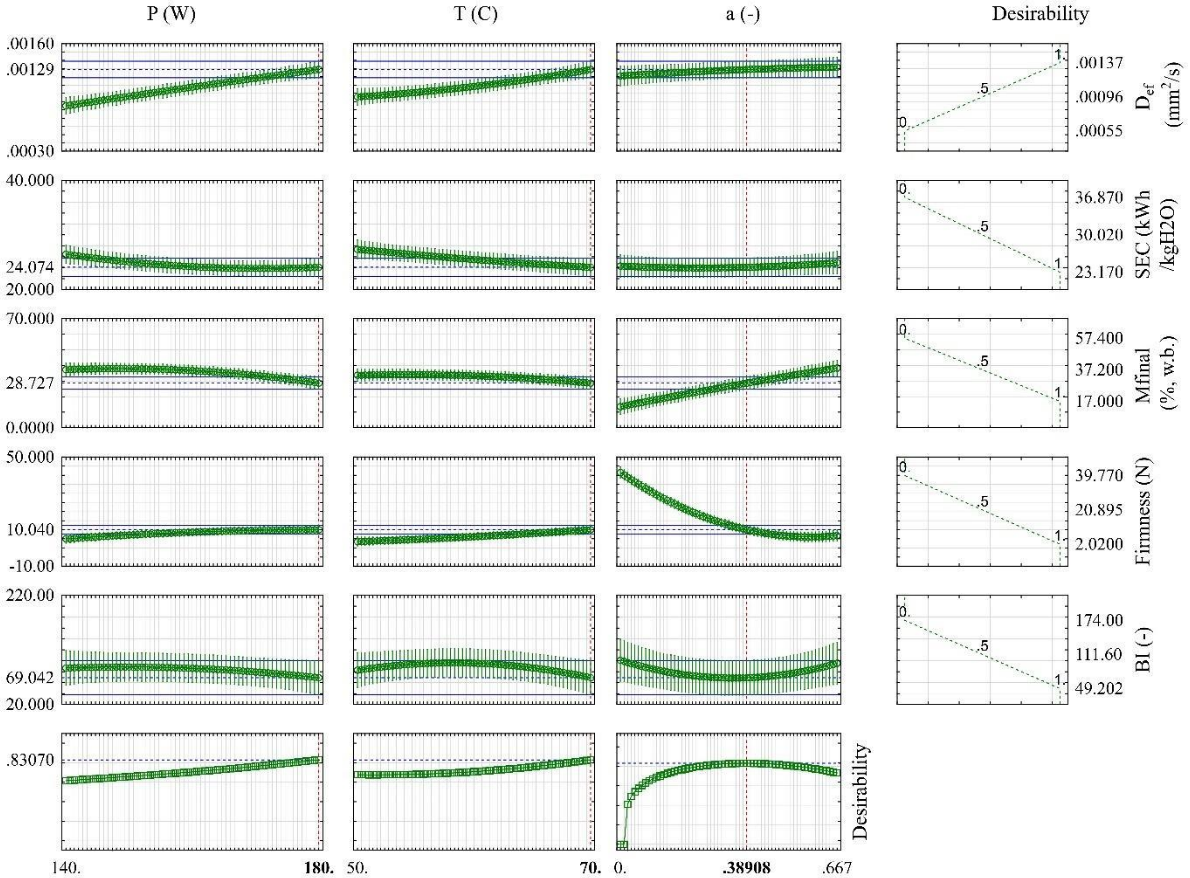


Fig. 4. Desirability function for minimising M_f, SE, BI and Firmness and maximising D_{ef}.

Figure captions

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Fig. 2. Moisture ratio as a function of effective drying at different temperatures with (a) P = 160W and T = 60 ºC, (b) T = 60 ºC and α = 0.333 and (c) P = 160W and α = 0.333.

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Fig. 4. Desirability function for minimising M_f, SE, BI and Firmness and maximising D_{ef}.

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Table list

Table 1. Independent variables in the 3^3 experimental design, and the experimental results of responses: final moisture content, parameters of the Arrhenius equation effective diffusivity, SEC and CO2 emissions.

P (W)	T (°C)	α (-)	Effective drying time (min)	M_{final} (% w.b.)	D0 (mm^2/s)	Ea (kJ/mol)	Def (mm^2/s)	R^2	χ^2	RMSE	SEC (kWh /kgH_2O)	qCO_2 (mg CO_2)
140	50	0.000	620	22.0	0.21	15.97	$5.47\cdot10^{-4}$	0.960	0.003	0.05	36.87	0.048
140	50	0.333	420	37.7	0.20	15.92	$5.52\cdot10^{-4}$	0.941	0.003	0.04	34.43	0.048
140	50	0.667	220	54.2	0.20	17.36	$5.91\cdot10^{-4}$	0.862	0.005	0.07	31.48	0.048
140	60	0.000	580	20.0	0.21	16.10	$6.56\cdot10^{-4}$	0.958	0.003	0.06	31.84	0.048
140	60	0.333	400	46.3	0.20	15.99	$5.47\cdot10^{-4}$	0.940	0.003	0.05	32.10	0.048
140	60	0.667	190	56.7	0.20	16.92	$6.85\cdot10^{-4}$	0.870	0.005	0.07	28.24	0.048
140	70	0.000	540	19.0	0.21	15.48	$8.46\cdot10^{-4}$	0.964	0.003	0.05	27.09	0.048
140	70	0.333	360	34.2	0.21	15.11	$8.21\cdot10^{-4}$	0.941	0.004	0.06	26.28	0.048
140	70	0.667	180	49.4	0.20	16.71	$8.26\cdot10^{-4}$	0.889	0.005	0.07	27.26	0.048
160	50	0.000	460	21.5	0.21	15.08	$8.58\cdot10^{-4}$	0.954	0.004	0.05	28.45	0.050
160	50	0.333	320	44.0	0.21	15.28	$7.37\cdot10^{-4}$	0.930	0.004	0.06	28.39	0.050
160	50	0.667	160	57.4	0.20	17.65	$5.86\cdot10^{-4}$	0.810	0.006	0.07	32.45	0.050
160	60	0.000	440	20.5	0.21	14.93	$9.38\cdot10^{-4}$	0.960	0.003	0.05	26.91	0.050
160	60	0.333	300	40.3	0.21	15.13	$8.28\cdot10^{-4}$	0.938	0.004	0.04	27.44	0.050
160	60	0.667	150	51.4	0.20	16.83	$8.05\cdot10^{-4}$	0.855	0.006	0.07	28.29	0.050
160	70	0.000	420	18.0	0.21	14.64	$1.07\cdot10^{-3}$	0.963	0.000	0.05	25.72	0.050
160	70	0.333	280	33.4	0.21	14.75	$1.00\cdot10^{-3}$	0.940	0.004	0.04	25.48	0.050
160	70	0.667	140	45.6	0.20	15.98	$1.20\cdot10^{-3}$	0.887	0.006	0.08	23.17	0.050
180	50	0.000	460	20.0	0.21	14.92	$9.34\cdot10^{-4}$	0.963	0.003	0.05	27.74	0.052
180	50	0.333	320	27.2	0.21	14.42	$1.04\cdot10^{-3}$	0.950	0.003	0.06	26.76	0.052
180	50	0.667	160	45.3	0.21	16.69	$8.95\cdot10^{-4}$	0.863	0.006	0.08	28.91	0.052
180	60	0.000	440	17.5	0.21	15.17	$9.94\cdot10^{-4}$	0.956	0.003	0.05	25.78	0.052
180	60	0.333	300	27.3	0.21	17.13	$1.17\cdot10^{-3}$	0.950	0.004	0.06	24.59	0.052
180	60	0.667	150	43.1	0.20	15.79	$1.11\cdot10^{-3}$	0.897	0.005	0.07	26.24	0.052
180	70	0.000	420	17.0	0.21	15.05	$1.12\cdot10^{-3}$	0.957	0.000	0.06	25.21	0.052
180	70	0.333	280	23.7	0.20	13.69	$1.37\cdot10^{-3}$	0.952	0.003	0.06	23.62	0.052
180	70	0.667	140	42.8	0.20	15.55	$1.25\cdot10^{-3}$	0.890	0.006	0.08	24.59	0.052
160	60	0.333	300	40.3	0.21	15.01	$8.80\cdot10^{-4}$	0.941	0.004	0.06	26.12	0.050
160	60	0.333	300	40.4	0.21	14.97	$8.98\cdot10^{-4}$	0.945	0.003	0.06	25.81	0.050

Table 2. Effects of drying air temperature, IR and intermittency on the physical-chemical properties.

M_{final} (% b.u.) (R^2 =0.939)			
	Effect	Std.Err.	p-value
Mean	34.87	0.65	< 0.001
P	- 8.40	1.65	< 0.001
P^2	4.01	1.34	0.006
T	- 5.13	1.65	0.005
α	30.04	1.65	< 0.001
D_{ef} (mm^2/s) (R^2 =0.884)			
	Effect	Std.Err.	p-value
Mean	0.00089	0.000015	< 0.001
P	0.00042	0.000037	< 0.001
T	0.00031	0.000037	< 0.001
SEC (MJ/kg) (R^2 = 0.858)			
	Effect	Std.Err.	p-value
Mean	27.89	0.25	< 0.001
P	-4.68	0.63	< 0.001
P	-1.17	0.51	0.033
T	-5.23	0.63	< 0.001
P · T	2.03	0.78	0.016
P · α	1.64	0.78	0.046

Table 3. Colour measurements and physical-chemical properties for fresh and dehydrated banana samples.

Run	P (W)	T (°C)	α (-)	L* (-)	C* (-)	h ∘ (-)	ΔE (-)	BI (-)	A_w (-)	TSS (°Brix)	pH	Firmness (N)
fresh fruit reference				78.3	37.0	91.1	-	60.78	0.98	15.64	4.44	2.99
1	140	50	0	45.1	29.7	73.4	35.12	107.76	0.52	40	4.71	20.66
2	140	50	0.333	53.0	39.2	86.4	25.80	124.09	0.81	30	4.72	2.53
3	140	50	0.667	54.0	31.0	89.5	25.08	82.06	0.93	28	4.79	2.02
4	140	60	0	50.3	34.1	73.8	29.58	112.90	0.51	42	4.64	25.01
5	140	60	0.333	62.0	36.1	87.6	16.54	84.52	0.82	35	4.69	3.75
6	140	60	0.667	58.0	47.7	82.8	24.24	149.93	0.94	30	4.72	2.87
7	140	70	0	46.7	34.6	71.7	33.41	127.73	0.49	50	4.57	28.07
8	140	70	0.333	66.0	37.7	81.9	14.51	86.40	0.73	45	4.64	8.3
9	140	70	0.667	59.0	40.1	86.9	19.87	107.57	0.88	37	4.68	5.47
10	160	50	0	45.3	30.5	68.5	35.64	110.64	0.51	50	4.61	23.77
11	160	50	0.333	53.0	20.2	78.7	30.70	50.44	0.81	42	4.64	5.51
12	160	50	0.667	53.0	41.2	63.4	27.63	137.94	0.94	30	4.69	3.21
13	160	60	0	41.4	32.9	69.8	38.81	141.44	0.49	55	4.57	34.26
14	160	60	0.333	63.0	43.0	86.2	16.64	107.10	0.73	48	4.6	6.75
15	160	60	0.667	59.0	44.2	83.8	21.05	126.11	0.84	32	4.66	3.95
16	160	70	0	49.6	35.5	74.1	30.19	121.36	0.48	57	4.5	39.67
17	160	70	0.333	64.0	47.7	82.8	19.49	127.63	0.74	50	4.57	10.31
18	160	70	0.667	63.0	39.6	80.5	17.24	98.97	0.81	42	4.61	7.72
19	180	50	0	52.6	36.1	73.2	27.60	114.21	0.43	70	4.49	35.61
20	180	50	0.333	49.0	19.0	86.1	34.43	49.20	0.66	60	4.57	3.26
21	180	50	0.667	52.0	40.2	89.5	26.88	133.26	0.78	52	4.64	3.01
22	180	60	0	39.9	25.1	67.4	41.76	100.77	0.48	80	4.33	36.6
23	180	60	0.333	50.0	31.1	86.1	29.05	93.46	0.66	63	4.48	7.23
24	180	60	0.667	57.0	51.0	82.7	27.14	174.00	0.78	60	4.54	4.48
25	180	70	0	41.2	27.3	61.3	41.14	106.47	0.43	83	4.35	39.77
26	180	70	0.333	49.0	24.3	71.6	32.39	71.08	0.60	70	4.42	11.57
27	180	70	0.667	67.0	29.6	78.8	15.38	61.86	0.73	62	4.5	8.54
28	160	60	0.333	62.0	41.1	87.9	17.18	103.44	0.72	50	4.61	7.01
29	160	60	0.333	65.0	44.0	87.6	15.26	105.67	0.73	48	4.6	6.54

Table 4. Effects of drying air temperature, intermittency ratio and IR on the physical-chemical properties.

	pH (R^2 = 0.954)		
	Effect	Std.Err.	p-value
Mean	4.59	0.00	< 0.001
P	-0.20	0.01	< 0.001
P^2	0.02	0.01	0.014
T	-0.11	0.01	< 0.001
α	0.12	0.01	< 0.001
P · α	0.04	0.01	0.007
	A_w (R^2 = 0.979)		
	Effect	Std.Err.	p-value
Mean	0.69	0.01	< 0.001
P	-0.12	0.01	< 0.001
P^2	0.03	0.01	0.023
T	-0.05	0.01	< 0.001
α	0.37	0.01	< 0.001
$α^2$	0.06	0.01	< 0.001
P · α	-0.05	0.02	0.007
	TSS (R^2 = 0.976)		
	Effect	Std.Err.	p-value
Mean	49.97	0.47	< 0.001
P	29.22	1.19	< 0.001
P^2	-6.24	0.97	< 0.001
T	10.44	1.19	< 0.001
α	-17.11	1.19	< 0.001
P · α	-3.67	1.46	0.019
	Firmness (N) (R^2 = 0.978)		
	Effect	Std.Err.	p-value
Mean	14.22	0.39	< 0.001
P	5.71	0.99	< 0.001
T	6.65	0.99	< 0.001
α	-26.91	0.99	< 0.001
$α^2$	-11.44	0.81	< 0.001
P · α	-5.43	1.21	< 0.001

TERCEIRA PARTE

CONSIDERAÇÕES FINAIS

Este estudo investigou a aplicação da secagem híbrida convectiva-infravermelha para a produção de banana-passas, avaliando tanto o modo contínuo quanto o modo intermitente, com o objetivo de otimizar o processo, reduzir o impacto ambiental e melhorar a qualidade do produto final. Reconhecendo as desvantagens dos métodos convencionais de secagem de banana, como a degradação da qualidade sensorial (cor e textura) e o alto consumo energético, esta pesquisa explorou o potencial de técnicas avançadas e combinadas para mitigar tais limitações.

No que tange à secagem híbrida contínua apresentada no primeiro artigo, observou-se que o aumento da potência infravermelha e da temperatura do ar de secagem promoveu uma remoção de umidade mais rápida5. A otimização utilizando a função de desejabilidade permitiu identificar uma condição ótima de processo (180 W e 59 °C) com uma desejabilidade global (0,60) considerada satisfatória para equilibrar o desempenho do processo, o impacto ambiental e a qualidade do produto. É importante destacar que todas as condições experimentais no modo contínuo resultaram em bananas secas com teor de umidade abaixo do limite regulamentar brasileiro de 25% (base úmida). Além disso, as bananas-passa produzidas neste estudo apresentaram coloração geralmente mais clara do que amostras comerciais, indicando um potencial avanço tecnológico para a indústria.

Já análise da secagem intermitente apresentada no segundo artigo demonstrou que a intermitência modula o efeito da potência infravermelha e da temperatura do ar na difusividade efetiva, e, crucialmente, constitui uma estratégia eficaz para mitigar o impacto térmico no produto. Os resultados indicaram melhorias significativas na qualidade do produto, evidenciadas pela redução da firmeza e do índice de escurecimento (BI), impactando positivamente a cor final. Adicionalmente, a aplicação da intermitência contribuiu para a redução do consumo energético. A otimização para o processo intermitente resultou em uma desejabilidade global superior (0,83) em comparação com o processo contínuo (0,60), indicando um potencial para obtenção de produtos de qualidade superior. Contudo, a condição ótima identificada para a secagem intermitente resultou em um teor de umidade final (28,7% b.u.) ligeiramente acima do limite máximo estabelecido pela legislação brasileira (25% b.u.), um aspecto a ser considerado para a aplicação prática.

De modo geral, este trabalho contribuiu para a literatura ao estudar a secagem híbrida convectiva-infravermelha intermitente de bananas. Os resultados contribuem para a validação da intermitência na melhora tanto a qualidade sensorial quanto a eficiência energética. Além disso, foram gerados dados importantes e um modelo que pode ajudar no desenvolvimento de processos de secagem mais eficientes e sustentáveis. O uso de metodologias como a superfície de resposta e a função de desejabilidade nos dois métodos de secagem ajudam a analisar de forma eficiente os diferentes parâmetros do processo. Esse conjunto de ferramentas representa uma contribuição importante para futuras pesquisas sobre secagem híbrida.

Como sugestão para trabalhos futuros, recomenda-se aprofundar a otimização do processo intermitente, ajustando os critérios de desejabilidade para garantir o atendimento rigoroso aos limites regulamentares de umidade final sem comprometer as melhorias na qualidade, e investigar a escalabilidade do processo para aplicação industrial.