Agriculture and Food

AIMS Agriculture and Food, 10(3): 756–769.
DOI: 10.3934/agrfood.2025039
Received: 24 March 2025
Revised: 30 July 2025
Accepted: 18 September 2025
Published: 30 September 2025

https://www.aimspress.com/journal/agriculture

Research article

Vacuum impregnation for β-carotene retention in mango prior to solar drying

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Abstract: Vacuum impregnation (VI) is a versatile processing technique that enhances the nutritional and functional properties of fruits and vegetables by infusing bioactive compounds into their porous structures. This study demonstrates the utility of VI for fortifying fresh mango with β-carotene, a critical nutrient for addressing vitamin A deficiency, and for mitigating nutrient loss during solar drying. Fresh mango slices were impregnated with β-carotene emulsions prepared using homogenization at two different pressures and were then dried under controlled solar simulation conditions. VI increased β-carotene content in mango tissue from an average of 10.5 ± 2.3 ppm (control) to 20.4 ± 1.1 ppm or 24.0 ± 6.6 ppm depending on homogenization pressure, demonstrating effective nutrient incorporation. The emulsion's particle size distribution had no measurable impact on impregnation efficiency ($p < 0.05$), as the particle size was compatible with the mango's porous microstructure. Despite significant β-carotene degradation due to solar drying ($p < 0.05$), the β-carotene levels in the impregnated dried mangoes (9.4 ± 3.9 ppm and 12.6 ± 4.3 ppm) remained close to those in untreated fresh mangoes. This result highlights VI's potential to produce dried mango products that retain essential nutrients even under challenging drying conditions. In regions like sub-Saharan Africa, where vitamin A deficiency affects millions and post-harvest mango losses are as high as 40%, this approach offers a dual solution: improving nutritional outcomes and reducing food waste. The study also positions VI as a cost-effective, scalable technology for developing countries, with implications

for reducing malnutrition, supporting economic livelihoods, and enhancing the utilization of abundant local fruit resources. Future research will focus on in-situ trials with freshly harvested mangoes and optimization of solar drying methods to further validate this strategy and enhance its scalability.

Keywords: vacuum impregnation; β-carotene fortification; solar drying; nutritional retention

1. Introduction

Vacuum impregnation (VI) is a processing technique that allows solutions to penetrate the porous structure of fruits and vegetables. The process begins by immersing porous materials in a solution of specific composition and concentration, followed by a two-step pressure change. First, applying a vacuum causes the gas in the pores to expand, displacing native liquid until mechanical equilibrium is reached. Next, when atmospheric pressure is restored, the remaining gas compresses, allowing the solution to replace the air in the pores [1]. This process enables the controlled infusion of beneficial compounds, altering the structural, functional, and nutritional properties of plant tissues depending on the infused molecules (for a review see [2]).

Vacuum impregnation has been used effectively to incorporate bioactive compounds, such as calcium, zinc, and phenolics, into fruits and vegetables like melons and potatoes [3–5]. This technology holds particular promise for fortifying fruits and vegetables with higher nutrient levels than naturally present or with nutrients not naturally occurring in these foods [5]. While VI fortification of fresh-cut fruit products remains relatively underexplored [6,7], demand for nutrient-enriched horticultural products is growing as consumers prioritize health-conscious options. Therefore, fresh-cut or minimally processed fruits and vegetables offer a practical means of nutrient delivery, driven by expanding horticultural production and renewed interest in underutilized crops [5].

VI for incorporating bioactive compounds can be applied before dehydration using two primary approaches. The first approach involves enriching the product with nutrients that are naturally absent or present in low concentrations before drying, ensuring the final dried product has an enhanced nutrient profile [8–10]. The second approach, a novel aspect of this study, focuses on mitigating nutrient degradation during drying by pre-loading the product with the nutrient most susceptible to thermal or oxidative losses, even when the nutrient is already abundant in the raw material. In this context, VI acts as a compensatory strategy, offsetting anticipated nutrient depletion and helping to preserve the overall nutritional quality of the dried product. To our knowledge, no prior study has applied VI to mango for the purpose of compensating for β-carotene loss during solar drying, despite the fruit's natural richness in this compound. This study addresses that gap, demonstrating how VI can be used not just to fortify but to strategically preserve nutritional quality in dried products.

In developing countries with abundant fruit and vegetable resources, VI fortification could be highly beneficial in addressing micronutrient deficiencies. Despite this agricultural abundance, nutritional shortfalls remain severe-especially among children. Vitamin A deficiency, for instance, is a widespread public health issue across Africa, affecting millions of children and pregnant women [11]. Mozambique is no exception; although mangoes are widely cultivated and consumed, vitamin A deficiency persists. This highlights an opportunity to better utilize mango’s natural richness in β-carotene to improve dietary vitamin A intake. During the mango harvest season in countries such as Niger, mangoes contribute significantly to children’s vitamin A supply, serving as a primary source

for nearly half of the young child population [12]. This example illustrates the nutritional potential of mango when effectively integrated into public health strategies. However, in Mozambique, post-harvest mango losses of 20% to 40% present serious economic and nutritional challenges, reducing both farmer income and the availability of provitamin A sources [13].

To address these challenges, solar drying of mangoes has been explored as a preservation method. Solar drying could transform this perishable fruit into a nutrient-dense snack rich in carotenoids (pro-vitamin A) [14,15]. However, solar drying conditions can also degrade β-carotene, with losses ranging from 40% to 90% depending on the drying system and conditions used [16,17].

In this study, we investigate the feasibility of using VI to enrich fresh mango slices with β-carotene prior to solar drying, as a strategy to mitigate nutrient loss and enhance the final product's nutritional value. Specifically, the study aims (1) to evaluate the effectiveness of β-carotene enrichment in mango slices via VI and (2) to assess how the characteristics of the β-carotene-containing emulsion influence the retention of this nutrient after solar drying. This VI-based fortification approach has potential implications for improving the vitamin A content of dried mango products, particularly in regions where dietary vitamin A deficiency is prevalent.

2. Materials and methods

2.1. Preparation of β-carotene emulsion

2.1.1. Solubility in oil

To define the solubility of β-carotene in canola oil, a series of solutions of increasing β-carotene (ICN Biomedicals INC, Aurora, Ohio) concentration in the oil (from 50 ppm to 600 ppm) were prepared. Canola oil was selected due to its favorable lipid profile, wide availability, and previous evidence of its ability to effectively solubilize carotenoids [18]. The β-carotene was dissolved in the oil using a magnetic stirrer (Heidolph, Germany, 2002) under mild heating (50 °C for 50 min) in a dark environment. The oil was then filtered and examined in a spectrophotometer (SPECTROstar Nano, BMG Labtech, Ortenberg, Germany) at 550 nm. Solubility was defined as the highest concentration at which the absorbance increased linearly with concentration, beyond which no further increase was observed (indicating saturation). Two measurements were done on each solution of the series, and each series was prepared three times.

2.1.2. Emulsification

The aqueous phase was prepared by dispersing Tween 80 (Sigma-Aldrich, UK) in water using an Ultra Turrax T10 (IKA, X-1020, Germany) for 30 s at 560 g. The oil phase was composed of canola oil containing the dissolved β-carotene at its solubility limit. The O/W emulsion was prepared using a 20:80 oil to aqueous phase weight ratio. The O/W emulsion was prepared using a 20:80 oil-to-aqueous phase weight ratio. This ratio was selected to ensure sufficient β-carotene delivery while maintaining emulsion stability and low viscosity, which are critical for effective vacuum impregnation into fruit tissue. Similar oil-to-water ratios have been employed in previous studies targeting bioactive compounds encapsulation and delivery in food systems [19,20]. The concentration of Tween 80 in the final emulsion was 4% (w/w).

Homogenization was performed using a Panda homogenizer (GEA Niro Soavi, GEA Mechanical Equipment Italia S.p.A., Parma, Italy) at two different pressures: 330 Ba and 660 Ba. Three passages were made in the homogenizer with a mean flow rate of 220 mL/min.

2.2. Raw material handling

Brix values were measured for 53 mature mango fruits purchased from local supermarkets in Lund, Sweden, yielding an average of 14.2 ± 3.0. Brix measurements were conducted at room temperature using a Kern Optics Analog Refractometer (Kern, Germany). For each experiment, samples were prepared by cutting a mango into 8 to 12 pieces, each measuring 5cm × 1cm × 1cm. Pieces from 3 different mangoes were combined to create a uniform mix, from which the required sample amount was randomly drawn before each test.

2.3. Vacuum impregnation

2.3.1. Automatic vacuum controller system

The automatic vacuum controller system (AVCS, S.I.A., Bologna, Italy) is a programmable device designed to regulate the pressure on the impregnating solution during the impregnation process. Connected to the VI chamber via a Teflon tube, the AVCS includes several key components: a pressure transmitter, vacuum actuators (valves and a vacuum pump), a computer, and a programmable logic controller (PLC, Series 90–30, General Electric, Charlottesville, VA, USA) as illustrated in Figure 1. The PLC serves as the central unit of the AVCS, controlling the vacuum actuators and monitoring parameters such as pressure, duration, and vacuum release rate by managing the start and stop of the vacuum pump and the operation of the air inlet and outlet valves. A software interface (CIMPLICITY Workbench Version 6.10, Service Pack 3, General Electric, Charlottesville, VA, USA) allows the AVCS's operating parameters to be set and monitored [21].

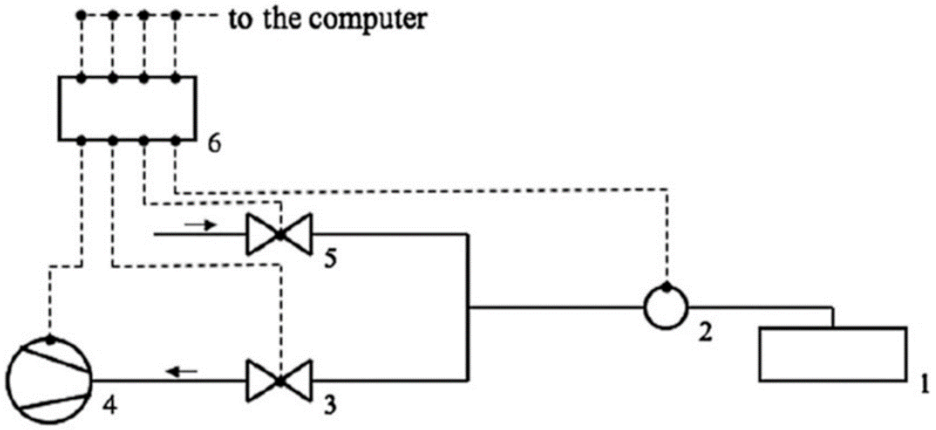

Figure 1. Schematic illustration of the AVCS: 1. Treatment chamber, 2. Pressure transmitter, 3. Valve regulating air outlet, 4. Vacuum pump, 5. Valve regulating air inlet, 6. PLC. Arrows indicate the direction of air flow. Solid lines represent pneumatic connections, and dashed lines represent electrical connections.

2.3.2. Vacuum impregnation

Preliminary experiments were conducted to determine the maximum weight gain that mangoes could sustain without visible tissue damage, assessed through visual inspection. Tissue damage was indicated by a loss of texture (softening) and fluid leakage. These experiments also guided the selection of vacuum impregnation (VI) parameters. Specifically, a minimum pressure of 150 mbar and a total treatment time of 10 min were found to maximize weight gain while avoiding any visible damage to the mango tissue.

For each experiment, mango pieces (204.02 ± 23.70 g) were immersed in 400 mL of emulsion and subjected to a stepwise VI protocol. During the first phase, pressure was gradually reduced from 1000 mbar to 150 mbar over 3 minutes, followed by a 1-minute hold at 150 mbar. In the second phase, pressure was gradually restored to atmospheric level over 6 minutes. After VI, excess emulsion was removed from the surface using absorbent paper, and the weight gain was calculated from the following equation, in percent:

$$weight\ gain = \frac{m-m_0}{m_0} * 100 \quad (1)$$

Where m is the mass of the infused mango and m_0 is the initial mass of the fresh mango.

Measurements were performed on five independent batches of impregnated mango samples for each emulsion.

2.4. Drying

Fresh and impregnated mango pieces were dried using a solar dryer designed and built by the Division of Energy and Building Design at Lund University, Sweden. Figure 2 provides a schematic of the dryer, illustrating the airflow patterns for both cold and warm air, and the place where temperature and relative humidity sensors were located. An indoor solar energy simulator served as the energy source for the drying process, utilizing a 10 m² array of lamps delivering an irradiation of approximately 900 W/m². The simulator's irradiation can be considered parallel light due to the arrangement of reflectors within the system.

Batches of fresh mango pieces and mango pieces vacuum-impregnated with β-carotene emulsions, homogenized at 330 Ba and 660 Ba, were placed on a centrally located tray within the dryer and dehydrated over a 21-hour period. Three batches of dried mango pieces were prepared for both the untreated fruits and the impregnated mangos with each emulsion.

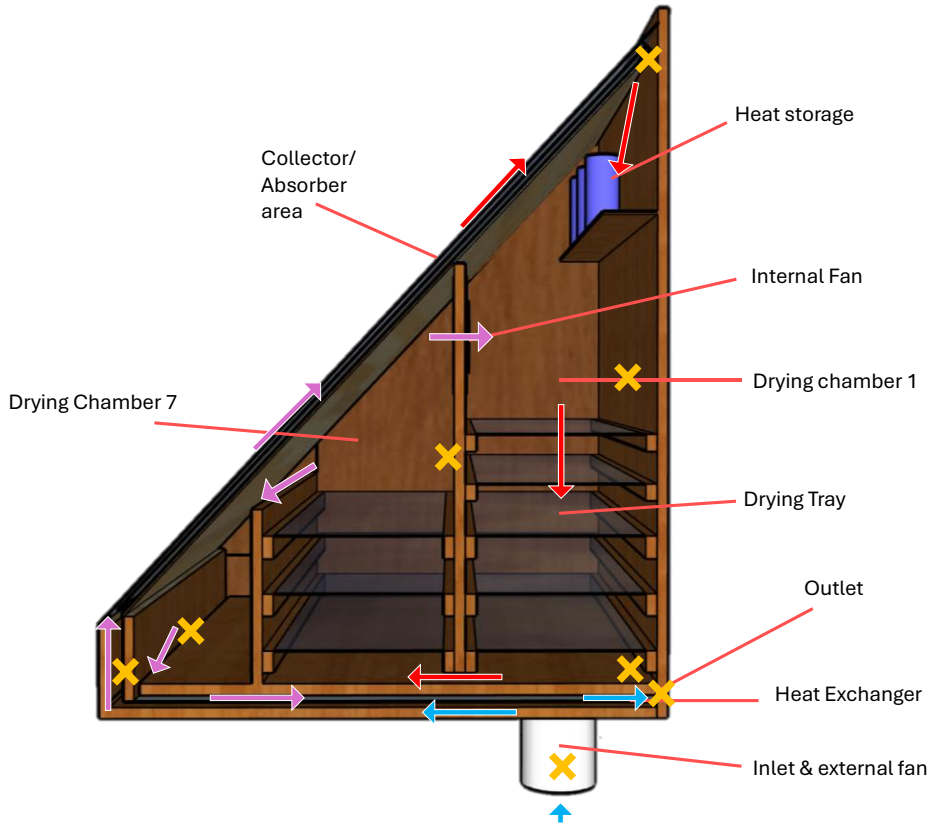

Figure 2. Solar drier used for producing dehydrated mango pieces. Blue arrows represent circulating ambient air, pink arrows represent middle-war air, and red arrows represent warmed air. The crosses indicate where thermocouples were located. Mango samples were located on the drying tray in the centre of the drier. The source of energy for the drying process was a solar energy simulator located above the drier, as described in the Materials and method section.

2.5. Analysis

2.5.1. Particle size distribution

The particle size distribution of emulsions droplets was analyzed by light scattering (Malvern, Mastersizer 2000 Ver 5.60, Worcestershire, UK). The dispersing unit was filled with MilliQ-water, and the pump speed was set to 2000 rpm. The glass tubes containing emulsions were turned upside down three times to allow representative sampling. The refractive index (RI) of the sample was set to 1.50 and 1.33 for the continuous phase (water). The absorption was set to 1.0, and the obscuration rate was 10–20%. Each emulsion was measured at least 3 times.

2.5.2. Carotenoids

The β-carotene content of the emulsion and mango samples was analyzed using a modified method by Rodriguez-Amaya [22]. Specifically, 5 g of emulsion was combined with 25 mL of

acetone (VWR International S.A.S, France) and 25 mL of n-hexane (Fisher Scientific, Loughborough, UK) in a separation funnel. After 1 minute of mixing, two phases formed. The colorless acetone phase was drained, washed with distilled water, and filtered through a 0.2 μm syringe filter. Absorbance was measured at 450 nm with a spectrophotometer (SpectroStar Nano, BMG Labtech GmbH, Ortenberg, Germany), and samples were diluted with n-hexane if needed. A standard curve of β-carotene in n-hexane was used for result calculation. Two measurements were done on each emulsion, and each emulsion was prepared three times.

To analyze the β-carotene content in fresh and dried mango samples, 5 g of mango were mashed and homogenized in an Ultra-Turrax with 25 mL of acetone. The filtered extract was then mixed with 25 mL of n-hexane in a separation funnel. After phase separation, the colorless acetone layer was discarded, and the remaining extract was washed with 20 mL of distilled water and dried with 5 g of anhydrous sodium sulphate to remove residual water. This final extract was filtered through a 0.2 μm PTFE syringe filter and analyzed in a spectrophotometer at 450 nm in a 1 cm quartz cuvette, with dilution in n-hexane as necessary. At least three measurements were done on each of the three batches of dried mangoes.

2.5.3. Water activity of mango samples

Water activity was assessed using an Aqualab water activity analyzer (Model CX-2, Decagon Devices Inc., Pullman, WA). Three measurements were conducted for each experimental condition.

2.6. Statistical analysis

Statistical significance between treatments was tested by means of one-way ANOVA ($p < 0.05$) using MINITAB software v.17 (Minitab Inc., PA, USA). The Newman-Keuls stepwise multiple comparisons procedure was used to evaluate true differences in treatment means.

3. Results

3.1. β-carotene Emulsion

Figures 3a and 3b illustrate the particle size distribution of the β-carotene emulsion after homogenization at pressures of 330 Ba and 660 Ba. At 330 Ba, the majority of particles have a size around 1 μm, with a noticeable tail in the distribution indicating the presence of particles up to 100 μm. In contrast, homogenization at 660 Ba eliminates this tail, resulting in a narrower distribution where most particles fall within the 0.1 μm–1 μm range.

Figure 2c presents the total carotenoid content, predominantly β-carotene, of the emulsions, showing a significantly higher concentration in the emulsion homogenized at 660 Ba. This difference may be attributed to the operational conditions of the homogenizer. At 330 Ba, a portion of the emulsion appeared to become trapped within the equipment's tubing, leading to a reduction in the recoverable carotenoid content. In contrast, at 660 Ba, the tubes were observed to be clearer, potentially allowing for better recovery of the emulsion and, consequently, a higher measured carotenoid content.

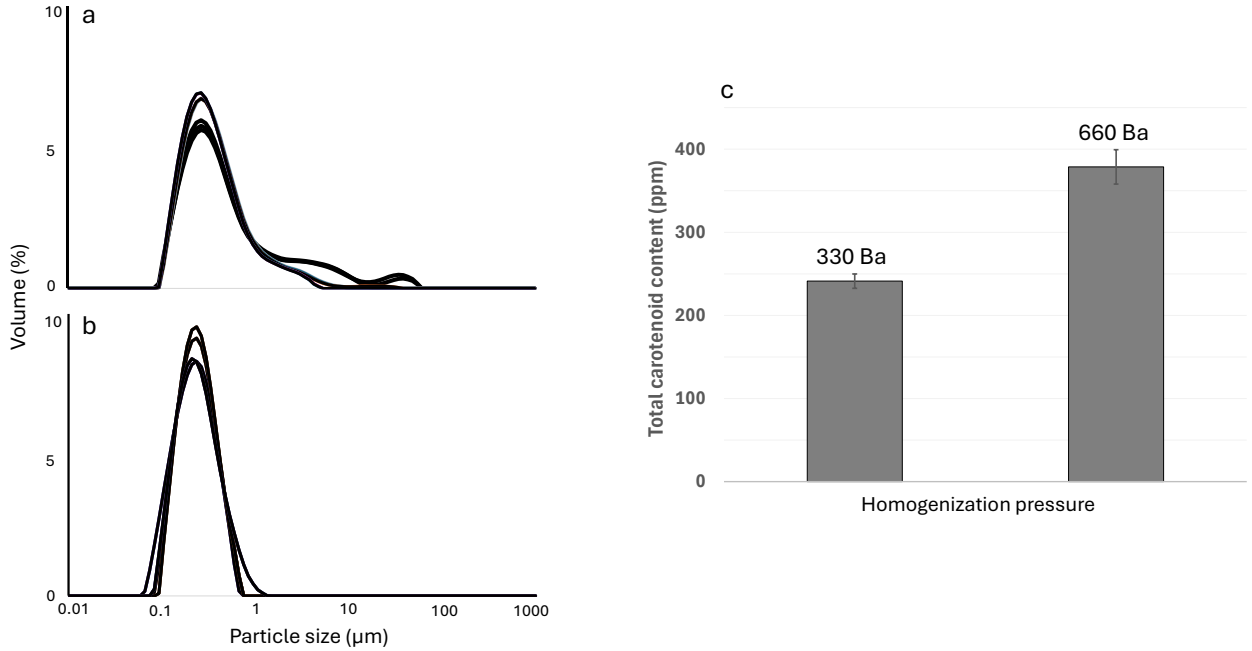

Figure 3. Characterization of β-carotene emulsions produced using two homogenization pressures. (a, b) Particle size distribution of emulsions homogenized at 330 Ba (a) and 660 Ba (b). (c) Total carotenoid content in each emulsion.

3.2. Vacuum impregnation

Table 1 reports the weight gain of mango pieces impregnated with the two emulsions studied. The results indicate that the differences in particle size distribution between the emulsions did not influence the impregnation process, as no significant differences in weight gain were observed.

Table 1. Weight gain of mango pieces after vacuum impregnation with two β-carotene emulsions homogenized at two different pressures.

Homogenization pressure (Ba)	Weight gain (%)
330	6.37 ± 1.19^{a}
660	6.54 ± 1.13^{a}

Superscript letters next to standard deviation values indicate groups that are not significantly different from each other.

3.3. Dehydration

Figure 4 shows the variations in temperature and relative humidity within the dryer during the dehydration process. Additionally, Table 2, included in the figure, provides the water activity values of the mango pieces upon completion of dehydration. The water activity values of 0.4 ensure microbial safety.

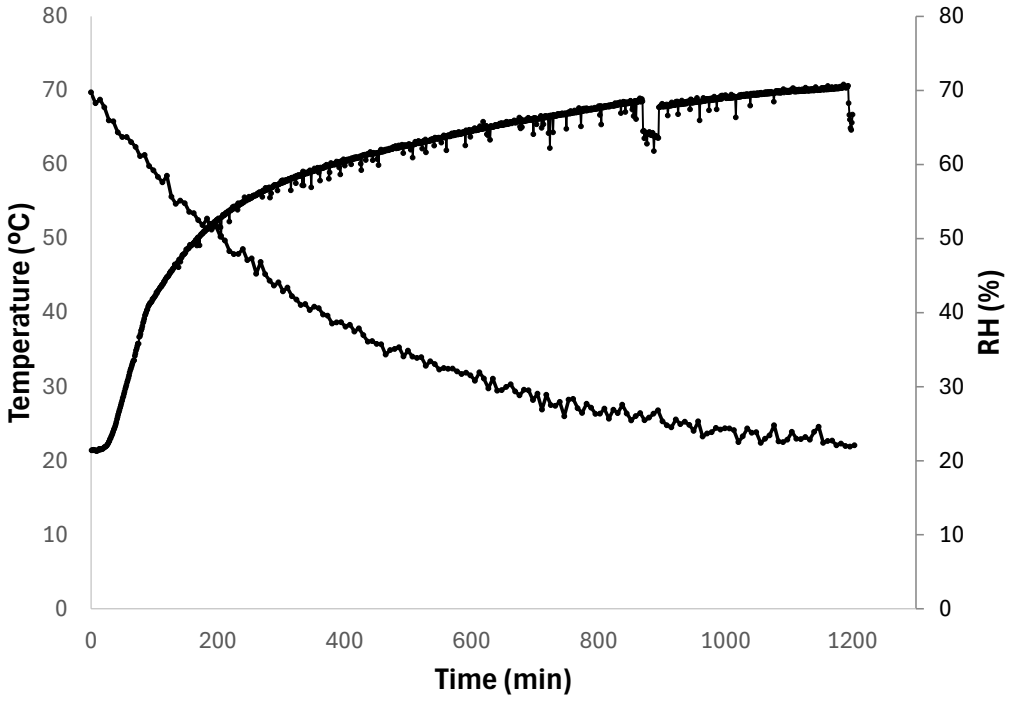

Table 2. Water activity of dried mango pieces

	Water activity
Dried control (not impregnated)	0.407 ± 0.022
Dried product impregnated with emulsion homogenized at 330 bar	0.408 ± 0.019
Dried product impregnated with emulsion homogenized at 660 bar	0.408 ± 0.001

Figure 4. Drying of mango pieces. Temperature and relative humidity (RH) inside the drier during the process. Reported are average curves of the data obtained from the 4 sensors located in the drier, as detailed in the materials and methods section. The values of the curves also represent the daily average for each drying day across the different samples. The table reports the water activity of the final product for each of the treatments.

The total carotenoid content, specifically β-carotene, in fresh mango, vacuum-impregnated mango, and impregnated dehydrated mango ranged from 5 ppm to 25 ppm, depending on the treatment (Figure 5). Vacuum impregnation effectively incorporates additional carotenoids into the fruit, regardless of the homogenization pressure used to prepare the impregnated emulsion. However, dehydration using the solar drier significantly reduces β-carotene levels, lowering them to about half their original content. Notably, the β-carotene content in impregnated, dehydrated mangoes remains comparable to that in fresh mangoes.

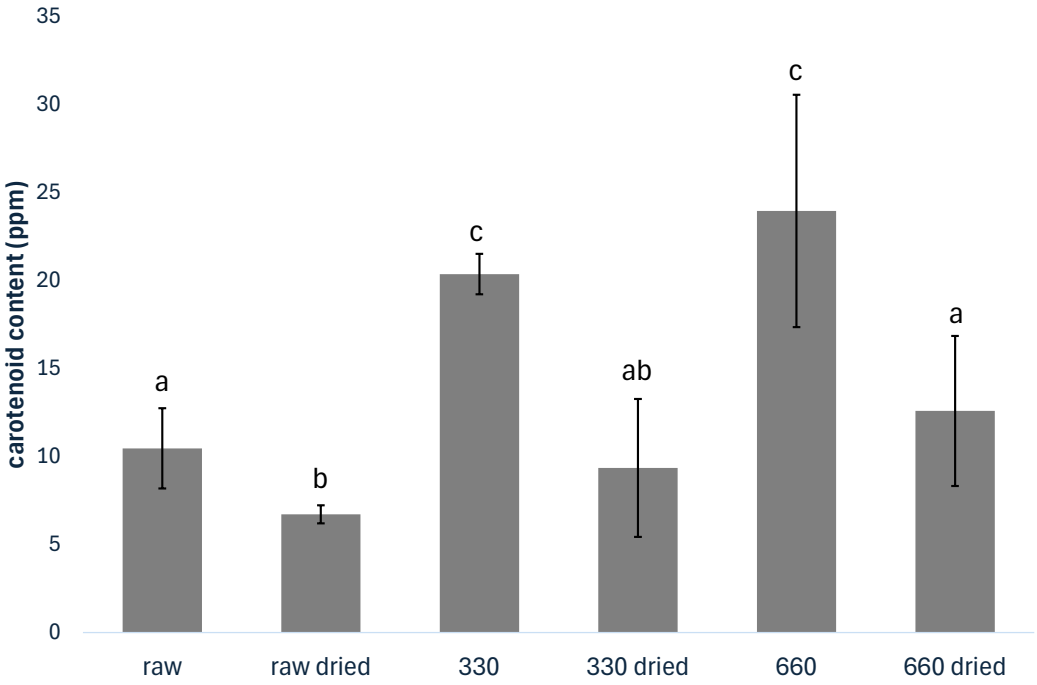

Figure 5. The total carotenoid content in fresh and vacuum-impregnated mango pieces before and after dehydration. Vacuum impregnation was done with two β-carotene emulsions homogenized at two different pressures (330 and 660 Ba). Bars represent the standard error of the carotene content of three different batches of the fruit. Different letters above to the error bars indicate significant differences.

4. Discussion

Vacuum impregnation showed to be an effective method for enhancing the β-carotene content in mangoes. Tests were conducted to evaluate the influence of particle size distribution in the impregnated carotene emulsion on the effectiveness of the impregnation process. These tests revealed that small differences in particle size between the emulsions (Figure 3) had no measurable effect on the impregnation efficiency (Table 1). Consequently, the variation in particle size did not significantly influence the amount of β-carotene incorporated into the mango tissue (Figure 5).

The porous microstructure of the fruit matrix plays a crucial role in making the fruit impregnable. This is because the emulsion particle size aligns closely with the size of the intercellular spaces in the fruit. The pore diameter of raw mango tissue has been reported to be approximately 27 μm [23], which facilitates the penetration of the β-carotene emulsions into the fruit matrix where most of the particles are in the range of 0.1 μm to 10 μm (Figure 3).

Dehydration under the solar drier and shaded conditions were detrimental to the β-carotene content in mango pieces dried to a water activity (aw) of 0.4 (Figure 4). The primary factors driving β-carotene loss during dehydration include tissue breakdown, oxygen exposure, light, and elevated temperatures, which collectively accelerate degradation. As noted by [24], such conditions result in substantial reductions in β-carotene levels during both processing and storage.

Chen and Huang [25] further examined the thermal degradation of dried β-carotene, heating it in an oven at 50 °C to 150 °C for up to 30 minutes and under reflux at 70 °C for 140 minutes. Their

findings demonstrated that degradation of all-E-β-carotene became significant after 10 minutes at 50 °C and after 25 minutes at 100 °C, highlighting its sensitivity to heat. During mango dehydration, temperatures above 50°C were maintained for several hours (Figure 4a), which explains the significant decline in β-carotene levels in the dried product.

Previous studies have also reported significant β-carotene losses in mango during drying. For instance, Ndawula et al. [17] observed up to 60% loss of β-carotene in solar-dried mango slices, while Pott et al. [26] quantified dried Thai cultivars using a tunnel dryer at 75 °C and observed not only significant reductions in all-trans β-carotene but also increased formation of cis-isomers, indicating pronounced provitamin A degradation. This shift in isomer profile has critical implications for provitamin A bioavailability. While cis-β-carotene isomers are more thermally stable, they exhibit substantially lower vitamin A activity compared to the all-trans form, often by 20–50% [27]. These mango-specific findings reinforce the vulnerability of β-carotene to heat-induced degradation and highlight the importance of optimizing processing conditions to preserve nutritional quality.

The primary objective of this investigation was to mitigate the loss of β-carotene during the drying process by infusing fresh mango slices with additional β-carotene before drying. The results are promising, as the β-carotene levels in the impregnated, dried mango were found to be comparable to those in fresh mango, highlighting the potential of this fortification strategy. Vacuum impregnation is relatively low-cost in comparison to other enrichment or encapsulation technologies. For example, VI equipment is less complex and energy-intensive than microencapsulation or freeze-drying setups, making it more accessible for small-scale processors in developing countries. Previous studies, such as Wahid et al [28], have also highlighted VI's cost-effectiveness and ease of scaling in agri-food systems. Therefore, VI represents a feasible intervention for improving the nutritional quality of dried fruits in low-resource settings.

Tests still need to be conducted at mango growing sites using freshly harvested fruits, which could potentially reduce data variability. Additionally, optimizing the drying process using natural solar radiation and assessing β-carotene content at varying levels of final water activity (0.4–0.6) would provide further validation for this pre-fortification strategy.

5. Conclusions

Incorporating β-carotene into an emulsion and vacuum impregnating it into the porous structure of mango is an effective pre-treatment to enhance its β-carotene content before solar drying. However, prolonged exposure to high temperatures during solar drying can degrade β-carotene. Therefore, the success of this pre-fortification strategy relies on optimizing both nutrient incorporation and the drying process. Our laboratory investigation of this approach showed promising results, as the dried mango retained a β-carotene content comparable to that of fresh fruit. Nevertheless, these results were obtained under controlled conditions, and their applicability in real-world settings remains to be tested. Therefore, future work should prioritize field trials to evaluate the feasibility, effectiveness, and cost-efficiency of this approach under variable environmental conditions typical of solar drying in low-resource contexts. Moreover, assessing the scalability of vacuum impregnation is essential, particularly in smallholder or cooperative settings. This includes evaluating the availability of suitable equipment, local technical capacity, and the cost-benefit balance relative to other fortification methods. Demonstrating effectiveness and feasibility at scale will be key to ensuring rural adoption and nutritional impact.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Acknowledgments

The support of The Swedish International Development Agency (SIDA) [Grant No. Dr.n. 2017-05625], for the realization of the present study is gratefully acknowledged.

Conflict of interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Author contributions

MF: Lab analysis, writing; PVS: Idea conception, funding acquisition, lab analysis, writing, editing; HD: Lab analysis, editing; FGG: Idea conception, funding acquisition, writing, editing.

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