



Drying of guabiroba pulp: chemical characterization, kinetics and techno-economic analyses

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Abstract

Guabiroba is a native species of the Brazilian Atlantic Forest. Its fruits are known for their chemical composition, phenolic compounds and carotenoids, which promote antioxidant and antimicrobial activities. However, it has a high moisture content, which makes it perishable. In this study, three dried products were obtained from fruits after different processing (oven at 60 and 105 °C and freeze-drying), and were characterized according to their chemical composition, drying kinetics and technical–economic analysis. The results showed that guabiroba contains several compounds beneficial to health, with high amounts of dietary fiber (12.60% by weight, wet basis), highlighting its potential as a functional food. The different drying processes resulted in dried products with different physicochemical properties and different drying kinetics. Oven drying at 60 °C was observed as the best drying method, due to the preservation of chemical compounds and the second most economically viable, despite being the slowest process. Compared to conventional frozen guabiroba pulp, dry products are more expensive, although they have lower transportation costs and a longer shelf life, factors not evaluated in this study.

Keywords *Campomanesia xanthocarpa* · Yellow-orange fruit · Fruit pulp · Drying techniques · Economic viability

Introduction

Brazil is recognized as a prominent country due to its highly diverse flora. Its biodiversity includes numerous native species, among which small native fruits (e.g., pitanga, uvaia, jaboticaba, and guabiroba) are of significant interest due to their chemical composition, with innumerable bioactive compounds associated with improving human health (Grutzmann Arcari et al. 2020). Among these fruits, guabiroba (also known as guavira), native fruit from the Brazilian Atlantic Forest, is particularly notable for its organoleptic characteristics (flavor and aroma) and its technological properties.

The yellow-orange guabiroba fruits have a sweet flavor and are highly valued for human consumption in foods,

especially in juices, sweets and ice creams (Prestes et al. 2022). Additionally, guabiroba fruits have recently gained attention due to its antioxidant potential, which can be associated with the high contents of phenolic compounds, carotenoids, and ascorbic acid in their composition (Malherbi et al. 2019; Pereira et al. 2012). Recent studies report the use of guabiroba in edible films (Malherbi et al. 2019; Silva-Rodrigues et al. 2020), fermented milk (Prestes et al. 2021), and on antioxidant nanocapsules (Pereira et al. 2018).

Although presenting such benefits to human health, guabiroba fruits are seasonal and highly perishable, resulting in seasonal limitations, which could be addressed by the development of industrial processes to produce dried guabiroba products, which has not been previously reported. Several drying processes are commonly used to extend the shelf life of plant-based products, including microwave drying (Arantes et al. 2024), conventional oven drying at different temperatures, and freeze-drying (Lucas et al. 2018). Different drying methodologies, however, might result in changes in the physicochemical properties of the final products (Lucas et al. 2018; Tomasi et al. 2021), besides presenting

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Table 1 Nutritional composition of the frozen guabiroba pulp

Component	Composition (g 100 g ⁻¹)
Moisture	77.97±0.35
Ashes	0.89±0.15
Insoluble dietary fibers	10.15±1.01
Soluble dietary fibers	2.45±0.37
Total dietary fibers	12.60±1.38
Lipids	0.52±0.04
Proteins	1.97±0.08
Non-fibrous carbohydrates	6.05

Table 2 Mineral composition of the frozen guabiroba pulp

Mineral	Composition (mg 100 g ⁻¹)
Calcium	1.33
Copper	2.73
Iron	21.10
Potassium	3.12
Magnesium	0.43
Manganese	41.64
Phosphorus	0.32
Zinc	11.10

significant differences in economic aspects (Arantes et al. 2024).

Case studies are required to determine the best drying process for each plant product, in order to maintain the properties of interest from the plant matrix and to optimize the profitability of industries of dried products. Hence, this paper aims to evaluate the use of three conventional drying methods to produce dried guabiroba pulp, to compare the chemical composition of each dried product to the frozen guabiroba pulp, and to determine the best drying methodology according to economic aspects.

Materials and methods

Materials and methods are extensively described in the Supplementary Materials.

Results and discussion

Nutritional and mineral characterization of the guabiroba frozen pulp

The results on the physicochemical characterization of the guabiroba frozen pulp are presented in Table 1. Moisture is the predominant component of the fruit (77.97%), which was also observed in previous studies (Silva-Rodrigues et al. 2020; Vallilo et al. 2008). This result, combined with a considerable non-fibrous carbohydrate content (6.05%), indicates the importance of consuming the *in natura* guabiroba

fruits quickly after the harvesting, or, alternatively, proposing processes for preventing the matrix degradation and increasing its shelf life, such as drying or freezing methods.

Additionally, a significant amount of dietary fiber is observed in the guabiroba fruits (12.60%), predominantly represented by insoluble dietary fibers (10.15%). The values found in the work were higher than those reported in Prestes' review (6.3–9.7%) (Prestes et al. 2022). Dietary fibers are non-digestible carbohydrates which play an important role in human health: insoluble dietary fibers, mainly represented by holocellulose and lignin in plant matrices, can result in a reduction in bowel movement time while increasing fecal volume and reducing glucose absorption (Dhingra et al. 2012) while soluble dietary fibers, promote an increase in bowel movement time by decreasing or delaying glucose absorption (Dhingra et al. 2012). In general, fibers regulate bowel movements, decrease gastric emptying, slow glucose absorption, and reduce blood cholesterol (Bernaud and Rodrigues 2013).

The ash fraction determined in the current work (0.71%) is in accordance with the values previously reported by Morzelle et al. (2015) and Vallilo et al. (2008) (0.41 and 0.50%, respectively). The ashes represent the remaining material after the calcination process, which consists of the minerals present in the biomass. The considerable ash content in the guabiroba pulp (0.41–0.71%) indicates the potential of the fruit as a source of macro and micronutrients, which present beneficial effects on human health. This observation was corroborated by the mineral composition presented in Table 2.

Guabiroba frozen pulp presented a low lipid concentration (0.52%), which is consistent with the values reported by Vallilo et al. (2008) and Morzelle et al. (2015) for this fruit species. The low level of lipids enables its categorization as low in lipids according to the Brazilian National Health Surveillance Agency (ANVISA 2012) and confirms the favorable characteristics of guabiroba pulp as a food ingredient for fat-restricted diets. Part of its lipophilic compounds were determined in the chromatographic analysis, which is presented ahead.

The low Total caloric value (calculated based on the concentration of lipids, proteins and non-fibrous carbohydrates previously determined) obtained (36.85 kcal 100 g⁻¹) is a consequence of the low contents of lipids and proteins in the matrix, and it indicates the potential of the use of guabiroba frozen pulp in weight-loss diets as a healthy ingredient.

After the nutritional characterization, the mineral composition of the guabiroba frozen pulp was determined, and the results are reported in Table 2. The mineral can be associated with several benefits for human health. Micronutrients, for instance, are important for the body in cellular processes

related to energy metabolism, antioxidant defense and immune response (Panza et al. 2007).

It was observed that the predominant minerals in the sample were manganese and iron (41.64 and 21.10 mg 100 g⁻¹, respectively). Potassium content (3.12 mg 100 g⁻¹) was similar to the presented by Santos et al. (2012) of 3.88 mg 100 g⁻¹, who also found lower levels of manganese (0.57 mg 100 g⁻¹), and large amounts of phosphorus (46.43 mg 100 g⁻¹) and magnesium (43.01 mg 100 g⁻¹). Such differences in concentrations can be associated with edaphoclimatic factors.

The results presented in Tables 1 and 2 validate the nutritional value of the guabiroba fruits. Guabiroba frozen pulp presents a considerable content of dietary fibers, and minerals related to increasing human health were observed in significant concentrations. Additionally, to these characterizations, semi-volatile compounds of the guabiroba frozen

pulp were determined after extraction with toluene/ethanol and injection in a CG-MS equipment. The results on the hydrophilic and lipophilic chemical compounds determined in the extracts are reported in Tables 3.

During the analysis of the hydrophilic phase, 23 compounds were determined, and they were categorized into eight chemical classes according to their chemical structure. The semi-volatile compounds represent the primary and secondary metabolites of the plants, and they are related to several bioactive properties for food and cosmetics' products, being responsible for beneficial properties in human health.

Among all quantified compounds, fructose and glucose were the ones with the highest concentrations (68.5 and 23.9 mg g⁻¹, respectively). High levels of free sugars are commonly found in plant matrices, for they are the primary source of energy during plant growth (Ciereszko 2018). Although these compounds provide desired organoleptic characteristics to the fruit, high amounts of free sugars, combined with the high *in natura* moisture, promote micro-organism growth and are responsible for the high degradability of biomasses, which highlights the importance of evaluating drying processes for these matrices.

Organic acids such as citric, quinic, and malic acids were also found in significant concentrations (894, 216, and 126 µg g⁻¹, respectively). Citric acid is a natural antioxidant with anti-inflammatory activity, used in the food industry as a preservative, flavoring and acidifying agent (Singh et al. 2022); and quinic acid presents antioxidant and antimicrobial properties (Ercan and Doğru 2022).

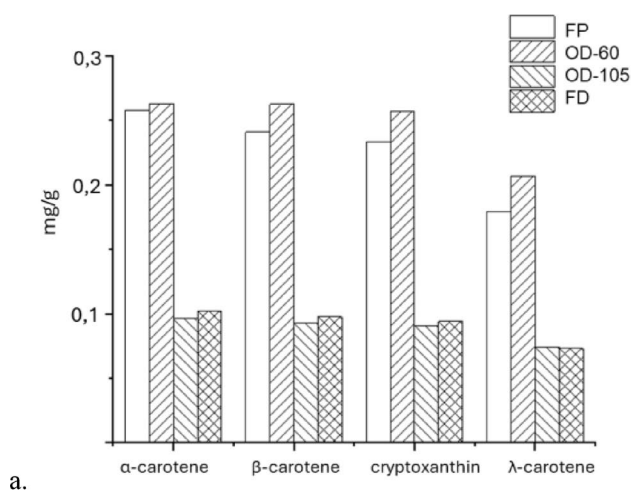
Additionally, other compounds of interest for human consumption presented considerable concentrations: myo-inositol (504 µg g⁻¹) is related to several biological functions, such including in the glucose and hormonal metabolisms (Joardar et al. 2023); glucuronic acid (112 µg g⁻¹) is reported as a compound involved in the detoxification of harmful substances in human body and converts them into non-toxic metabolites (Shendurse and Khedkar 2016); and gallic acid (102 µg g⁻¹) is extensively reported for its antioxidant, anti-inflammatory, and antineoplastics properties (Kahkeshani et al. 2019), and it was previously observed in guabiroba extracts (Grutzmann Arcari et al. 2020).

Regarding the lipophilic phase, 7 compounds were quantified and separated in three classes. The fatty acids were the compounds with the highest concentrations, and they are mostly represented by the hexadecanoic and oleic acids (11.7 and 2.76 mg g⁻¹, respectively).

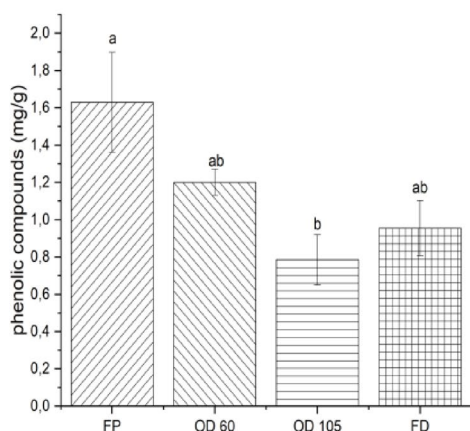
Considerable contents of other lipophilic compounds were observed in the guabiroba frozen pulp, such as: octadecanoic acid (430 µg g⁻¹) and n-9-(Z)-hexadecenoic acid (146 µg g⁻¹), structural components of cell membranes related to energy and metabolic reserves and to hormones

Table 3 Hydrophilic and lipophilic semi-volatile compounds determined in the guabiroba frozen pulp

Class	Compound	Content (µg g ⁻¹)
<i>Hydrophilic compounds</i>		
Amino acid	4-Hydroxy-1-methyl-proline (dimer)	381.06 ± 13.59
	4-amino-butanoic acid (GABA)	27.99 ± 1.39
	Glutamic acid	9.03 ± 1.01
Cyclitol	Myo-inositol	503.64 ± 44.56
Organic acid	Lactic acid	7.82 ± 0.60
	Glycolic acid	8.34 ± 0.34
	Succinic acid	6.60 ± 1.05
	Malic acid	125.85 ± 18.12
	Shikimic acid	7.33 ± 0.32
	Citric acid	894.32 ± 60.65
	Dehydroascorbic acid	54.79 ± 9.71
	Quinic acid	216.30 ± 13.07
Organic nitrogen	1-Pyrroline-3-hydroxy-5-carboxylic-acid	18.03 ± 1.28
Phenol	Gallic acid	101.73 ± 12.63
	Quercetin	12.99 ± 0.16
Sugar	Fructose	68,541 ± 4,185
	Glucose	23,877 ± 2,361
	Sucrose	14.17 ± 1.62
Sugar acid	Glyceric acid	31.60 ± 0.25
	Glucuronic acid	111.67 ± 11.14
	Galacturonic acid	26.91 ± 1.23
	Gluconic acid	43.82 ± 1.72
Sugar alcohol	Arabitol	8.28 ± 0.88
<i>Lipophilic compounds</i>		
Aromatic	Benzoic acid	19.97 ± 6.01
Fatty acid	n-9-(Z)-hexadecenoic acid	145.54 ± 15.23
	Hexadecanoic acid	11,692 ± 724
	n-9-(Z)-octadecenoic acid (oleic acid)	2,764 ± 356
	Octadecanoic acid	429.68 ± 32.45
	Eicosanoic acid	9.27 ± 0.59
Phenol	Trans-cinnamic acid	77.10 ± 11.33



a.



b.

Fig. 1 Concentration of carotenoids **a** and phenolic compounds **b** in the guabiroba frozen pulp (FP) and in the guabiroba dried pulp obtained after processing in an oven at 60 °C (OD-60) and at 105 °C (OD-105), and in a freeze-dryer (FD). For carotenoid content, only a single value was measured. In the case of phenolic compounds, different letters indicate a significant difference between them (ANOVA, Tukey LSD, $p < 0.05$)

and bile salts metabolisms (Valenzuela and Nieto 2003); and the phenol trans-cinnamic acid ($77 \mu\text{g g}^{-1}$), compound used as a food additive for its antimicrobial activity (Kuchi et al. 2018).

Comparison of the dried guabiroba pulps obtained at different drying processes

As previously observed, the composition of the guabiroba fruits indicates it as a plant food of interest for their high content of dietary fibers and the presence of several chemicals that promote human health. Its commercialization *in natura*, however, presents a severe drawback: its fast degradation

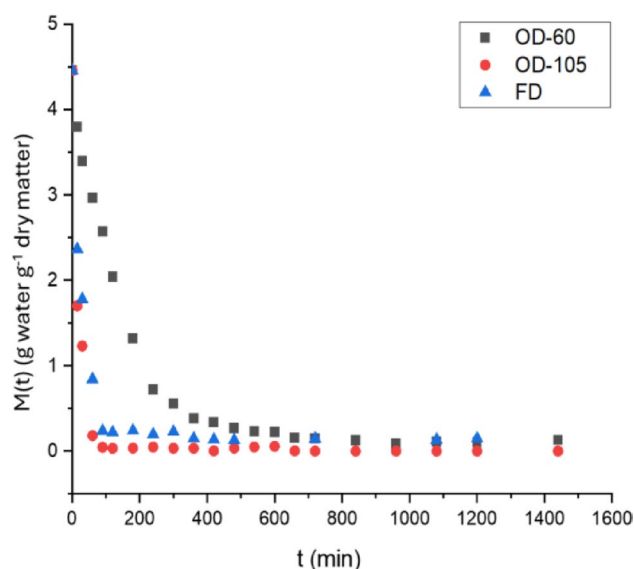


Fig. 2 Moisture kinetics on the drying of the guabiroba pulp in an oven at 60 °C (OD-60), in an oven at 105 °C (OD-105), and in a freeze-drying (FD)

due to its high moisture and sugar contents. In the current work, three methods were evaluated for the drying of the guabiroba pulp: oven-drying at 60 and 105 °C and freeze-drying. Firstly, the dried guabiroba pulps obtained after the use of the different methods were evaluated on their color characteristics (Table S5) and on their carotenoids content (Fig. 1a).

The color parameters of the samples after the different drying processes are shown in Table S5, alongside the color parameters of the guabiroba frozen pulp. The three drying processes resulted in significant changes in the color of the product (ΔE superior to 50%), however, OD-60 and FD were the ones that present the color most similar to the guabiroba frozen pulp. All dried samples presented lower values for both a and b chromaticity coordinates, which indicates the decrease of the redness and yellowness. It is clear, however, that the decrease of these colors, is smaller for the drying processes of OD-60 and FD, which indicates that these methodologies showed the highest preservation of the FD characteristics.

The bioactive compounds of the guabiroba dried products were evaluated considering two chemical classes: carotenoids (Fig. 1a) and phenolic compounds (Fig. 1b). Carotenoids are substances responsible for the yellow and red colors in fruits, and they play important roles in human health, from antioxidant to immunological activities (Delgado-Vargas et al. 2000). According to Fig. 2a, when comparing with FP, the products obtained after the OD-105 and FD drying methods presented a significant decrease in the carotenoid contents, while the OD-60 route was efficient in preserving such compounds. Naturally, drying at lower

temperatures results in a more effective nutrient retention, which justifies the higher preservation efficiency of the OD-60 processing when compared to the OD-105. On the other hand, the decrease in carotenoid content during freeze-drying is not commonly observed, but this effect could be associated with the disruption of tissue structure, which may lead to physicochemical changes in the material and its chemical composition (Lewicki 2006).

The phenolic compounds are chemicals present in plant matrices that are usually reported as antioxidant compounds (Angelo and Jorge 2007). This class includes compounds such as gallic acid and quercetin, which were previously quantified in the guabiroba frozen pulp during the chromatographic analysis. According to Fig. 2b, the amounts of phenolic compounds decreased significantly compared to the FP treatment only for the OD-105 treatment, despite all the drying processes yielding similar values, with no statistical difference ($p > 0.05$) between the drying treatments.

When considering exclusively the effects of the drying process in the physicochemical properties of the products, it is clear that the OD-60 is the best process, for it preserves the most the characteristics of the FP. The selection of the best process, however, must also consider the economic aspects, which are presented ahead.

Drying kinetics study

The drying of guabiroba pulp was evaluated on its kinetic characteristics for each drying method. The obtained kinetic curves (Fig. 2) indicate that OD-60 is the slowest method for the drying of the guabiroba pulp, followed by FD, and the fastest one is OD-105.

Six kinetic models (Table S1) were fitted to the experimental data, and the fitting results are presented in Table S6. It was observed that the different drying methods result in different equilibrium moisture. All treatments had values below 15% (moisture basis), the maximum limit established for wheat flours by Brazilian legislation (ANVISA 2022). This parameter is widely adopted as a reference for dry food ingredients, as it is associated with microbiological stability and a longer shelf life. Thus, the results obtained indicate that the food ingredients obtained from the guabiroba pulp meet the technological requirements for conservation and quality foreseen in current legislation (ANVISA 2022). Additionally, the data obtained on the drying of guabiroba pulp with the three different drying methods (OD-60, OD-105, and FD) were best represented by Midilli's kinetics model, which presented the lowest error (RMSD) and highest R^2 for the three drying techniques. Midilli's model is an empirical model that represents with accuracy single layer drying processes (Midilli et al. 2002).

Techno-economic analysis

After determining the chemical composition of the dried guabiroba pulps under the different drying methodologies (OD-60, OD-105 and FD) and the kinetics of these processes, a techno-economic analysis was conducted to determine the viability of each drying methodology, considering the parameters and the equations displayed in Tables S2, S3, and S4. The batch time on each drying methodology, determined considering the drying kinetics, was equal to 10.7, 1.4 and 4.0 h, resulting in a daily number of batches equal to 1, 5 and 2 for the OD-60, OD-105 and FD, respectively.

The drying equipment scale-up parameters are presented in Table S7, and the cost of equipment, calculated based on the parameters in Table S7, are presented in Table S8.

As observed in Table S8, the FP scenario, which consists of the production and commercialization of guabiroba frozen pulp, is the scenario with the lowest equipment cost, for it does not require a drying equipment, whereas the use of a freeze dryer (FD) results in the scenario with the most expensive equipment cost.

The equipment cost is the major parameter considered in the estimation of the Total Capital Investment, which is presented in Table S9.

As expected, the FP scenario exhibited the lowest TCI, whereas the FD is the most expensive one. Oven drying results in the intermediate costs. The Total Production Costs (Table S10) were then estimated.

It was considered that for the production of 1000 kg guabiroba pulp year⁻¹, an amount of 1,449 kg guabiroba fruits year⁻¹ must be submitted to the pulping step, which was calculated considering the pulping yield previously determined of 0.69 g pulp g⁻¹ fruit. The raw material cost was then determined considering the guabiroba cost of 0.60 US\$ kg⁻¹. Finally, the electricity cost was estimated based on the required power reported by the equipment suppliers and the energy cost in Brazil.

Finally, considering the FCI and the TPC, the minimum selling price for the guabiroba pulp products was estimated for different ROI taxes (10–20%), which consists of a pay-back time of 10–5 years. The results are presented in Table 4.

The selling price of guabiroba frozen pulp (FP, 3.22–3.32 US\$ kg⁻¹) is the lowest, when compared to the selling price of its dried alternatives. Such product is an interesting product for selling in local scale, for it generates higher costs of transport, which were not considered in the current work.

The guabiroba dried pulp, on the other hand, presents a cheaper transport cost, which enables its commercialization globally, and it presents a wide application possibility, from cosmetics to food industries. When considering the chemical composition and selling price of the guabiroba dried pulps, the oven-drying at 60 °C can be considered the most

Table 4 Estimated selling price for the guabiroba pulp

Parameters	Scenario			
	OD-60	OD-105	FD	FP
Product	Dried pulp	Dried pulp	Dried pulp	Frozen pulp
Annual production (kg year ⁻¹)	210	210	210	1,000
<i>Chemical characteristics</i>				
Phenolic compounds content (mg GAE g ⁻¹)	1.20±0.07	0.78±0.14	0.95±0.14	1.63±0.27
<i>Carotenoids (mg g⁻¹)</i>				
<i>α</i> -carotene	0.26	0.10	0.11	0.26
<i>β</i> -carotene	0.25	0.09	0.10	0.25
Cryptoxanthin	0.24	0.09	0.10	0.24
<i>λ</i> -carotene	0.18	0.07	0.07	0.18
<i>Processing parameters</i>				
Drying time* (h)	11.0	1.43	4.19	–
ROI (%)	<i>Selling price (US\$ kg⁻¹)</i>			
10	43.90	31.42	1,071	3.22
15	46.10	32.07	1,200	3.27
20	48.29	32.71	1,329	3.32

Drying time (*) was determined considering the fitted model of Midilli's (Midilli et al. 2002) for achieving a final moisture of 0.130 g water g⁻¹ pulp (equivalent to 0.149 g water g⁻¹ dry matter)

promising technique, for it maintains the most the composition of the bioactive compounds of the fruit and presents a selling price similar to the OD-105 and lower than the FD ones.

The techno-economic analysis presented in the current text is a preliminary estimation, and it might present an approximate error range of ±20% in the actual costs (Timmerhaus et al. 2004). Such result, however, is of great importance for providing an estimative of process costs and allowing the selection of the best engineering pathway based on the economics aspects. The scalability of the process, however, is limited to the annual production of guabiroba, which may vary according to edaphoclimatic factors, and to the high estimated FCI values (2123–424,306 US\$), which might be mitigated when considering producers' association that already exists in several Brazilian regions.

Conclusion

This study provided a comprehensive characterization of the guabiroba fruit chemical composition, focused on its nutritional potential, and a techno-economic analysis of Engineering pathways to obtain dried guabiroba products. The fruit is rich in dietary fiber, besides presenting low lipids and energy value, which highlights its potential in special diets. Notable contents of manganese, iron, and potassium were also found, alongside several chemicals highly

beneficial to human health. Guabiroba fruits' high *in natura* moisture content results in a high perishability, demanding drying processes for its off-season use in foods, beverages, and cosmetics. Oven and freeze-drying effectively reduced its moisture to below 15%, which could increase the product's shelf life. Among the methods studied, oven-drying at 60 °C stood out as the most promising process, with the least impact on product quality and the best technical–economic viability, with an estimated selling price of 43.90–48.29 US\$ kg⁻¹.

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Data availability Data available upon request.

Declarations

Conflicts of interest Nothing to disclose.

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