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Case Report

Influence of Wetting-Drying Cycles on Wood Behaviour of Coastal Pedestrian Walkways

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Abstract

In the context of inspection and maintenance actions for beach walkways in the North of Portugal, some samples of wood used in their construction were collected – the *Pinus sylvestris* wood, widely applied in the country. The sustainability of the beach walkways over natural coastal areas is very dependent on their material durability. One of the main problems of the timber used to build those structures is its behavior under wet-drying cycles. For that reason, this work aimed to simulate the effects of weathering on the long-term bending behavior of pinewood. Weathering slab samples with two decades of service life and new, unused slabs were subjected to wetting–drying cycles and tested between each wetting or drying phase. As the bending test characterizes one of the most representative efforts in pedestrian boardwalk slabs, the bending module of rupture was used as an indicator to characterize the resistance of timber. Thus, in this study, the samples' density, dimensional stability, and mechanical strength were determined at the end of each batch of cycle repetitions. The tests were carried out before and after a set of wetting-drying cycles caused by immersion in water and placement into an oven at 80°C to simulate environmental exposure. Thus, it was intended to simulate the use in service through the realization of successive wetting-drying cycles in a laboratory environment and to evaluate its influence on the density, dimensional stability, and mechanical strength of the pine wood tested. The extreme conditions used in the laboratory pretend to accelerate the degradation of samples and simulate, in a relatively short period, what would need years to occur in service. The results showed that the wood that had never been in service is more susceptible to bending resistance variations with cycles than the one already in service. Thus, after a few wet-drying cycles, the wood without any service life tends to approximate, in terms of bending behavior, to the one with two decades of service. This indicates that the method used could satisfy the need to obtain predictions for long-time behavior in a relatively short period.

Keywords
Wood aging; degradation; wet-drying; bending; life-cycle

1. Introduction

Wood has been used as a structural material for a long time. The rise of steel and concrete structures during previous centuries has contributed partly to reducing wood usage. However, with the current popularity of wood construction, particularly in terms of sustainability, it is quite likely that wood will be increasingly used.

The raised walkways or wooden decks have been around for a long time. They are intended to prevent soil and vegetation degradation, possibly also serving to overcome small obstacles such as small lakes or rivers. The recent construction of numerous wooden walkways is an example of this, with its proliferation in natural landscapes, particularly in coastal areas, to promote tourism and leisure, protecting the dunes of the beaches and, consequently, the life in them. It is therefore important to understand whether walkways fulfil their function by observing, through the prism of sustainability, whether they are durable enough to withstand the requirements during their 15 to 30 years life expectancy, as indicated for this type of structure [1].

The effects of coastal surroundings on wooden walkways are accelerators of the aging process of the material, so they can be conditioned about their durability. In areas close to the Portuguese Atlantic coast, the high environmental aggressiveness justifies a particular study of the behavior of wood in these conditions. The structures of the beach walkways are not covered, and, in addition to being exposed to ultraviolet radiation, they are subject to the direct action of rainwater and eventual splashes of the tides. In addition to the soil moisture transfer, this humidity can also favor the risk of biotic attack, to which the wood is particularly sensitive. The service class is 3 (exposed environment), according to NP EN 1995-1-1 standard (EC5) [2], and the risk class is 3.2 above ground and 4 in the ground, according to NP EN 335-2018 [3].

Wood extracted from trees contains liquids, so it must go through a drying process before use. The drying begins with the evaporation of free water, which fills the voids of the material, which evaporates quickly from the moment the wood is sawn and occurs without significant volumetric contractions or changes in resistant properties. In addition to free water, bound water is contained in cell walls, which can vary. The Fibber Saturation Point (FSP) has a value of around 25% to 30% of the dry weight [4, 5]. The absorption or desorption of this moisture may imply volumetric changes and a change in the mechanical properties of wood [4, 5]. The wood presents significant geometric variations when the water content present in the wood falls below the FSP. When this happens, the presence of water in the fibbers decreases, potentially causing the cell volume to decrease, and retraction occurs, with consequent cracking and warping. The greater the change in moisture content, the greater the increase in wood volume variation and shrinkage. When these dimensional changes, resulting from wood hygroscopicity, occur quickly, they induce internal stresses and lead to cracks that could favor the posterior appearance of biotic degradation agents [4-6]. In addition, although they do not cause significant decreases in the resistance of the wood, they can also decrease the material's mechanical properties and cause some deformations. Given that most fibers are orientated in the longitudinal direction, dimensional variations in the transverse direction (width and thickness) are more significant than in the longitudinal direction. In the transverse direction, the radial dimensional variation is about twice that observed tangentially [6].

Thermal modification can reduce the equilibrium moisture content of the wood and improve dimensional stability [7]. However, according to Cermak *et al.* [8], the dimensional stability of thermally modified wood tends to decrease during successive drying-wetting cycles, so it will not be so interesting in structures with environmental exposure, such as wood for walkways. In order to minimize the effects of shrinkage of wood in service, waterproofing of the material with suitable products is necessary, which should be periodically reapplied.

On coastal wooden walkways, due to the maritime proximity, there are no huge temperature variations, even if the temperature variation of the surface could be higher than the temperature variation of the air because of the sun exposure. However, the relative humidity of the air is always quite high. The moisture of wood has a very significant influence on its mechanical properties. According to Pestka *et al.* [9], the value of the bending-resistant moment of pine, determined with a 4-point test, may decrease by more than 40% in wet specimens compared to dry specimens.

Weathering of the wood is caused by sunlight exposure, but the caused degradation of the cell wall and subsequent breakdown of the microstructure are slow and confined to surface layers. Thus, such changes should have little influence on the mechanical properties of structural timber [10]. On the other hand, the wetting and drying cycles that occur in nature could have and higher impact. Liu *et al.* [11] studied the mechanical behavior of two types of treated pine wood after subjection to successive wet-drying cycles. They concluded that even without significant changes in compressive and bending resistance, it was possible to observe an increasing number of radial and tangential cracks at the top of the specimens as more cycles were performed due to the uneven dimensional changes caused by the repeated swelling and shrinking of the specimens.

However, the wood in some of the elements of the walkways is used in whole wood logs, so it will be even more resistant due to the continuity of the surface of wood fibers [12]. In addition, the variability of wood strength in round-section logs is about half to two-thirds of lumber [13].

In addition to the mechanical resistance of wood, it should be stressed that there are still other issues related to the safety of walkways, such as the attack of certain biotic wood agents and the problems of the connections between the several structural elements. However, those issues are not the subject of analysis in the present work. Moreover, resulting from coastline changes, the lifetime of the wooden walkways is sometimes reduced because the functionality limit states are reached, which leads to an early end of use even before the degradation of the structure.

Wood aged in old structures differs in its physical and mechanical properties from fresh wood [14]. Artificially accelerated aging tests can simulate the aging of wood and save time. However, the outdoor exposure tests correlate better with wood aging in the actual environment [15]. The present study combines these two types of analysis. It focuses on the characterization of the bending behavior of pine wooden test pieces that had never been in service when subjected to successive wetting and drying cycles, as well as its comparison with the same tests in pieces of woods with about two decades in service, appreciably corresponding to the expected service life for this type of infrastructure.

2. Experimental Method

The evaluation of wood, when submitted to several wetting and drying cycles, was experimentally tested in the laboratory. Two types of *Pinus sylvestris w*ood pieces (class 4 with Tanalith chemical treatment) from Portuguese beach pedestrian walkway slab boards were tested: new deck wood, without any time in service, and old deck wood aged in service for about 20 years without any kind of known maintenance during its working period. The old wood consisted of pieces collected from two different walkways, one from Cabedelo Beach and the other from Rodanho Beach, located on the Portuguese Atlantic coast in the Viana do Castelo district, as illustrated in Figure 1. The specimens' names were made as follows: the new wood was designated with the letter N, the old wood from Cabedelo Beach was designated with the acronym CO, and the old wood from Rodanho Beach was designated with the acronym RO.

Figure 1 Location of Cabedelo and Rodanho Beaches in the Viana do Castelo region-Google Maps.

The climate is mild in the vicinity of Viana do Castelo, located next to the Atlantic coast of northern mainland Portugal. Accordingly, to data from the Portuguese Institute of Sea and Atmosphere (IPMA), the values for Viana do Castelo between the years of 1981 and 2010 [16], presented in Table 1, have a monthly average temperature between 9.7ºC and 20.8°C, with absolute extremes of -5.1°C and 39.5°C. According to the same source, the average annual rainfall in Viana does Castelo is 1466.3 mm. The humidity levels always have high values – between 74% and 89%, with an average annual of 82% [17].

Table 1 Medium (TT), maximum (TX) and minimum (TN) monthly average temperature; higher daily maximum temperature value (Higher TX), lower daily minimum temperature value (Lower TN), average amount of precipitation (Rain) and average relative humidity at 9 am (Humidity) for Viana do Castelo [16, 17].

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
TT [ºC]	9.7	10.5	12.6	13.7	15.9	19.2	20.8	20.8	19.2	16.1	12.7	10.8	15.2
TX [ºC]	14.6	15.5	17.9	18.5	20.7	24.5	26.3	26.4	24.8	20.9	17.3	15.2	20.2
TN [ºC]	4.9	5.5	7.4	8.9	11.1	13.9	15.3	15.1	13.7	11.2	8.1	6.4	10.1
Higher TX [ºC]	24.0	25.0	30.5	31.6	35.6	38.6	38.0	39.5	36.4	32.6	26.2	24.6	39.5
Lower TN [ºC]	-3.9	-2.8	-3.7	-0.4	0.8	5.5	9.0	8.0	7.0	2.4	-1.2	-5.1	-5.1
Rain [mm]	180.8	131.0	112.5	125.9	99.0	52.0	29.1	38.5	94.5	190.0	199.9	213.3	1466.3
Humidity (%Hr)	88.0	87.0	81.0	76.0	76.0	74.0	75.0	78.0	81.0	86.0	89.0	89.0	82.0

The test specimens were obtained by sawing the original pieces of wood in the longitudinal direction, trying to obtain pieces with the following dimensions: 340 mm × 20 mm × 20 mm, according to NP 619 [18]. However, to preserve the quality of the samples, the height of the board has never been cut, so it may not correspond exactly to 20 mm, and the new, unused wood has some profiles on the surface, as presented in Figure 2. The tests were made to reproduce what is used in pedestrian walkway constructions without distinguishing the tangential and radial direction. The cuts did not avoid knots or other mistakes in the wood. In fact, according to Rede *et al.* [19], the bending resistance results of samples with the fibbers oriented more tangentially or radially at the top of the specimen are slightly the same. The measurement of the initial and final dimensions of the specimens was made with a Pachymeter with reading capacity in the hundredth of a millimetre and weighed on a scale with precision up to the hundredth of the gram. Figure 2 shows the test machine used and some tested wood pieces.

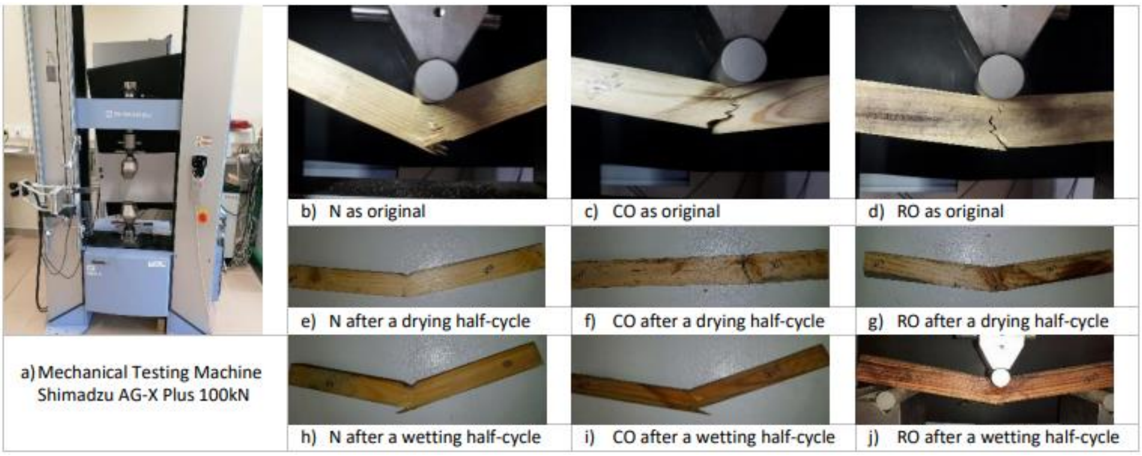

Figure 2 Images of the test machine and of some wood specimens.

To accelerate the degradation of the wood, extreme conditions were performed in the laboratory. A complete wetting-drying cycle of wood specimens was composed of two half-cycles-one of wetting, simulated by immersion in water at the temperature of 15°C, for 15 days, and another of drying, performed by the placement in an oven with the temperature of about 80°C for another 15 days. The half-cycles of wetting (W) and drying (D) were successively alternated and performed according to what is presented in Table 2. Before any half-cycle of drying or wetting, the initial state was designated as original (0). The sequential numbering of each phase is representative of the accumulated half-cycles performed, and the letter corresponds to the last half-cycle carried out by the specimen before the test. For example, specimen D1 was tested after one drying half-cycle. In contrast, specimen D2 was tested after one complete cycle (one wetting half-cycle at the beginning and one drying half-cycle at the end).

Table 2 Drying-wetting cycles codification ("W"-wetting half-cycle and "D"-drying half-cycle).

0	D = **D1**	W = **W1**	W + D **= D2**	D + W = **W2**	D + W + D = **D3**	W + D + W = **W3**

For the original phase and at the end of each drying and wetting half-cycles, the weight and dimensions of all specimens were registered according to three directions: length, width, and height. At the end of each half-cycle, three specimens were tested for bending. These tests were performed according to NP 619 [18], with a 3-point bending test performed with the Mechanical Testing Machine Shimadzu AG-X Plus 100 kN. For the calculation of the modulus of rupture, equation 1 was used:

$$MOR = \frac{3F_f L}{2bd^2} \tag{1}$$

Where:

MOR-Modulus of Rupture (MPa);
F_f-Fracture Force (N);
L-Distance inter-supports (mm);
b-Width of the specimen (mm);
d-Height of the specimen (mm).

3. Results and Analysis

Wood is a natural material and, as such, is subject to fluctuations in its properties. Therefore, not all wood of the same species has the same properties. Moreover, wood is an anisotropic material, with different behavior depending on its fibers' orientation and a behavior that can be affected by unique elements in its elements, such as knots. With this preamble established, we will now analyze the results obtained for pine wood walkways comparing the properties evidenced by samples of wood that have never been in service and samples of wood with about 20 years in service in a coastal area of northern Portugal.

Table 3 presents the average results obtained for the density of the considered samples, evaluated by dividing the weight by the volume. The gathered values are within the range reported in the literature for pine wood [13, 20-22]. The density values obtained for wood with 20 years in service are slightly lower than that of new wood, particularly CO. The density measured is lower for aged wood, so it may reflect that the wood dries with its use, even in not very hot and reasonably humid environments such as the coastal environment near Viana do Castelo. Thus, when laying the wetted wood in an oven at 80°C, it is noticed that the new wood is the one that loses the most moisture and the older wood has a greater weight increase when immersed in water since it has already been in service (CO and RO specimens).

Table 3 Results for initial density and for density and dimensions variations with wetting half-cycles (W1) and drying half-cycles (D1).

Wood	Initial Density (kg/m^3)	Drying semi-cycles - 80˚C/15 days Variation					Wetting semi-cycles - 80˚C/15 days Variation				
		Weight (%)	Density (%)	Length (%)	Height (%)	Width (%)	Weight (%)	Density (%)	Length (%)	Height (%)	Width (%)
N	548	-16.00	-6.58	-0.37	-6.03	-4.00	35.50	31.27	-0.08	2.03	1.25
CO	483	-10.00	-4.80	-0.33	-3.15	-2.05	60.10	53.45	-0.20	1.91	2.53
RO	517	-11.30	-6.03	-0.15	-3.07	-2.47	52.90	48.43	-1.29	1.85	2.60

Table 3 presents the dimensional variations of the woods when subjected to an introduction in an oven at 80°C or a water immersion. These results clearly evidence anisotropy in the structure of the wood and, consequently, in its properties. The greatest changes are obtained in the variation of width or height, and minor modifications are observed in the length of the specimens. This reflects how the wood was cut to obtain the pieces for the walkways; that is, the wood was cut lengthwise with the direction of the length of the pieces. In 20-year-old wood specimens, there is less swelling by immersion in water and a lower shrinkage by placing in an oven compared to the new wood specimens.

Analyzing the results of the mechanical bending tests of a set of three different specimens before any drying or wetting half-cycles, shown in Figure 3, it is observed that the behavior of the new wood is substantially different from the registered for the aged wood. The greatest differences are observed in the type of fracture. While the specimens from aged wood present a fragile fracture, the new wood samples present evident plastic deformation before fracture. This is due to the lower water content in aged wood, with lower initial density and smaller weight loss in the first drying semi-cycle, as shown in Table 4. However, it should be noted that wood with about 20 years of age in use, in conditions as adverse as those of the northern coast of Portugal, still has a significant bending resistance.

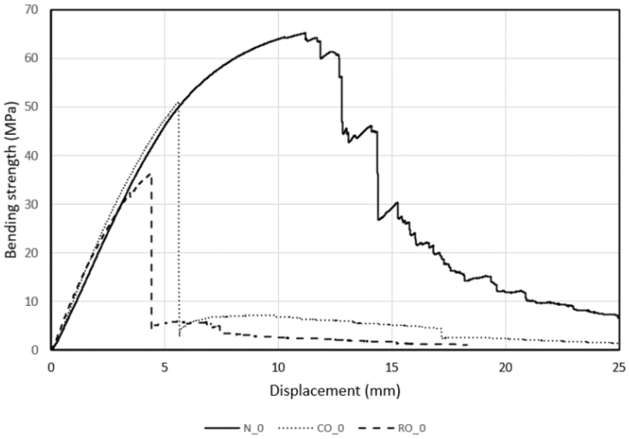

Figure 3 Results of bending tests of new wood (N_0) and aged wood (CO_0 and RO_0) for initial state.

Table 4 Summary of Modulus of Rupture of the tested woods for each half-cycle.

Wood	Modulus of Rupture (MPa)						
	Half-cycles						
	0	W1	D1	W2	D2	W3	D3
N	62,2	22,7	108,9	29,5	88,5	29,8	66,3
CO	48,1	30,2	41,8	19,6	36,8		
RO	55,3	25,7	45,3				

Applying a half-cycle of oven or immersion of the specimen in water for 15 days causes significant changes in the wood's behavior, as seen through the observation of Figure 4. Each shown curve corresponds to the most representative curve for each set of tested samples, the average values presented in Table 4. The immersion of the wood in water causes a sharp decrease in its yield stress and substantially increases its plastic deformation. On the other hand, the maintenance of wood in an oven for 15 days promotes fragile behavior, that is, without plastic deformation or with a very faint plastic deformation before rupture. However, after the first half-cycle in an oven, the mechanical bending resistance of the wood undergoes a significant increase.

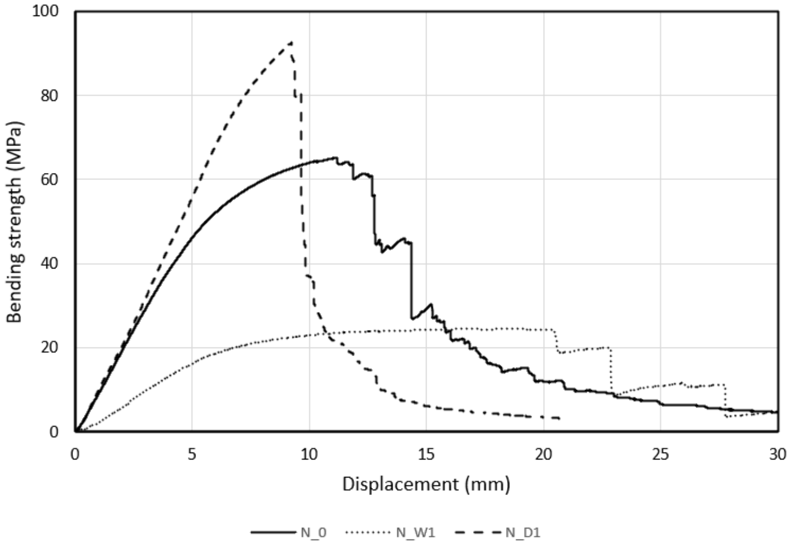

Figure 4 Results of bending tests of original new wood (N_0) and after subjecting to a half-cycle of 15 days of wetting (N_W1) or drying (N_D1).

The evolution of the modulus of rupture on different woods is illustrated in Table 4. As previously explained, three specimens were tested at the end of each half-cycle. Due to the limited quantity of aged wood available, a different number of half-cycles were carried out for N, CO, and RO. It is noticeable that wet wood has a lower modulus of rupture and no significant differences are noticeable with the number of half-cycles to which the wood is subjected. The decrease in the modulus of rupture with immersion is more pronounced in the new wood. Wood that had already been in service (CO and RO) is less sensitive to aging half-cycles, immersion in water, or drying, so the effect of moisture variations will be less significant over time.

The consecutive realization of several cycles promoted a sharp decrease in the mechanical resistance of the wood. However, the new wood, after the first drying procedure, presents a modulus of rupture value of almost twice the initial value, but subjecting this wood to another complete cycle causes a sharp decrease of the modulus of rupture to about half and equal to the value of the wood at the beginning. It will be important to do these tests by extending the number of cycles to which wood is submitted to achieve some kind of correlation between an aging cycle and the equivalent time when used.

From the results obtained, there is a clear perception that changes in wood properties occur very quickly at the beginning, but after that, the advance of degradation caused by the succession of drying-wetting half-cycles occurs much more tenuously. This is evident when it is found that woods with two decades of use still have high mechanical strength and will not jeopardize the safety of the users of the walkways where they are applied. By the analysis of the wood used in this study, it can be concluded that the wood's deterioration does not justify replacing a walkway with 20 years of use. Boards exposed to adverse weather conditions, such as those observed in a coastal environment in northern Portugal, without any kind of maintenance and with such significant values of mechanical resistance, may continue their performance if there are no other problems for economic and sustainability reasons. Moreover, according to some aesthetic evaluations, aged-looking boards better fulfill their role of staying in the environment more integrated with the surrounding nature.

4. Conclusions

The performed tests try to characterize the behavior of the wood when subjected to weathering during its normal service life and some successive wetting-drying cycles. These wetting-drying cycles are an accelerated way to represent the aging of the wood when subjected to an aggressive coastline environment. However, they could not simulate other degradation factors like sun exposure and utilization times.

The gathered results showed that the decreased bending resistance of wood with two decades of service doesn't seem very significant, despite it showing a more fragile rupture. Plus, the evolution of the results obtained in new wood with some cycles seems to correspond to exposure of the wood for several years in service since the values of bending resistance tend to quickly approach the values presented by the wood with the use of about two decades.

In terms of wet-drying cycles, the changes in dimensions and resistance will be much more significant in unused wood, corresponding to the early use times. The use of wood, without any kind of maintenance intervention, increases its drying and increases its fragility. With the increasing aging of wood, the magnitude of the differences successively decreases. The most favorable situations will be those where the wood is not even exposed to high-temperature situations for long periods without any hydration or where the wood is not too time saturated without the ventilation necessary to prevent its humidity from reaching too high.

In new wood, there is an increase in the modulus of rupture in drying half-cycles and a decrease to about half in wetting half-cycles. Bringing that wood in water causes a sharp decrease in its yield stress and substantially increases its plastic deformation. On the other hand, introducing new wood in an oven promotes fragile behavior, despite its increased bending resistance. In wood with 20 years of service, the bending resistance decrease with immersion in water, but it is no longer observed the increased modulus of rupture with the drying half-cycles. However, these observed variations have less amplitude than the ones observed with the new wood.

Further studies of this nature, with a higher number of aging cycles, will also be appropriate to better understand the evolution of wood degradation and to be able to make a better association between an accelerated aging cycle and the number of equivalent years in the coastal environment of the North coast of Portugal.

Anyway, with the presented study, it could be noticed that the wood that had never been in service is more susceptible to bending resistance variations when wet-drying cycles are performed. Plus, the wood, with 20 years of service without any maintenance, still has a noticeable mechanical bending resistance.

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Author Contributions

Conceptualization, Joana Oliveira Almeida, Pedro Delgado and António Labrincha; Methodology, Joana Oliveira Almeida, Pedro Delgado and António Labrincha; Validation, Joana Oliveira Almeida, Pedro Delgado, António Labrincha, Helena Parauta and Charles Löwenström; Formal analysis, Joana

Oliveira Almeida, Pedro Delgado, António Labrincha and Helena Parauta; Investigation, Joana Oliveira Almeida, Pedro Delgado, Antonio Labrincha and Helena Parauta; Resources, Joana Oliveira Almeida; Data curation, Joana Oliveira Almeida, Pedro Delgado, António Labrincha and Helena Parauta; Writing — original draft, Joana Oliveira Almeida, António Labrincha and Helena Parauta; Writing — review & editing, Joana Oliveira Almeida, Pedro Delgado, António Labrincha, Helena Parauta and Charles Löwenström; Visualization, Joana Oliveira Almeida; Pedro Delgado, António Labrincha, Charles Löwenström and Helena Parauta; Supervision, Joana Oliveira Almeida, Pedro Delgado and Antonio Labrincha; Project administration, Joana Oliveira Almeida; Funding acquisition, Joana Oliveira Almeida.

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Competing Interests

The authors have declared that no competing interests exist.

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