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Hygrothermal behaviour of external thermal insulation composite systems (ETICS) to withstand biological colonisation

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A R T I C L E I N F O

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A B S T R A C T

ETICS are multilayer building solutions applied to the building external walls to provide an improved thermal performance to the building envelope. However, several questions have been raised concerning the durability of ETICS, namely related to biological colonisation phenomena. Considering the high susceptibility of ETICS to bio-colonisation, the following research questions arise: (i) what is the impact of surface temperature (ST) and surface relative humidity (SRH) fluctuation on mould growth in ETICS facades? (ii) is it possible to predict mould growth on ETICS under fluctuating conditions considering favourable and unfavourable growth conditions? This study aims to investigate the influence of the hygrothermal behaviour of five different ETICS (with thermal mortars and insulation boards) on mould growth. ETICS were exposed for one year at an urban site in Lisbon, Portugal, facing North, during which the ST and the SRH were monitored. Concurrently, numerical simulations were performed to evaluate the hygrothermal behaviour of the ETICS. Three theoretical indices were applied, using numerically and experimentally obtained values of ST and SRH as input to provide an indication of the risk of mould growth. The results were complemented and validated by assessing the bio-colonisation, water performance and aesthetic properties of the ETICS. Index 1 (percentage of time with SRH $\geq$80%) indicated similar potential of mould growth for all systems. Both index 2 (percentage of time with SRH = 100%) and index 3 (percentage of time with SRH $\geq$80% and 15 °C $\leq$ ST $\leq$ 30 °C) indicated a higher potential of mould growth for the lime-based ETICS and a lower potential for the acrylic-based ETICS with an EPS-based mortar. Moreover, the lime-based system obtained the highest rate of mould growth after one year of outdoor exposure. Therefore, results suggested that indices 2 and 3 are in agreement with field observations and thus can provide an indication on mould growth for the analysed ETICS. Results also showed that an increase of capillary water absorption after ageing to levels higher than 1 kg/m^2 after 24 h in direct contact with water can favour mould growth. Thus, the combination of unfavourable microclimatic conditions (SRH <80%; ST < 15 °C or ST > 30 °C) and surface hydrophobicity are fundamental to avoid mould growth on ETICS, regardless of the incorporation of biocide in the finishing coat composition.

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Nomenclature

a*	Green/red coordinate, according to CIELAB colour space
A_w	Capillary water absorption coefficient (kg/(m^2.min$^{0.5}$))
b*	Blue/yellow coordinate, according to CIELAB colour space
BC	Base coat
CR	External condensation risk
EPS	Expanded polystyrene
ETA	European Technical Assessment
ETICS	External Thermal Insulation Composite Systems
FC	Finishing coat
ICB	Expanded cork board
L*	Lightness coordinate, according to CIELAB colour space
MW	Mineral wool
RH	Relative humidity
RS	Rendering system
T	Temperature
TI	Thermal insulation
TM	Thermal insulating mortar
SRH	Surface relative humidity
ST	Surface temperature
W_{ETICS}	Total water content in the ETICS
ΔE	Global colour difference

1. Introduction

1.1. Background

External Thermal Insulation Composite Systems (ETICS) are multilayer building solutions applied to the building external walls and consisting of three layers (the thermal insulation, the base coat, and the finishing coat) [1,2]. The thermal insulation layer can be an insulation board or a thermal mortar, while both the base coat and the finishing coat layers can have different formulations. These systems grant an improved thermal performance to the building envelope, thus contributing to minimise the energy consumption of new and retrofitted buildings [3]. In fact, over the last few decades, there has been an increase in the use of ETICS in Europe, most probably due to stricter EU directives aimed at decreasing the energy demand of existing buildings and improving the energy performance of new buildings [4]. ETICS increases the thermal insulation level of the building envelope, reduces thermal bridges, increases the thermal inertia and provides better indoor thermal comfort while reducing the risk of internal condensation on the wall [5–7]. However, several questions have been raised on the long-term durability of ETICS, namely related to biological colonisation phenomena [8–13]. Biological growth is often identified on several ETICS facades shortly after the building construction and/or refurbishment [6,14,15]. This anomaly can cause cladding defacement, altering the building aesthetics and compromising a more widespread use of ETICS technology. Moreover, some microorganisms can possibly induce chemical and mechanical deterioration on the ETICS surfaces, potentiating further anomalies and decreasing the system efficiency [2,16].

1.2. Literature review

Biological growth on the surface of ETICS facades is a complex phenomenon influenced by several factors, such as surface moisture content [5,17,18], surface temperature [10,19], nutrient availability [20], surface pH [21], surface roughness [22], soiling [23], among others. ETICS facades are more prone to biological colonisation than traditionally rendered facades due mostly to the hygrothermal behaviour of the ETICS [2,24]. The thermal insulation layer of the system (i.e., thermal insulation board or thermal insulating mortar) is applied to the building external wall and then covered by a thin rendering system (base coat + finishing coat) [25,26]. Due to the small heat capacity of the ETICS, the outdoor climate will have an immediate and major influence on the surface properties of the system (e.g., the surface temperature will rise significantly in a few minutes if the ETICS facade is exposed to direct sun radiation; during the night, an undercooling phenomenon is frequently observed possibly leading to surface condensation and increasing the risk of bio-colonisation). Surface condensation occurs when the surface temperature is lower than the dew point temperature of the air, resulting from the exchange of long wave radiation between the external surface and the atmosphere [5]. Additionally, slow drying kinetics of the rendering system favours moisture retention for a longer period, again potentiating a greater risk of bio-colonisation, namely by moulds [27]. In fact, moisture and temperature have been identified as crucial parameters to determine the risk of mould growth on various building materials [28–30].

Several mould prediction models, e.g., the VTT model [31], the bio-hygrothermal model [32], or the mould resistance design (MRD) model [33], have been developed over the years, mostly requiring relative humidity (RH) and temperature (T) as input data.

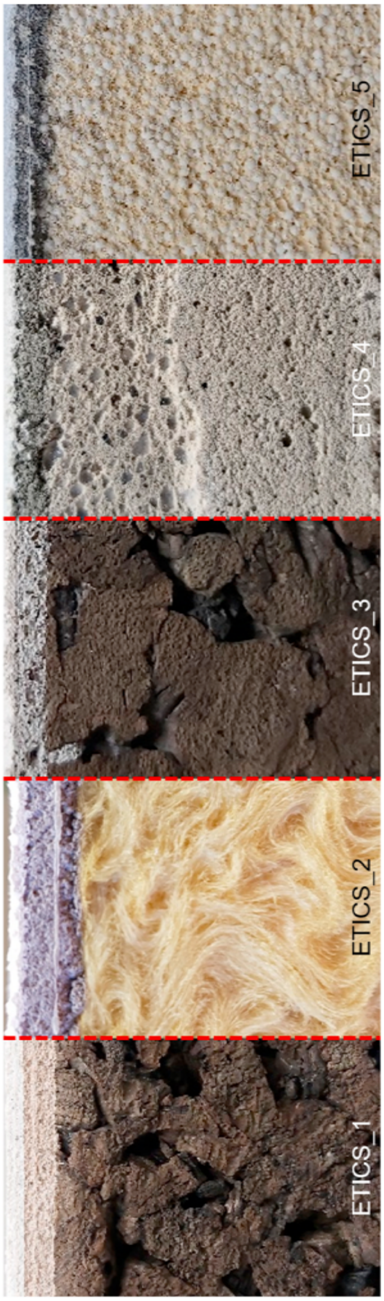

Fig. 1. Photographs of the ETICS.

However, these models are mainly intended for interior surfaces with a more controlled environment when compared to the exterior [34,35]. Thiis et al. [36] evaluated the effects of transient wetting on mould growth and concluded that using microclimatic conditions (i.e., surface relative humidity (SRH) and surface temperature (ST)) as input data in existing mould models can enhance mould growth prediction. This is explained by the significant differences found between climatic conditions (i.e., T and RH) and surface conditions (i.e., ST and SRH) [10,36]. As suggested by Gradeci et al. [34], significant research work has been done to develop and enhance mould prediction models considering different hypotheses and methodologies and comparing outputs. Nevertheless, a lack of experimental data has been frequently identified by several authors as a limitation, especially regarding fluctuating climatic conditions [34,37].

The VTT model is one of the most used mould prediction models using RH and T as input variables [31,38]. This deterministic dynamic model was first developed to predict mould growth on pine and spruce and later improved to be able to account for a decline in mould growth under unfavourable conditions [28]. In fact, a minimum threshold value of 70-80% RH is usually considered for mould growth, with the optimum growth conditions requiring high levels of RH (i.e., >80%) [21,39,40]. Additionally, an air T range between 15 °C and 30 °C can be considered generally favourable for mould growth [32,40]. When air temperatures are low, the cellular processes are slower, resulting in lower mould growth rates [21]. In this case, an increased level of moisture content (i.e., higher RH) is required for mould growth. Finally, the exposure time under favourable growth conditions is of fundamental importance, i.e., greater exposure time leads to a higher risk of mould growth [28].

Isopleth curves have also been used in the formulation of bio-hygrothermal models, which separate favourable and unfavourable T and RH conditions, considering the effect of fluctuating climatic conditions [37,41]. Johansson et al. [10] used these models to evaluate mould growth in a test cell with ETICS facades in Sweden and concluded that ETICS with thermal insulation boards present a higher risk of mould growth when compared to conventional rendered facades.

1.3. *Problem statement*

In outdoor environments there is a constant variation of T and RH, which causes the conditions for mould growth to vary over time [42,43]. The differences found in the output results of several mould prediction models are generally justified by the complexity of mould growth processes together with the different simplifications and/or assumptions of each model, e.g., Refs. [28,34]. Indeed, a lack of experimental data under fluctuating climatic conditions is frequently identified as a limitation to develop and enhance existing and new mould growth models. Considering the high susceptibility of ETICS facades to bio-colonisation, the following research questions arise:

- What is the impact of ST and SRH fluctuation on mould growth in ETICS facades?
- Is it possible to predict mould growth on ETICS under fluctuating conditions considering favourable and unfavourable growth conditions?

1.4. *Research aims*

The work described in this paper aims to investigate the influence of the hygrothermal behaviour of five different ETICS on mould growth. The tested systems have different thermal insulation materials (thermal mortars and insulation boards) and rendering system formulations (silicate-based, acrylic-based and lime-based finishing coats). ETICS specimens were exposed for one year at an urban site in Lisbon, Portugal, facing North. During outdoor exposure, the ST, the SRH and the meteorological data (i.e., air temperature, air relative humidity, precipitation and solar radiation) were monitored. Numerical simulations were also performed to evaluate the hygrothermal behaviour of the ETICS using relevant hygrothermal properties as input data. Three theoretical indices were applied using experimentally and numerically obtained values of ST and SRH as input to provide an indication on mould growth. At the same time, the water performance, the aesthetic properties and the bio-colonisation of the five ETICS were assessed. Results obtained through the theoretical indices were compared to field test results. This paper ultimately aims to provide information about the effects of fluctuating climatic conditions on mould growth in ETICS facades.

Table 1
Identification and composition of the ETICS in accordance with the information provided in the ETA documents or made available by the manufacturers (adapted from Parracha et al. [13,44]).

System	Thermal insulation (TI)	Rendering system (RS)		Average system thickness [mm]
		Base coat (BC)[a]	Finishing coat (FC)	
ETICS_1	Expanded cork agglomerate board (ICB)	Natural hydraulic lime, cement, mineral fillers, resins, and synthetic fibres	Air lime, hydraulic binder, and organic additives	65.9
ETICS_2	Mineral wool (MW)	Cement, mineral fillers, resins, and synthetic fibres	Acrylic-based, mineral aggregates, pigments, additives, and biocide[b]	64.3
ETICS_3	Expanded cork agglomerate board (ICB)	Natural hydraulic lime, mixed binders, and cork aggregates	Silicate-based, organic additives, and pigments	44.8
ETICS_4	Thermal mortar with mixed binders and silica aerogel	Cement, mineral fillers, resins, and synthetic fibres	Acrylic-based, mineral aggregates, pigments, additives, and biocide[b]	45.1
ETICS_5	Thermal mortar with lime and EPS aggregates	Cement, mineral fillers, resins, and synthetic fibres	Acrylic-based, mineral aggregates, pigments, additives, and biocide[b]	66.0

[a] Includes a glass fibre mesh as reinforcement.
[b] e.g., terbutryn or isothiazole.

2. Materials and methods

2.1. ETICS and natural ageing

Five different ETICS (with thermal mortars and insulation boards) supplied by two manufacturers were selected and tested in this study (Fig. 1). The systems were selected considering they have different thermal insulation materials (expanded cork board – ICB, mineral wool – MW, aerogel-based thermal mortar, and EPS-based thermal mortar), base coat (with cementitious or hydraulic lime binders) and finishing coat (acrylic, silicate, or lime-based). ETICS_1 to ETICS_3, both with thermal insulation boards, are commercially available systems having a European Technical Assessment (ETA) confirming their acceptable performance and suitable quality, in accordance with the requirements of the European guideline EAD 040083-00-0404 [26]. Additionally, ETICS_5, with a thermal mortar, is also available in the market, while ETICS_4 is currently in a prototype phase under investigation. None of the systems with thermal mortars hold an ETA. The detailed composition of the five ETICS is provided in Table 1, based on the information collected from the ETAs (ETICS_1 to ETICS_3) and technical datasheets (ETICS_4 and ETICS_5).

The five ETICS used in this study were manufactured by the respective companies and delivered to our research institution as boards measuring approximately 1000 mm × 1000 mm × thickness. This approach aimed to mitigate any potential deviations in results deriving from the manufacturing of the systems in our lab. Subsequently, the boards were cut into smaller specimens.

Two specimens of each system with dimensions of 150 mm × 150 mm × thickness were exposed outdoors for one year (from July 2022 to June 2023) on the rooftop of a building located on the campus of the National Laboratory for Civil Engineering (LNEC) at an urban area in Lisbon, Portugal (geographical coordinates – 38°45′31″N, 9°08′29″W). ETICS specimens were waterproofed on the four edges and the backside with scotch tape and silicone and then placed on a rack at ~45° of inclination and facing North.

2.2. Test procedures

ETICS performance was assessed by non-destructive tests (i.e., visual and stereomicroscope observations, capillary water absorption, gloss and colour evaluation) carried out on the unaged specimens and after six, nine and twelve months of outdoor ageing. The naturally aged ETICS were collected from the ageing site after those periods of time to be evaluated and tested in the laboratory for approximately one week.

The external surfaces of the ETICS were visually examined using a stereo microscope Olympus SZH10 (Olympus SC30 image acquisition system; Olympus LabSens software) to evaluate the presence of surface anomalies, such as stains, cracks, material loss, etc.

Previous research (e.g., Ref. [76]) showed that gloss reduction and discolouration are among the initial symptoms of coating degradation. Consequently, this study evaluated these aesthetic properties of the ETICS to provide early indications of surface alterations that may be linked to biological colonisation but are not easily discernible to the naked eye in the early stages.

A colorimeter Chroma Meter Minolta CR-410 was used for the colour characterisation (Fig. 2A), considering the CIELAB colour space (L^*, a^*, b^*). L^* is the lightness coordinate and ranges between 0 (black) and 100 (white). a^* and b^* are the green/red and blue/yellow coordinates, respectively. Values for these coordinates range between -a^* (green) and +a^* (red) and between -b^* (blue) and +b^* (yellow). The surfaces of the ETICS were analysed at nine different spots using a grid (Fig. 2B), and with specular component included mode (observer angle = 2°; area of measurement = 50 mm diameter; illuminant = D_{65}).

The global colour difference (ΔE) is obtained using Eq. (1) and considering the initial colour (unaged condition) and the colour after six, nine and twelve months of ageing.

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

Human eyes can discern colour variations under various conditions (illuminant source, observer angle, and human psychological perceptibility). Previous research studies [13,45] established a benchmark for the global colour difference (ΔE) ranging between 2 and 3 CIELAB units as perceptible to humans. The study of Mokrzycki and Tatol [45] concluded that a global colour difference higher than 2 CIELAB units can be detected by an inexperienced observer. Additionally, a recent study [74] investigating the effect of several

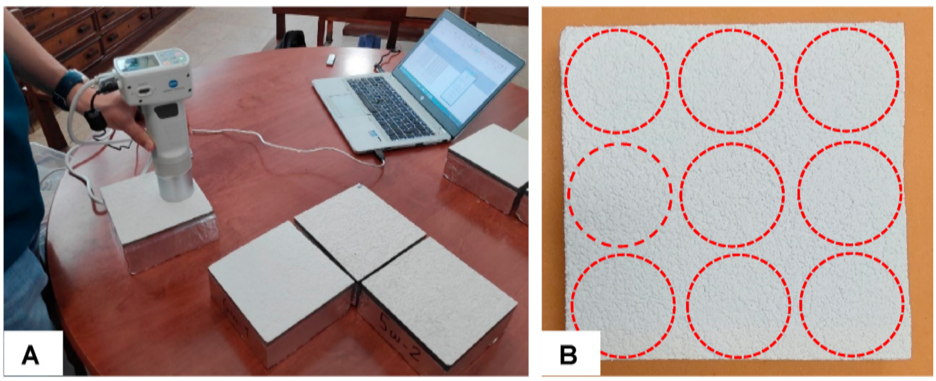

Fig. 2. Colour characterisation test using a colorimeter Chroma Meter Minolta CR-410 (A) and grid on the surface of an ETICS system defining the nine points for the colour assessment (B).

nanoparticles' incorporation on the thermo-optical properties of dark-coloured ETICS facades categorised colour perception into different levels as follows: level 0: $\Delta E \leq 1$ – not perceptible by human eyes; level 1: $1 < \Delta E < 2$ – perceptible upon close observation; level 2: $2 \leq \Delta E \leq 10$ – perceptible at a glance; level 3: $10 < \Delta E \leq 49$ – colours are more similar than opposite; level 4: $\Delta E = 100$ – colours are exact opposites. This scale was derived from a previous study [75] and used in our study to assess the global colour difference.

A specular gloss meter Rhopoint Novo-Gloss Lite was used to evaluate surface gloss. In accordance with previous studies [7,27,77], a measurement geometry of 60° was used. ETICS surfaces were analysed at nine different spots using a grid.

The capillary water absorption was determined in a conditioned room (T = 23 ± 2 °C; RH = 65 ± 5%) following the guideline EAD 040083-00-0404 [26]. After the colorimetric and visual analysis, ETICS specimens were first stored in the same room for mass stabilisation. Then, the finishing coat of each system was placed in direct contact with water, with total submergence of the rendering system (∼3 mm depth). The mass variation of the specimens was monitored after 3 min, 1 h, 2 h, 4 h, 8 h and 24 h of water absorption. Results were analysed taking into account the absorption curves (i.e., mass of absorbed water (kg/m^2) as a function of the square root of time ($min^{0.5}$)) and the coefficient of capillary water absorption (A_w), representing the initial rate of absorbed water (Eq. (2)).

$$A_w = \frac{M_2 - M_1}{A \times \sqrt{3}} \quad (2)$$

where A is the area of the immersed surface (m^2) and M_1 (kg) and M_2 (kg) correspond to the mass of the ETICS at the beginning and after 3 min, respectively.

2.3. Onsite monitoring and meteorological conditions

As previously stated, two specimens of each ETICS were exposed outdoors for one year (from July 2022 to June 2023) on the rooftop of a building in Lisbon, Portugal. Lisbon has a Csa Mediterranean climate, in accordance with the Köppen-Geiger classification, where the weather is characterised by hot and dry summers, mild to cool wet winters and high solar irradiation [81,82]. At the same time (i.e., from July 2022 to June 2023), the surface relative humidity (SRH) and the surface temperature (ST) of the five ETICS were continuously monitored using monolithic IC devices (Honeywell HIH-4000) and T-type thermocouples connected to a datalogger Mezão MZLOG014d_V1R2. However, some problems with the sensor's configuration and position were detected in the beginning of the monitoring campaign, resulting in inconsistent SRH and ST data. After solving these sensor-related difficulties, SRH and ST data for all five ETICS were successfully monitored for nine months, from October 2022 to June 2023. Despite the absence of monitoring data for the initial three months of exposure (i.e., July 2022 to September 2022), it is expected that this did not affect the objectives of the study, as data were obtained for both summer and winter periods (e.g., January 2023 for winter and June 2023 for summer).

The datalogger was set to record averages in 10-min intervals from 1-min readings. According to the technical datasheets, the total accuracy of the IC devices and the thermocouples is ±3.5% RH and ±0.5 °C, respectively. The datasheet of the IC devices indicated that the sensors were calibrated at the factory [72]. However, at the outset of the experimental campaign, all sensors underwent testing in a climatic chamber with constant temperature and relative humidity, demonstrating conformity with the technical specifications. The sensors were attached to the surface of the ETICS specimens, as shown in Fig. 3.

The meteorological data (i.e., air temperature, air relative humidity, precipitation and solar radiation) were also monitored during the full exposure period (i.e., an entire year) using a weather station Vantage Pro2™ Plus (Davis Instruments) installed on the rooftop near the specimens. The collected meteorological data are shown in Fig. 4.

The mean air temperature ranged between 11.8 °C (January 2023) and 24.9 °C (July 2022), and the mean relative humidity between 59% (July 2022) and 90% (December 2022). On the other hand, the mean solar radiation ranged between 50 W/m^2 (December 2022) and 302 W/m^2 (July 2022), with an annual accumulated precipitation of approximately 1063 mm.

Analysis of variance (ANOVA), followed by the Tukey test, was carried out to assess the differences between ETICS considering the

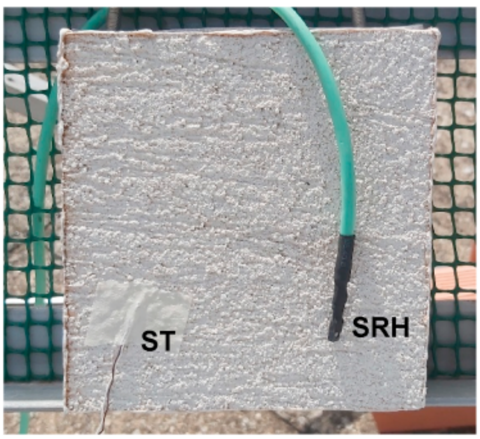

Fig. 3. Example of the placement of the ST and SRH sensors on the surface of the ETICS.

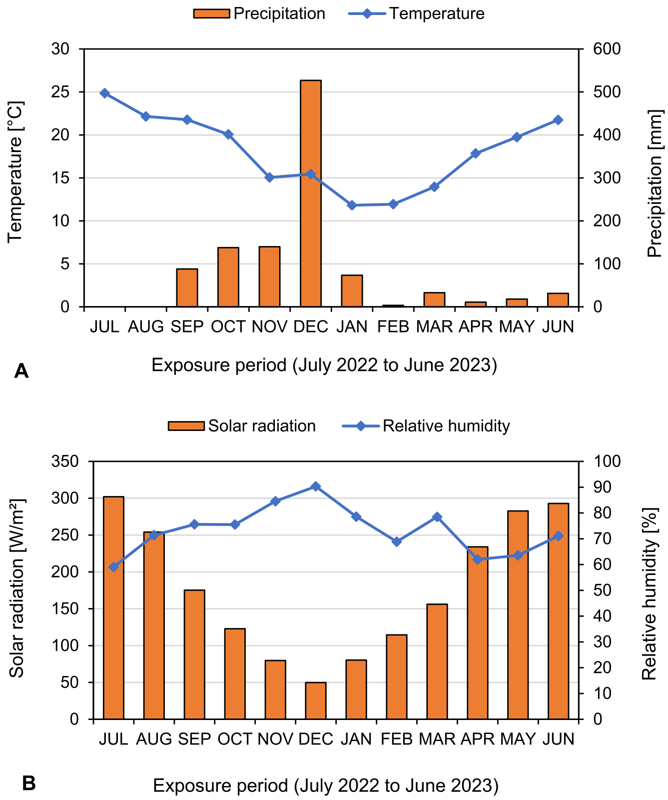

Fig. 4. Meteorological data collected for one year (July 2022–June 2023): monthly mean air temperature and precipitation (A); mean air relative humidity and mean solar radiation (B).

monitored and the simulated results. The statistical analysis was carried out with the software SPSS Statistics V26 from IBM, assuming a significance level $p < 0.05$.

3. Onsite monitoring results

Fig. 5 shows the average results of ST measured during the onsite monitoring period. It can be observed that the highest average ST was measured in the spring and summer and the lowest in the autumn and winter. Moreover, the average results of ST showed considerably higher differences between ETICS in the warmer months of May and June 2023, with the systems with thermal insulating mortars ETICS_4 and ETICS_5 presenting greater ST values.

The average results of SRH measured during the onsite monitoring period are shown in Fig. 6. The highest average SRH for all systems was obtained in December 2022 and the lowest in April 2023. The accumulated values with SRH = 100% point to a greater risk

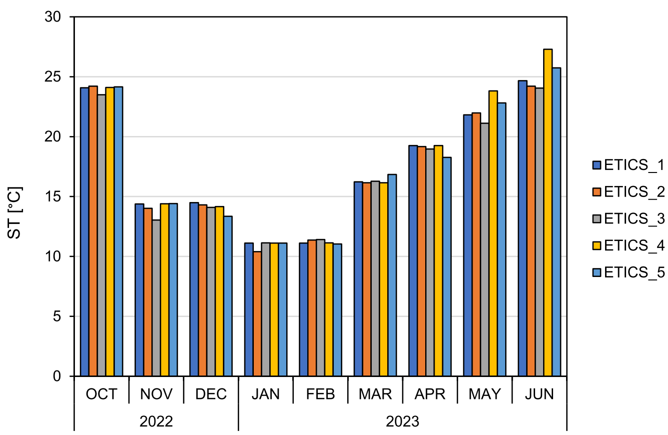

Fig. 5. Average values of surface temperature (ST) measured during the onsite monitoring period (October 2022–June 2023).

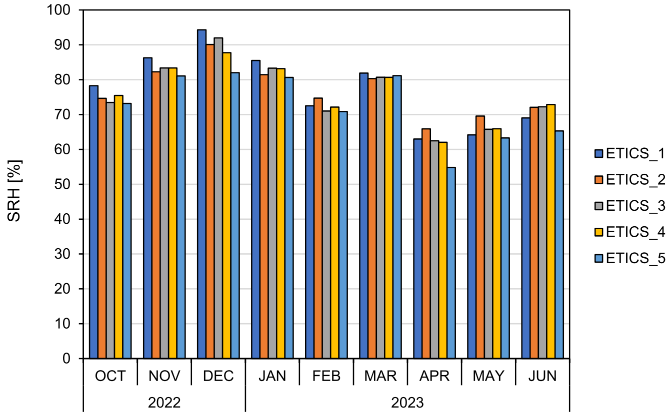

Fig. 6. Average values of surface relative humidity (SRH) measured during the onsite monitoring period (October 2022–June 2023).

of surface condensation during December, January, and March for ETICS_1 and ETICS_3 (Fig. 7). These results contribute to the increased risk of mould growth. In fact, previous research [5,17,18] established that biological growth is largely influenced by high levels of surface moisture content, mostly resulting from surface condensation and wind-driven rain. In countries like Portugal, external surface condensation is particularly significant in comparison to wind-driven rain, as it can occur during all the year, whereas wind-driven rain does not consistently reach the facades, especially during the spring and summer seasons [5]. Therefore, external surface condensation emerges as one of the main factors affecting mould growth on ETICS facades.

The greatest condensation potential was obtained for ETICS_1 (ICB as TI and lime-based RS), totalising more than 1500 h (~63 days) with SRH = 100% during the nine months of monitoring. The second highest amount of condensation (>1100 h) was obtained for ETICS_3 (ICB as TI, lime-based BC and silicate-based FC), followed by ETICS_2 (MW as TI, cement-based BC and acrylic-based FC) with more than 850 h of surface condensation risk. On the other hand, the lowest risk was obtained for ETICS_4 (~780 h) and ETICS_5 (~140 h), both presenting a thermal insulation mortar as TI.

4. Hygrothermal simulation

4.1. Model description and input data

This study used the WUFI Pro 6.7 software to model and compare the hygrothermal behaviour of the different ETICS using relevant hygrothermal properties as input data. The software was developed by the Fraunhofer Institute for Building Physics considering the differential equations for the simultaneous transport of moisture and heat [46]. The model considers three different types of moisture transfer (i.e., liquid transfer by absorption and redistribution, and vapour diffusion) and counts the dynamic outdoor climate (external environment) and the indoor climate (internal environment) as boundary conditions [47]. The temperature and moisture content present in each layer of the ETICS are then calculated for each time step. WUFI Pro software has been validated by several studies (e.g., Refs. [48–51]) and it is widely accepted by the scientific community to study the hygrothermal behaviour of building components.

Fig. 8 shows the model configuration consisting of five different layers from the outside (outdoor environment) to the inside (indoor environment): finishing coat (FC), base coat (BC), thermal insulation board or thermal insulating mortar (TI), substrate (in this case, aerated clay brick) and the internal lime-based plaster. The relevant hygrothermal properties of each ETICS (i.e., FC + BC + TI) were

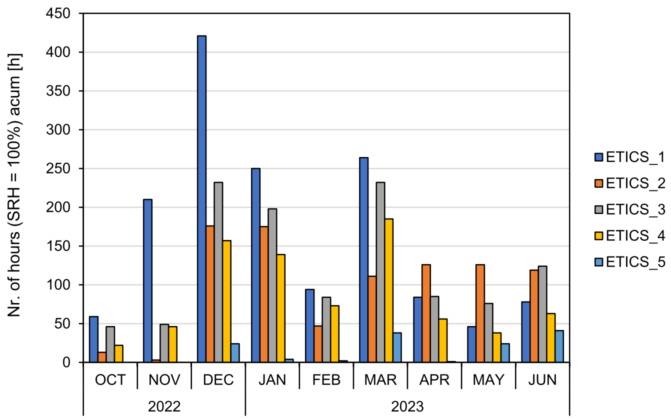

Fig. 7. Total number of hours with (SRH = 100%) during the onsite monitoring period (October 2022–June 2023).

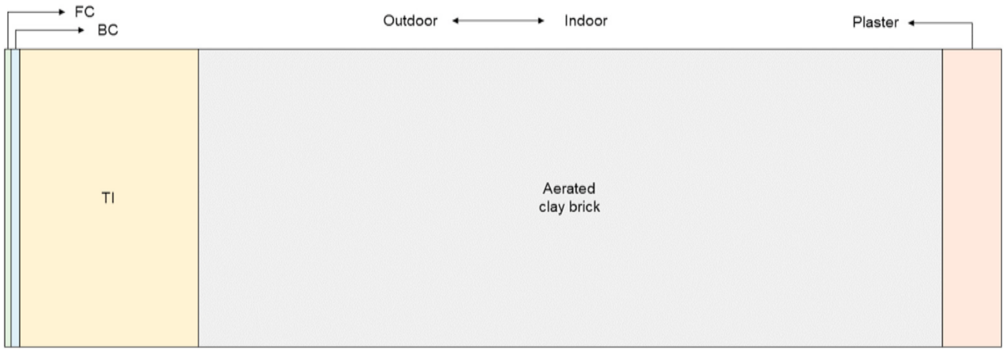

Fig. 8. Model configuration consisting of five different layers: ETICS (layers FC, BC and TI), substrate (aerated clay brick) and the plaster. Note: the composition of each ETICS, including the thickness of the components, is shown in Table 2.

obtained from previous studies by the authors, technical datasheets and the WUFI database (Table 2). The properties of the substrate and the plaster were exclusively collected from the WUFI database.

Hygrothermal simulations were performed considering the outdoor climate dataset of Lisbon, Portugal, available in the WUFI database, with a mean temperature of 15.6 °C, a mean relative humidity of 74.6% and a precipitation total of 675 mm/year. The indoor climate was defined in accordance with the standard EN 15026 [55] considering the WUFI dataset for Lisbon, Portugal. The ETICS facades were North-oriented, where the risk of biological growth is higher [2]. In order to consider the effect of rainwater leakage on the hygrothermal performance of the ETICS, 1% of the wind-driven rain incident on the façade was considered as a moisture source between the thermal insulation and the substrate, in accordance with ASHRAE standard 160 [56]. Moreover, a medium exposure category and a building height lower than 10 m were considered when calculating the wind-driven rain. The simulated ETICS façade was modelled with an inclination of 45° and subject to rain runoff [56]. However, it should be noted that the wind-driven rain effect was not validated in WUFI for inclined elements. Furthermore, a solar absorption coefficient of 0.25 corresponding to a white render was selected for the simulations [52,54]. All simulations were run until reaching dynamic equilibrium.

To evaluate the effect of the hygrothermal behaviour of the ETICS on mould growth, the numerical simulation results were

Table 2
Configuration of the models and input data for the numerical simulations.

Model	Configuration (from outside to inside)
#1	Lime-based FC1 (0.002 m) + lime-based BC1 (0.003 m) + cork insulation board TI1 (0.06 m) + substrate (0.25 m) + lime-based plaster (0.02 m)
#2	Acrylic-based FC2 (0.0015 m) + cement-based BC2 (0.003 m) + mineral wool insulation board TI2 (0.06 m) + substrate (0.25 m) + lime-based plaster (0.02 m)
#3	Silicate-based FC3 (0.001 m) + lime-based BC3 (0.004 m) + cork insulation board TI1 (0.04 m) + substrate (0.25 m) + lime-based plaster (0.02 m)
#4	Acrylic-based FC2 (0.0015 m) + cement-based BC2 (0.003 m) + aerogel-based mortar TI3 (0.04 m) + substrate (0.25 m) + lime-based plaster (0.02 m)
#5	Acrylic-based FC2 (0.0015 m) + cement-based BC2 (0.003 m) + EPS-based mortar TI4 (0.06 m) + substrate (0.25 m) + lime-based plaster (0.02 m)

Property	FC1[1]	FC2[1]	FC3[2]	BC1[3]	BC2[3]	BC3[3]	TI1[3]	TI2[3]	TI3[4]	TI4[5]	Substrate[6]	Plaster[6]
Dry bulk density [kg/m^3]	1617	1200	1617	1617	1300	1050	130	75	165	453	600	1900
Open porosity [−]	0.31	0.37	0.31	0.31	0.36	0.36	0.90	0.95	0.89	0.55	0.77	0.24
Specific heat capacity [J/(kg.K)]	850	850	850	850	850	850	1400	850	669	1000	850	850
Thermal conductivity at dry state [W/(m.K)]	0.700	0.870	0.700	0.700	0.450	0.330	0.040	0.034	0.029	0.042	0.120	0.800
Thermal conductivity – moisture-dependent (water content [kg/m^3]; thermal conductivity [W/(m.K)])	–	–	–	–	–	–	(300; 0.12) (600; 0.3) (900; 0.6)	(300; 0.0959) (600; 0.267) (900; 0.549)	*	**	–	–
Water vapour diffusion resistance factor [−]	106	82	737	18.3	8	8	9	2	5	8	16	19
Water content at 80% RH [kg/m^3]	11.40	9.06	2.55	12.20	15.00	15.00	4.03	4.26	6.00	2.50	4.28	45.00
Free water saturation [kg/m^3]	276.7	366.6	276.7	276.7	192.0	192.0	42.4	44.8	320.0	346.5	188.0	210.0
Capillary water absorption coefficient [kg/(m^2.min$^{0.5}$)]	0.193	0.159	0.034	–	–	–	–	–	–	–	0.123	0.017

Note: Data collected from: [1] technical datasheets, WUFI database, Maia et al. [52] and Parracha et al. [7]; [2] technical datasheets, WUFI database, Parracha et al. [7] and Posani et al. [53]; [3] technical datasheets, WUFI database and Parracha et al. [7]; [4] Maia et al. [54] and Parracha et al. [44]; [5] Maia et al. [52] and Parracha et al. [44]; [6] WUFI database; * Available in Maia et al. [54]; ** Available in Maia et al. [52].

analysed considering different hygrothermal indicators as follows: (i) surface temperature (ST); (ii) surface relative humidity (SRH); (iii) water content in the entire ETICS (W_{ETICS}); and (iv) external condensation risk (CR) through the calculation of the number of hours with RH = 100%.

4.2. Hygrothermal simulation results

Fig. 9 shows the average results of ST obtained considering the simulation period between October 2022 and September 2023.

In accordance with the onsite monitoring results, greater values of average ST were obtained during spring and summer compared to autumn and winter. The highest average ST (~21.5 °C) was obtained for all systems in August, whereas the lowest average ST (8.16 °C) was obtained in January for ETICS_2 (MW as TI, cement-based BC and acrylic-based FC). In fact, there were only small differences in ST between the five simulated ETICS, regardless of the month considered. Indeed, all ETICS have a white-coloured render with the same solar absorption coefficient and were exposed facing North. In accordance with previous studies (e.g., Refs. [5,54]), the factors that most influence the external surface temperature are the wall orientation, the building location and the solar absorption coefficient. In the present study, these factors were kept constant in all simulations. Furthermore, Gonçalves et al. [57] concluded that lower values of ST on the outer surface of the systems can be obtained for ETICS with greater insulation capacity (i.e., lower thermal conductivity). Our results showed no significant differences ($p > 0.05$) of ST between ETICS_4 (with the lowest thermal conductivity) and ETICS_5 (with the highest thermal conductivity). This can be explained by the higher monthly water content registered in the case of ETICS_4 (Fig. 10), potentiating higher values of long-term thermal conductivity and increasing ST [58].

The lowest monthly water content (W_{ETICS}) was obtained for ETICS_2, finished with an acrylic-based FC and with MW as TI, whereas the highest W_{ETICS} was obtained for ETICS_4 (aerogel-based TM, cement-based BC and acrylic-based FC) from October 2022 to February 2023 and ETICS_3 (ICB as TI, lime-based BC and silicate-based FC) from March 2023 onwards. Despite the lower capillary water absorption coefficient of the silicate-based FC (Table 2), system ETICS_3 obtained greater values of W_{ETICS} when compared to systems finished with an acrylic-based FC (ETICS_2 and ETICS_5) or a lime-based mortar (ETICS_1), especially after December 2022. This result can be explained by the significantly lower water vapour permeability of the silicate-based FC (Table 2), affecting the drying kinetics of the system. This finding reinforces the importance of a favourable balance between capillary absorption and drying to guarantee hygric compatibility and to decrease the risk of biological colonisation [44,51]. It is important to note that the results shown in Fig. 10 represent the monthly water content within the ETICS, representing the balance between water absorption and drying kinetics.

Fig. 11 shows the average values of surface relative humidity for the simulation period between October 2022 and September 2023. The highest average SRH for all systems was obtained in February and the lowest in August. In accordance with the results of ST, only small differences of SRH were detected between the five simulated ETICS, regardless of the month considered.

Fig. 12 presents the accumulated number of hours per month with SRH = 100%. It can be observed that the greatest values were registered in the month of February, showing an increased risk of surface condensation. On the other hand, in the period between May 2023 and September 2023 the SRH rarely reached 100%. In fact, the risk of surface condensation is much higher in the colder months, with greater values of relative humidity. In the period between December 2022 and April 2023, the ETICS with thermal insulation boards (ETICS_1 to ETICS_3) obtained the highest number of hours with SRH reaching 100% and therefore greater risk of surface condensation when compared to the ETICS with thermal insulating mortars. The results can be possibly explained by the higher long-term thermal conductivity and density of the thermal mortars when compared to the thermal insulation boards, reducing the undercooling phenomenon during the night, and consequently the risk of surface condensation.

5. Onsite monitoring results *VS* hygrothermal simulation results

Similar trends can be observed when comparing the numerical and monitored results, with the highest average ST measured in the spring and summer and the lowest in the autumn and winter. However, the monitored ST results were significantly higher ($p < 0.05$) compared to the numerical results, especially in the warmer months. Additionally, except for ETICS_5 (with an EPS-based thermal

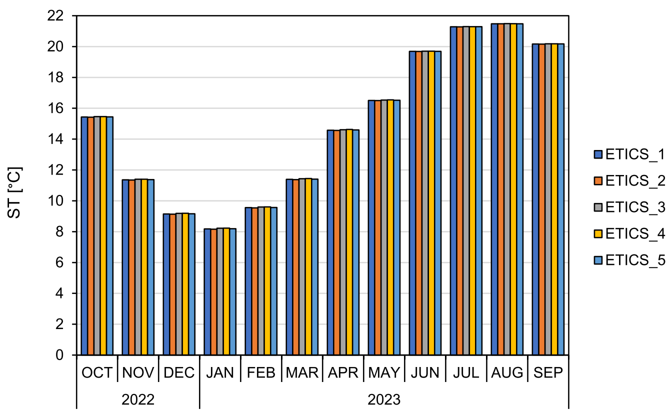

Fig. 9. Average values of surface temperature (ST) obtained for one-year simulation period (October 2022–September 2023).

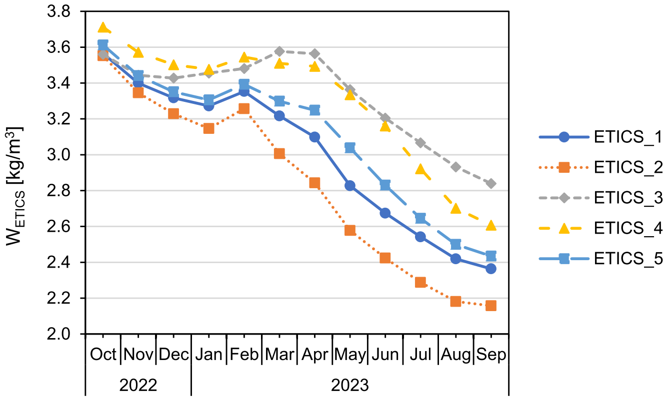

Fig. 10. Monthly water content in the ETICS (W_{ETICS}) obtained for one-year simulation period (October 2022–September 2023).

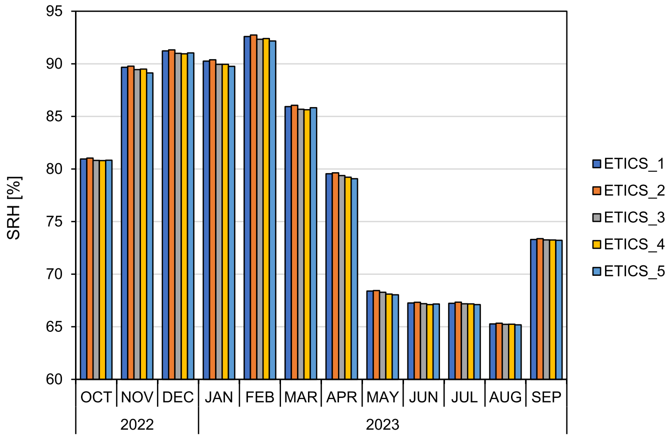

Fig. 11. Average values of surface relative humidity (SRH) obtained for one-year simulation period (October 2022–September 2023).

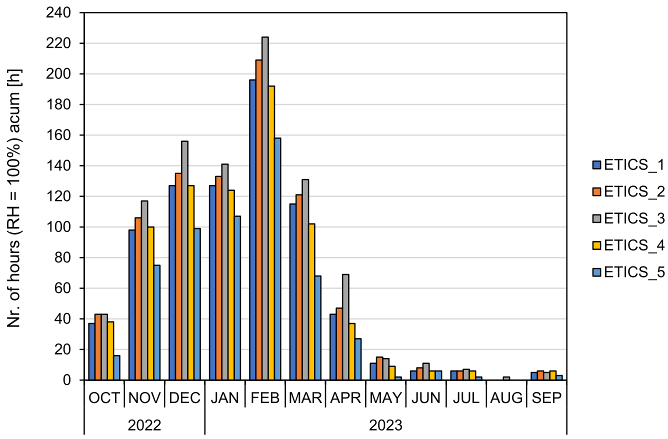

Fig. 12. Total number of hours with (RH = 100%) during one-year simulation period (October 2022–September 2023).

mortar as TI), significantly lower values of accumulated number of hours with SRH = 100% were numerically obtained ($p < 0.05$) (Fig. 13). These discrepancies between the monitored and simulated results can be attributed to different assumptions made during the simulations, the lack of validation for the effect of wind-driven rain in WUFI software for inclined elements, and variations in the set of outdoor climate data used in the simulations.

Considering the climate dataset, a significantly higher annual mean temperature (18.0 °C) was recorded during the exposure period (Fig. 4A) compared to the mean temperature obtained from the outdoor weather file (15.6 °C) in the WUFI database for Lisbon,

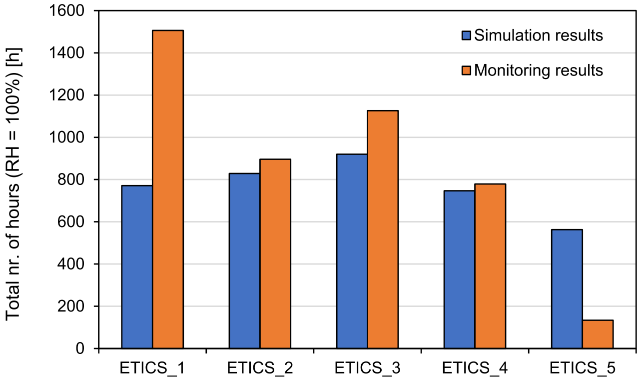

Fig. 13. Accumulated number of hours with (SRH = 100%) during the nine months of exposure.

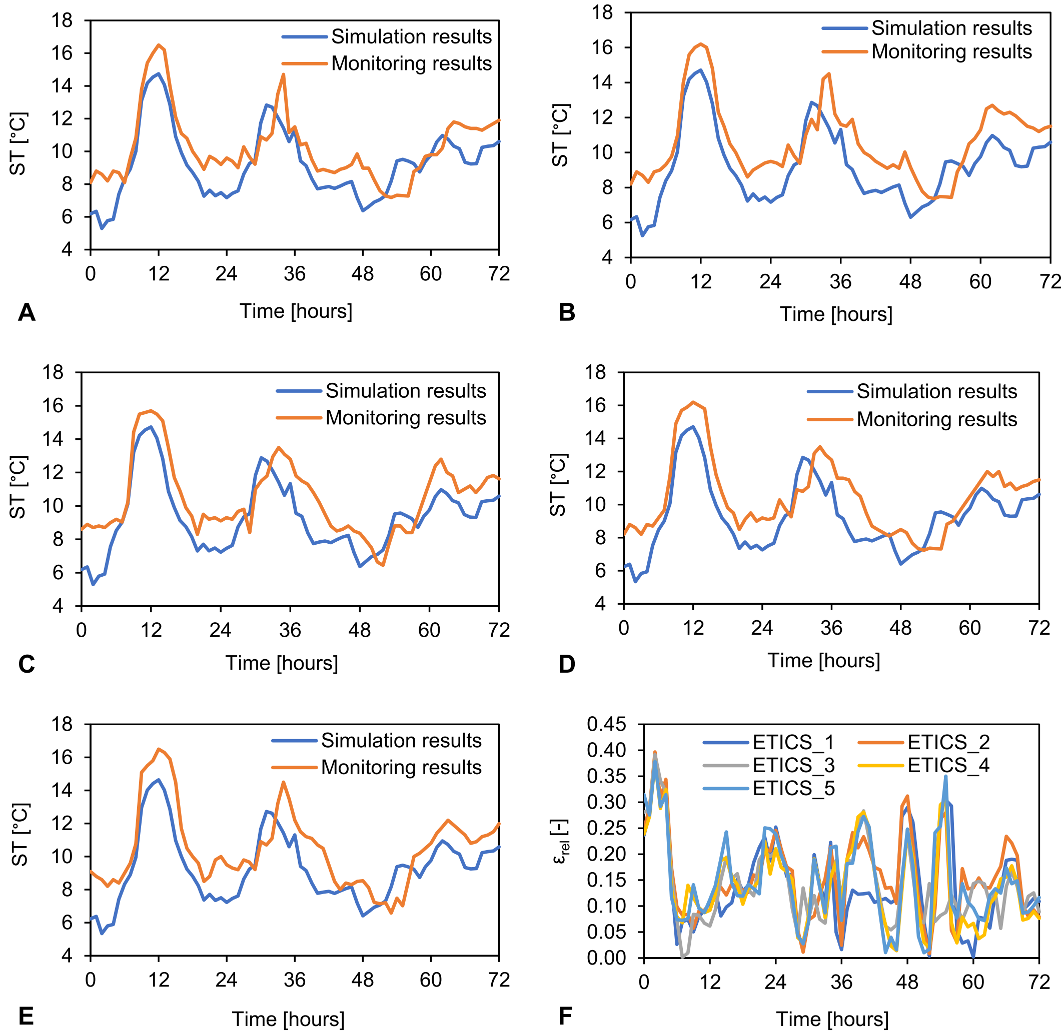

Fig. 14. Onsite monitoring and numerical results of ST for a representative period of February 2023: ETICS_1 (A), ETICS_2 (B), ETICS_3 (C), ETICS_4 (D) and ETICS_5 (E), and relative errors between onsite monitoring and numerical results for the same period (F).

Portugal. With regard to the wind-driven rain effect, the lack of validation in the WUFI software could significantly influence the simulation results of surface temperature (ST). In fact, previous studies [58,71] have established that rain incidence can notably contribute to the reduction of ST.

In Fig. 14, both onsite monitoring and numerical results of ST are presented for a representative period in February 2023. The results showed that, even during colder months such as February, the monitored ST for all systems tends to be higher compared to the simulated ST. This trend can be attributed to the elevated air temperatures registered during the exposure period, surpassing those in the input dataset from WUFI used for the simulations. Fig. 14F shows the relative errors of ST between onsite monitoring and numerical results during the representative period. As observed, the typical relative error for all systems ranges from 0.05 to 0.25, with values reaching up to 0.40.

The results shown in Fig. 14 indicate negligible differences between the five ETICS systems considering the hygrothermal simulation results, with ST values ranging between 5.3 °C and 14.7 °C. Indeed, regardless of the month considered, these trends between systems were anticipated, given that all ETICS have white-coloured renders with the same solar absorption coefficient and were exposed in the same cardinal direction (i.e., North). Consistent with prior research [5,54], the main factors influencing ST include wall orientation, building location, and solar absorption coefficient, all of which remained constant throughout the hygrothermal simulations. Conversely, slight differences of ST were obtained between systems considering the onsite monitoring results, with values ranging between 6.4 °C and 16.3 °C (Fig. 14).

Fig. 15 shows the onsite monitoring and numerical results of SRH during a representative period in March 2023. It can be observed that the numerical SRH results generally exceed those obtained through onsite monitoring. This difference can be attributed to both the lower air RH registered during the exposure period compared to the climatic data input of WUFI for Lisbon and the position of the RH

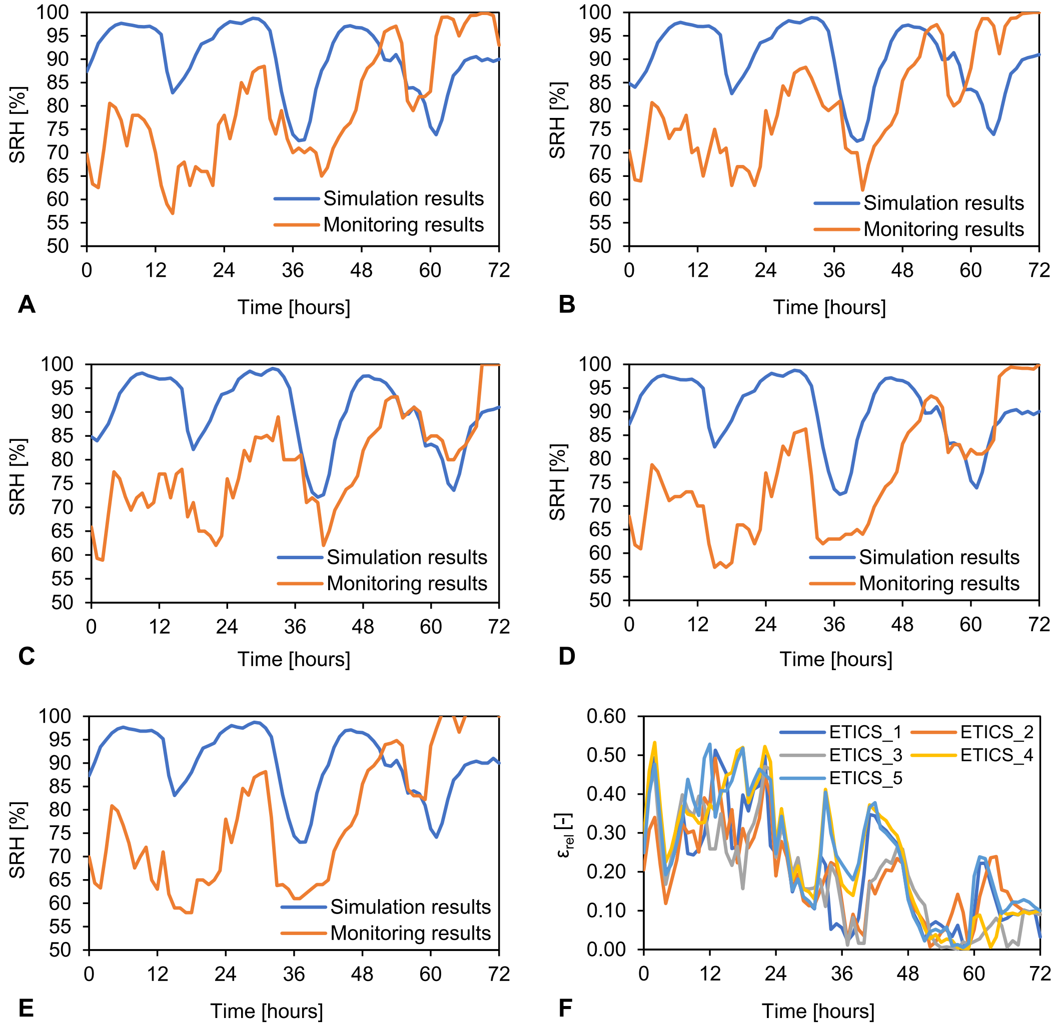

Fig. 15. Onsite monitoring and numerical results of SRH for a representative period of March 2023: ETICS_1 (A), ETICS_2 (B), ETICS_3 (C), ETICS_4 (D) and ETICS_5 (E), and relative errors between onsite monitoring and numerical results for the same period (F).

sensors in the ETICS specimens. In fact, the sensors were positioned as close as possible to the surface, but not entirely attached due to their sensitivity to condensation, possibly leading to a slight decrease in the measured SRH value. The relative errors of SRH between onsite monitoring and numerical results are shown in Fig. 15F, revealing a typical range of 0 to 0.40 for all systems, with some values reaching up to 0.53.

6. Experimental results

Visual and stereomicroscope observations performed after six months of outdoor exposure confirmed the presence of dirt deposition (Fig. 16A) and microcracking (Fig. 16B) on the surface of the ETICS. Moreover, the surfaces become considerably more yellowish, especially in the case of systems with ICB as thermal insulation (Fig. 17B). After nine months of outdoor exposure (March 2023), some bio-colonisation stains were visually observed on the surface of ETICS_1 (with ICB TI and finished with a lime-based RS) (Fig. 17C). Additionally, surface condensation was observed in all ETICS in the early morning periods since the beginning of the exposure, being more pronounced in the case of ETICS_1 and ETICS_3 (ICB as TI, lime-based BC and silicate-based FC).

Fig. 18 shows the capillary water absorption curves of each system in the unaged state and after six, nine and twelve months of outdoor ageing. The capillary absorption of the unaged ETICS (with thermal mortars and insulation boards) was lower than 1 kg/m^2 after 1 h testing for all specimens, in agreement with the requirement defined in the European guideline EAD 040083-00-0404 [26]. In fact, with the exception of ETICS_1 (~0.9 kg/m^2), all specimens obtained a capillary absorption in the unaged state lower than 0.65 kg/m^2 after 1 h. The lowest long-term capillary absorption (i.e., after 24 h testing) in the unaged state was obtained for ETICS_3 (ICB as TI, lime-based BC and silicate-based FC) and the highest for ETICS_2 (MW as TI, cement-based BC and acrylic-based FC).

Different trends of capillary water absorption can be observed after natural ageing (Fig. 18). In the case of the lime-based ETICS_1, results showed that capillary absorption increases with exposure time (Fig. 18A), achieving approximately 2.5 kg/m^2 of absorbed water (at the end of the test) after one year of ageing. This trend is mainly attributed to the occurrence of surface microcracking and surface wear caused by ageing. On the other hand, a decrease in water absorption was registered for the acrylic-based ETICS_2 after six and nine months of outdoor exposure, followed by an increase after twelve months (Fig. 18B). These variations between systems can be primarily attributed to the composition of the finishing coats (Table 1). ETICS_1 has an air lime-based finishing coat with a hydraulic binder and organic additives, while ETICS_2 has an acrylic-based finishing coat containing mineral aggregates and additives providing hydrophobic properties to the system. Moreover, the decrease in the water absorption of the acrylic-based system ETICS_2 after six and nine months of ageing was previously attributed to a possible reduction of the capillary pores of the render [27]. In fact, the combination of leaching, carbonation and dissolution-recrystallization processes of $CaCO_3$ with ageing can facilitate a reduction of the capillary pores, thereby enhancing the compactness and stiffness of the acrylic-based render [78–80].

Furthermore, a slight increase of capillary water absorption was obtained for the silicate-based system ETICS_3, most probably due to the surface microcracking observed after ageing. Nevertheless, results tend to stabilise after six months of outdoor exposure, with no significant differences registered in the capillary absorption obtained after 6-, 9-, and 12-months of ageing (Fig. 18C).

Concerning the ETICS with a thermal insulating mortar (Fig. 18D and E), results showed a significant increase of capillary water absorption after natural ageing, especially for the acrylic-based system with an aerogel-based mortar ETICS_4 (Fig. 18D). In this latter case, the capillary water absorption values at the end of the test increase between 221% (after six months ageing), 630% (after nine months ageing) and 704% (after one-year ageing) when compared to the unaged values. The results showed that the finishing coats can no longer effectively protect the aged ETICS against liquid water penetration. Considering that thermal insulating mortars absorb more water by capillarity compared to thermal insulation boards, the loss of hydrophobicity of the finishing coats caused by several reasons, such as microcracking or surface wear, will be more relevant in the case of ETICS with a mortar as thermal insulation.

The systems with thermal mortars exhibited the highest levels of capillary water absorption after one year of natural ageing, thereby increasing the risk of biological colonisation and compromising the long-term thermal performance of the ETICS [44]. These results were attributed to greater water absorption of the thermal mortars compared to the insulation boards, together with the

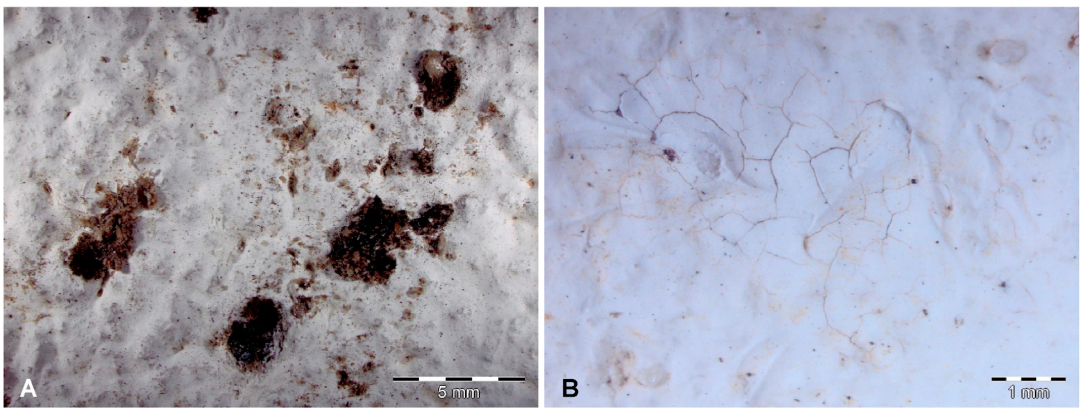

Fig. 16. Stereo microscope images showing dirt deposition on the surface of ETICS_2 after six months of outdoor exposure (A); and microcracking and yellow stains on the surface of ETICS_3 after six months of exposure (B).

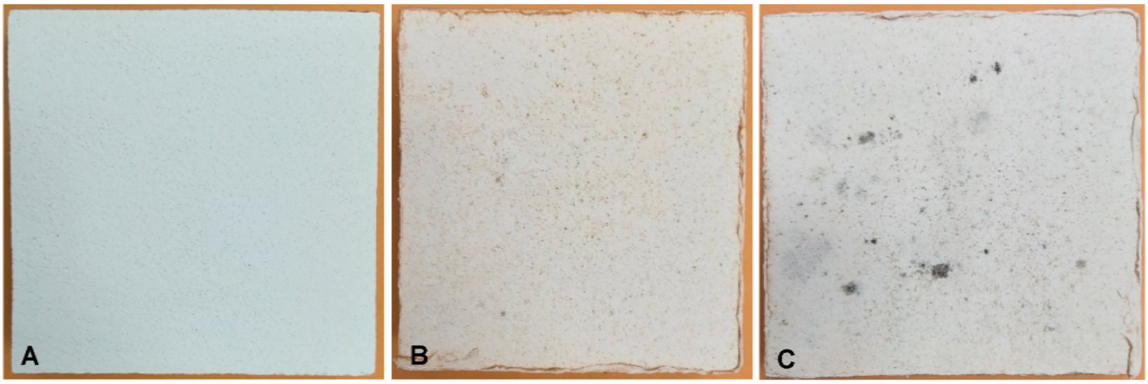

Fig. 17. Photographs of the unaged surface of ETICS_1 (A); yellowish surface of ETICS_1 after six months of exposure (B); and bio-colonisation stains detected on the surface of ETICS_1 after nine months of exposure (C).

significant degradation observed on the systems surface after ageing, characterised by extensive surface microcracking. In fact, surface microcracks can contribute to increase the water absorption within the systems and increase the risk of biological colonisation, serving as potential entry points for water and facilitating the accumulation of dirt and dust, which in turn provide favourable conditions for fungal development [16,73]. This scenario can be exacerbated in cases where the cracked renders contain noticeable amounts of organic additives [20], as seen in the case of ETICS_1 (Table 1). Conversely, the silicate-based ETICS_3 demonstrated the lowest long-term capillary water absorption, registering values below 1 kg/m^2 after one year of ageing (Fig. 18C). This indicates a reduced risk of biological colonisation over time.

The results of the coefficient of capillary water absorption (A_w) obtained before and after ageing are shown in Fig. 19.

A_w represents the rate of absorbed water in the first 3 min of test, with the objective of providing some indication of the water absorption of the rendering system. The highest A_w was obtained for the lime-based ETICS_1, especially after one year of ageing and in accordance with the results of the capillary absorption curves. The acrylic-based ETICS_2 and the silicate-based ETICS_3 obtained significantly lower values of Aw. ETICS_2 presented a significant decrease of Aw after six and nine months of exposure, followed by an increase after twelve months, which is also in line with the results of the absorption curves (Fig. 18B). For ETICS_3, the A_w was slightly lower after six and nine months of ageing and rather similar to the unaged performance after twelve months of exposure. Therefore, this latter system presented the best long-term capillary water performance. Finally, a significant increase of A_w after ageing was also obtained for the systems with a thermal mortar (ETICS_4 and ETICS_5).

Results of surface gloss obtained before and after ageing are shown in Fig. 20. A decrease of gloss can be observed after ageing for all systems, being more pronounced in the lime-based ETICS_1. In fact, the surface gloss values obtained for the acrylic-based systems (ETICS_2, ETICS_4, and ETICS_5) are considerably lower compared to those obtained for the lime-based ETICS_1 or silicate-based ETICS_3, regardless of the ageing duration (i.e., 0, 6, 9, or 12 months).

The results of the colorimetric coordinates (L*, a*, b*) obtained before and after ageing are shown in Fig. 21. A significant decrease of lightness (L*) was observed after ageing in all systems, indicating a darker tone of the surface possibly due to dirt deposition. Moreover, it can be noted that acrylic-based systems become considerably darker (lower L* values) when compared to the silicate-based and lime-based systems (ETICS_3 and ETICS_1) (Fig. 21A). In fact, acrylic-based systems presented a significantly darker tone right after six months of outdoor exposure, followed by a less marked decrease after nine months of outdoor ageing.

A significant increase of a* (i.e., a more reddish colouration) was registered after six months of exposure for all systems. The highest a* increase was also obtained for the acrylic-based systems when compared to the silicate-based or lime-based systems (Fig. 21B), possibly due to the greatest surface roughness of the acrylic renders facilitating dirt accumulation [13,27]. Furthermore, all systems gained a considerably yellowish tone (higher b*) after six months of ageing (Fig. 21C). A stabilisation of the yellow colour was then detected, with no significant differences registered after that period ($p > 0.05$). The highest b* increase was registered for the acrylic-based systems, in accordance with the results of lightness (L*) and a* coordinate.

Finally, a global colour difference higher than 2 CIELAB units (Fig. 22) was obtained for all systems after six months of outdoor exposure. The results confirmed that aesthetic alteration can be detected by an inexperienced observer [45] and is perceptible at a glance [74]. It can be concluded that the highest aesthetic alteration (higher ΔE) was observed on the surface of the acrylic-based system ETICS_4, with $\Delta E > 10$ indicating that colours are more similar than opposite [75]. On the other hand, the lowest ΔE was registered on the surface of the silicate-based system ETICS_3, with values lower than 4 CIELAB units (i.e., colour difference can be perceptible at a glance).

In summary, the acrylic-based systems with thermal insulating mortars (ETICS_4 and ETICS_5) exhibited the highest levels of capillary water absorption after one year of outdoor exposure. These acrylic-based systems, along with ETICS_2, also experienced significant darkening compared to lime-based (ETICS_1) or silicate-based (ETICS_3) systems, attributable to increased surface roughness facilitating the accumulation of dirt and dust on the surfaces. Conversely, the silicate-based system (ETICS_3) obtained the lowest capillary water absorption, with a slight increase observed after one year of natural ageing. Additionally, this system presented the lowest aesthetic alteration (i.e., gloss and colour variation) after ageing. Finally, the system finished with a lime-based mortar

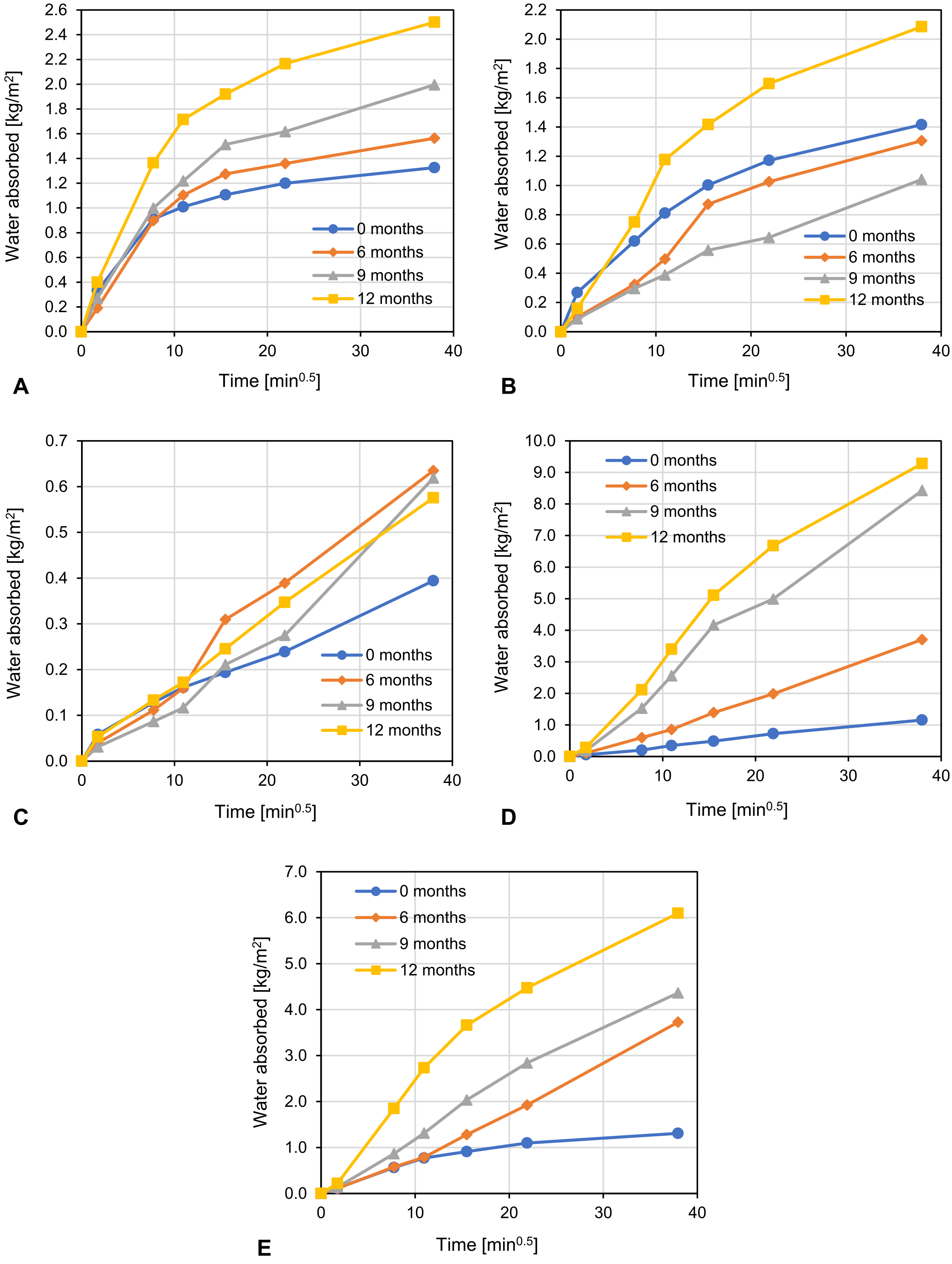

Fig. 18. Capillary water absorption curves of ETICS_1 (A), ETICS_2 (B), ETICS_3 (C), ETICS_4 (D) and ETICS_5 (E) in the unaged state and after 6, 9 and 12 months of outdoor exposure.

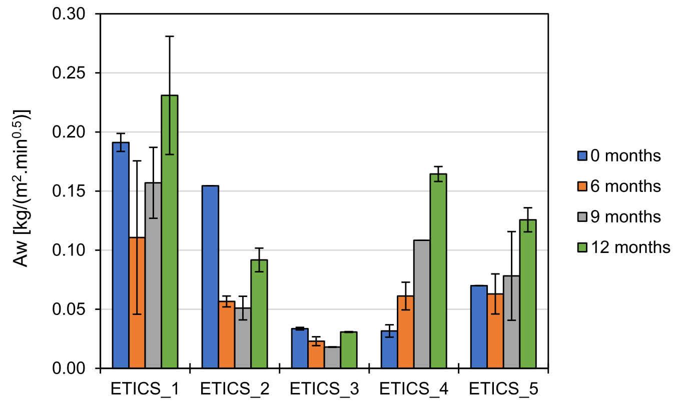

Fig. 19. Capillary water absorption coefficient of the ETICS before and after ageing (average values and relative standard deviation).

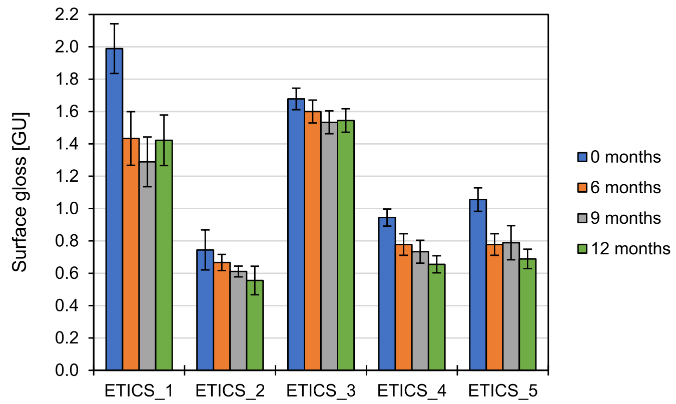

Fig. 20. Surface gloss of the ETICS before and after ageing (average values and relative standard deviation).

(ETICS_1) presented higher capillary water absorption after ageing, along with some stains possibly of biological origin observed after nine months of outdoor exposure in an urban environment.

7. Biological colonisation assessment

7.1. Onsite observations

Biological colonisation on the surface of two specimens of the different ETICS was visually assessed after six, nine and twelve months of exposure with the help of a stereo microscope Olympus SZH10 (Olympus SC30 image acquisition system; Olympus LabSens software). The rate of mould growth was classified using the scale defined in Parracha et al. [7]: 0 – no apparent growth (0% of contaminated surface); 1 – traces of growth (<10% of contaminated surface); 2 – light growth (10 to 30% of contaminated surface); 3 – moderate growth (30 to 60% of contaminated surface); and 4 – heavy growth (>60% of contaminated surface). The specimens were always rated by the same experienced observer.

7.2. Theoretical indices

In this study, three theoretical indices were applied using experimentally and numerically obtained values of ST and SRH as input to provide an indication of the risk of mould growth. The results were expressed as the average percentage of monthly hours during which specific ST and SRH conditions were observed. According to previous studies [5,10,17–20] the risk of mould growth is influenced by moisture levels, temperature, nutrient availability and time. The nutrient availability was not considered in this analysis.

Index 1 is a simple index commonly used for the indoor assessment of mould growth [40] and also applied by Johansson et al. [10] for building facades. It consists of the percentage of time for which the SRH is equal to or higher than 80%. It is worth noting that a minimum threshold value of 70-80% RH is generally considered for mould growth in buildings [59].

Previous studies have shown that external surface condensation is one of the most relevant factors affecting mould growth on ETICS [5,18,60]. Therefore, index 2 represents the external surface condensation risk, which is calculated by considering the percentage of time for which the SRH equals 100% [54].

Finally, index 3 considers the influence of both SRH and ST and represents the percentage of time for which SRH is equal to or higher than 80% and ST is between 15 °C and 30 °C. According to Sedlbauer [32] the optimum air temperature for mould growth is set

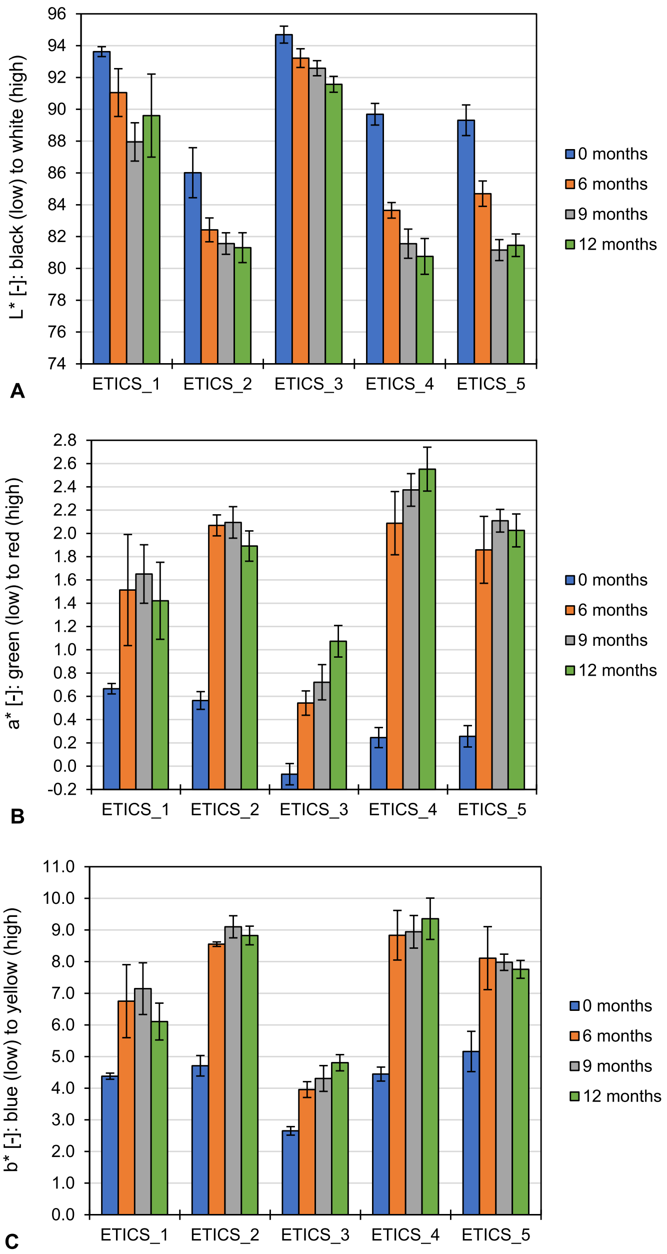

Fig. 21. Colorimetric coordinates L* (A), a* (B) and b* (C) of the ETICS before and after ageing (average values and relative standard deviation).

between 20 °C and 30 °C, with ideal values registered in the range of 25-30 °C [61].

7.3. Results

The results of the percentage of time for which the SRH is equal to or higher than 80% (index 1) considering the monitoring and simulation inputs are presented in Table 3.

It can be noticed that higher values of index 1, thus more favourable to mould development, were obtained between November 2022 and February 2023 with the simulation inputs. On the other hand, the lowest results of index 1 were obtained between May 2023 and August 2023, regardless of the type of ETICS considered and in accordance with the average numerical SRH results (Fig. 11). In fact, the average index 1 obtained during the one-year simulation period is the same for the five ETICS (i.e., 58% of the year with SRH ≥80%). When considering the index 1 values obtained with the monitoring inputs, results showed significantly higher values of index 1 during December 2022, except for the acrylic-based system ETICS_5 (with an EPS-based thermal mortar as TI). The average results of the index 1 were slightly higher considering the simulation inputs, thus leading to a more conservative scenario. Moreover, the results of index 1 were considerably higher during the night for all systems when lower values of ST were also obtained. Nevertheless, index 1

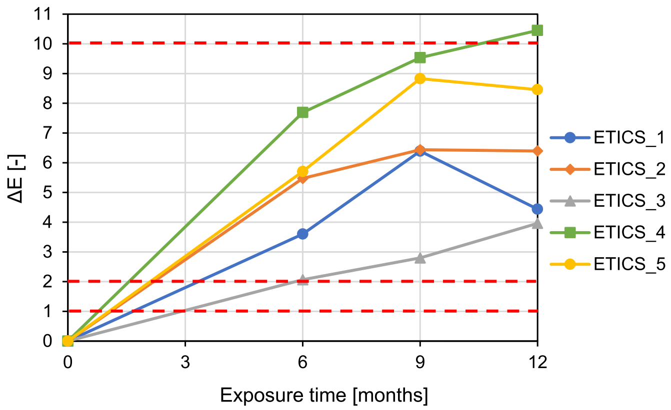

Fig. 22. Global colour difference after outdoor ageing. Note: the connection between the points is not a fitting result and only intends to provide a better visualisation of their position throughout the natural ageing.

Table 3
Matrix of risk (index 1 – percentage of time for which the SRH is equal to or higher than 80%).

		Index 1: % of time with SRH ≥ 80%									
		ETICS_1		ETICS_2		ETICS_3		ETICS_4		ETICS_5	
		Simulation results	Monitoring results	Simulation results	Monitoring results	Simulation results	Monitoring results	Simulation results	Monitoring results	Simulation results	Monitoring results
2022	Oct	54%	54%	54%	48%	54%	49%	54%	52%	54%	50%
	Nov	82%	71%	82%	54%	81%	67%	81%	67%	82%	63%
	Dec	87%	86%	87%	81%	86%	85%	87%	74%	87%	59%
2023	Jan	86%	63%	87%	60%	86%	59%	86%	58%	86%	59%
	Feb	88%	33%	88%	37%	87%	34%	88%	36%	88%	32%
	Mar	68%	58%	68%	61%	67%	59%	67%	61%	68%	57%
	Apr	55%	32%	55%	35%	54%	32%	54%	34%	54%	27%
	May	38%	36%	38%	39%	38%	36%	37%	37%	37%	34%
	Jun	37%	31%	38%	40%	37%	39%	37%	43%	36%	35%
	Jul	35%		36%		35%		35%		35%	
	Aug	26%		27%		26%		26%		26%	
	Sep	41%		41%		40%		40%		40%	
Average (Oct 2022 – Jun 2023)		66%	51%	66%	51%	66%	51%	66%	51%	66%	46%

Legend: index 1 < 40% - green colour (low risk); 40% ≤ index 1 < 70% - yellow colour (medium risk); index 1 ≥ 70% - red colour (high risk). Grey cells – not measured.

does not consider the effect of temperature, thus, it is only meaningful when applied for the study of indoor environments with more constant ST values [10,28]. Considering the effects of the fluctuating climatic conditions, high values of SRH can be associated with very low values of ST, thus limiting mould growth [10].

The results of the percentage of time for which the SRH equals 100% (index 2) considering the monitoring and simulation inputs are presented in Table 4. It can be observed that results are significantly different between each other, with remarkably low values obtained for all systems with the simulation results as input. Additionally, during the nine months of monitoring, the highest index 2 was registered in December 2022 for ETICS_1 (with ICB TI and finished with a lime-based RS), increasing the risk of surface condensation and, therefore, the risk of bio-colonisation [5,27]. Regarding the average results of the index 2 of the five ETICS along the nine months of monitoring, the highest percentage of time (25%) with SRH = 100% was obtained for the lime-based ETICS_1, whereas the lowest (4%) was registered for the acrylic-based ETICS_5.

The results of index 3 (i.e., percentage of time with SRH ≥80% and 15 °C ≤ ST ≤ 30 °C) clearly show the influence of the temperature on the assessment of the mould growth risk (Table 5). When considering the simulation inputs, the results of index 3 were significantly higher in the autumn and summer, with values lower than 10% observed in the spring and winter due mostly to the lower ST values registered in that period (Fig. 6). In accordance with the results of indices 1 and 2, there were no significant differences in the average index 3 obtained for the five ETICS with the simulation results as input. On the other hand, considering the monitoring results, the highest average index 3 (18%) was obtained for the lime-based ETICS_1 and the lowest (12%) for the acrylic-based system with an

Table 4
Matrix of risk (index 2 – percentage of time for which the SRH equals 100%).

		Index 2: % of time with SRH = 100%									
		ETICS_1		ETICS_2		ETICS_3		ETICS_4		ETICS_5	
		Simulation results	Monitoring results	Simulation results	Monitoring results	Simulation results	Monitoring results	Simulation results	Monitoring results	Simulation results	Monitoring results
2022	Oct	5%	10%	6%	2%	6%	8%	5%	4%	2%	3%
	Nov	13%	29%	15%	0%	16%	7%	14%	7%	10%	0%
	Dec	17%	59%	18%	25%	21%	31%	17%	23%	14%	3%
2023	Jan	17%	37%	18%	26%	19%	30%	17%	21%	15%	3%
	Feb	27%	12%	29%	6%	31%	11%	26%	9%	22%	0%
	Mar	16%	39%	17%	30%	18%	34%	14%	28%	9%	14%
	Apr	6%	12%	6%	18%	9%	13%	5%	8%	4%	0%
	May	2%	6%	2%	17%	2%	10%	1%	5%	0%	3%
	Jun	1%	16%	1%	21%	2%	21%	1%	11%	1%	7%
	Jul	1%		1%		1%		1%		0%	
	Aug	0%		0%		0%		0%		0%	
	Sep	1%		1%		1%		1%		0%	
Average (Oct 2022 – Jun 2023)		12%	25%	12%	16%	14%	18%	11%	13%	9%	4%

Legend: index 2 < 10% - green colour (low risk); 10% ≤ index 2 < 30% - yellow colour (medium risk); index 2 ≥ 30% - red colour (high risk). Grey cells – not measured.

Table 5
Matrix of risk (index 3 – percentage of time for which the SRH is equal to or higher than 80% and ST is between 15 °C and 30 °C).

		Index 3: % of time with SRH ≥ 80% and 15 ºC ≤ ST ≤ 30 ºC									
		ETICS_1		ETICS_2		ETICS_3		ETICS_4		ETICS_5	
		Simulation results	Monitoring results	Simulation results	Monitoring results	Simulation results	Monitoring results	Simulation results	Monitoring results	Simulation results	Monitoring results
2022	Oct	23%	47%	23%	43%	24%	37%	24%	50%	23%	46%
	Nov	4%	6%	4%	5%	4%	3%	4%	8%	4%	7%
	Dec	1%	10%	1%	9%	1%	8%	1%	9%	1%	4%
2023	Jan	2%	8%	2%	6%	2%	8%	2%	9%	2%	2%
	Feb	3%	2%	3%	3%	3%	1%	3%	2%	3%	0%
	Mar	6%	18%	6%	12%	6%	16%	6%	17%	6%	8%
	Apr	5%	9%	5%	11%	4%	9%	4%	9%	4%	4%
	May	2%	19%	2%	20%	2%	19%	2%	19%	2%	10%
	Jun	14%	41%	14%	35%	14%	37%	14%	24%	14%	32%
	Jul	18%		18%		18%		18%		18%	
	Aug	17%		18%		18%		18%		18%	
	Sep	29%		29%		29%		29%		30%	
Average (Oct 2022 – Jun 2023)		7%	18%	7%	16%	7%	15%	7%	16%	7%	12%

Legend: index 3 < 10% - green colour (low risk); 10% ≤ index 3 < 30% - yellow colour (medium risk); index 3 ≥ 30% - red colour (high risk). Grey cells – not measured.

EPS-based mortar (ETICS_5), thus in accordance with the results of index 2. The highest values of index 3 for all systems were registered in the months of October 2022 and June 2023.

Table 6 presents the results of the average rate of mould growth on the surface of two specimens of the different ETICS after six, nine, and twelve months of outdoor exposure. Traces of mould growth (<10% of contaminated surface) were first observed on the surface of the lime-based ETICS_1 after six months of exposure (Fig. 23A and B). The percentage of contaminated surface continued to increase in this system after nine and twelve months, with one specimen rated as 3 (moderate growth – 30 to 60% of contaminated surface) after one year of exposure (Fig. 23C and D). In fact, the lime-based ETICS_1 has no biocide in the FC layer and is composed of an insulation cork board as TI and also a BC with cork aggregates included as additive. Therefore, the aged system is more susceptible

Table 6
Mould growth on the surface of the ETICS after six, nine and twelve months of outdoor exposure.

System	Nr. of specimen	Exposure time		
		6 months	9 months	12 months
ETICS_1	1.1	1	2	3
	1.2	1	2	2
ETICS_2	2.1	0	0	1
	2.2	0	1	1
ETICS_3	3.1	0	0	0
	3.2	0	0	0
ETICS_4	4.1	0	1	1
	4.2	1	1	1
ETICS_5	5.1	1	1	1
	5.2	0	0	1

Rating scale: 0 – no apparent growth (0% contaminated surface); 1 – traces of growth (<10% contaminated surface); 2 – light growth (10 to 30% contaminated surface); 3 – moderate growth (30 to 60% contaminated surface); 4 – heavy growth (>60% contaminated surface).

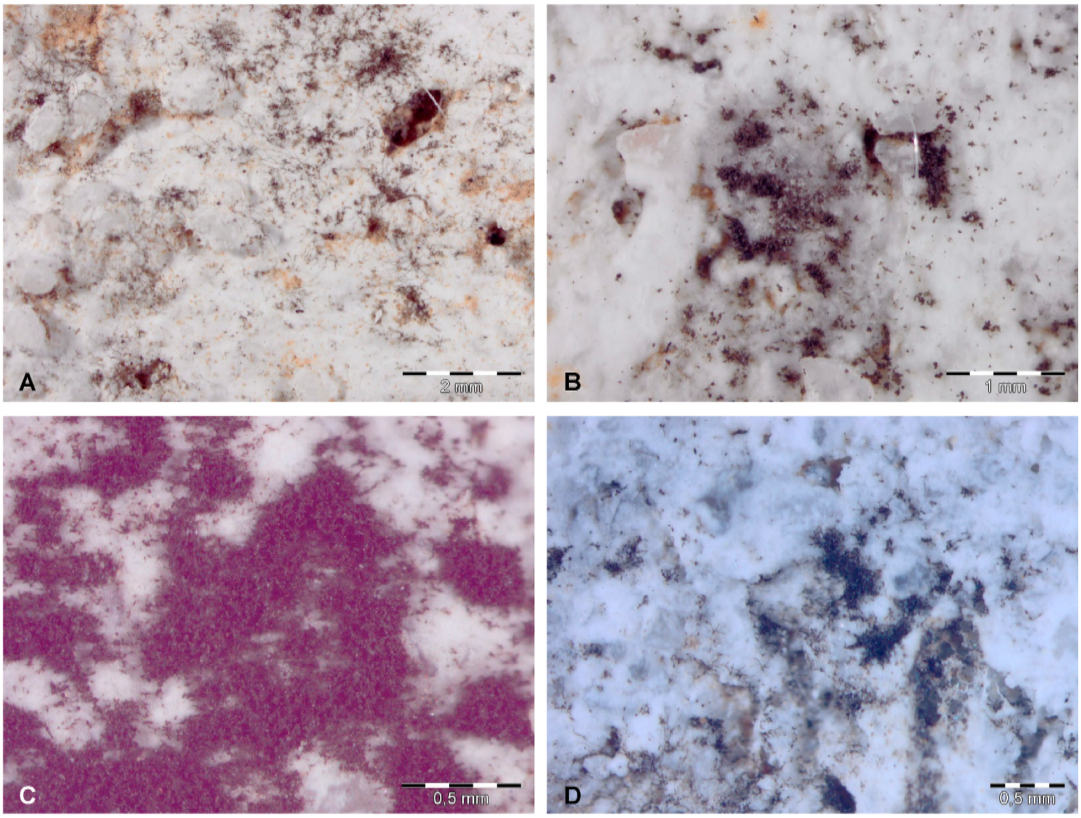

Fig. 23. Stereo microscope images of bio-colonisation observed on the surface of ETICS_1 after six (A, B) and twelve (C, D) months of outdoor exposure.

to biological colonisation due to the lack of biocide in the FC and surface microcracking caused by hygric stresses and contributing to a greater water absorption after ageing [2,62,63].

On the other hand, the acrylic-based systems ETICS_2, ETICS_4 and ETICS_5 showed only traces of mould growth (<10% of contaminated surface) on their surfaces after twelve months of ageing (Table 6). In the case of ETICS_4 and ETICS_5, both with thermal mortars as TI, mould growth was observed three months earlier (i.e., after six months of exposure). The acrylic-based systems have biocide in the FC composition (see Table 1) and rougher surfaces when compared to the lime-based or silicate-based ETICS, thus facilitating dirt accumulation which can contribute to mould growth [64]. Furthermore, results showed no biological growth on the surface of the silicate-based system ETICS_3 after one year of natural ageing, which is in accordance with the results of previous studies [13,27].

8. Discussion

It is extensively documented that moisture and temperature are among the most relevant degradation agents affecting mould growth on building facades [65,66]. In fact, both relative humidity and temperature are widely used as input variables in several mould prediction models [31–33]. Therefore, to provide an indication of the risk of mould growth on ETICS facades, three theoretical indices were applied in the present study using experimentally and numerically obtained values of SRH and ST as input. The results were complemented and validated by assessing the bio-colonisation, water performance and aesthetic properties of the ETICS throughout outdoor natural exposure.

When comparing the rate of mould growth on the surface of the ETICS after one year of exposure with the results of the three indices (risk matrices), it can be observed that both index 2 and index 3 can be used to give an indication on mould growth considering the nine months of monitoring. In fact, the lime-based system ETICS_1 obtained the highest percentage of time with SRH = 100% and also with SRH ≥80%; 15 °C ≤ ST ≤ 30 °C (25% and 18% of the time, respectively). This system also obtained the highest mould growth rate, with the two specimens presenting light growth (10 to 30% of contaminated surface) and moderate growth (30 to 60% of contaminated surface) after one year of outdoor exposure. Therefore, the highest rate of mould growth observed on the lime-based system can be attributed not only to a greater percentage of time with favourable ST and SRH conditions [10,18], but also to the relative increase of capillary water absorption with ageing caused by surface wear and microcracking [63,67]. The lack of biocide in the render of ETICS_1 can also be seen as the reason for mould growth on the surface of this system since the six months of exposure [68]. However, previous studies showed that favourable microclimatic conditions and surface hydrophobicity are more relevant with regard to a risk of long-term mould growth, if compared to biocide concentration [69,70]. It is worth noting that the silicate-based system ETICS_3 has a biocide-free render and, despite that, showed the best bio-colonisation performance, with no signs of mould growth observed after one year of exposure. ETICS_3 also presented the lowest aesthetic alteration (i.e., global colour difference) after one year of ageing, the second lowest value of index 3 considering the monitoring results (15%), and the lowest capillary water absorption of all systems after ageing (capillary absorption <1 kg/m^2 after 24 h in direct contact with water). Nevertheless, this system presented the second highest value of index 2 (16% of the monitored time with SRH = 100%), which has not yet been sufficient to cause mould growth on the surface of this system when compared to the traces of growth observed in the acrylic-based ETICS. It can thus be concluded that the capillary water absorption of the renders is fundamental in preventing long-term mould growth, i.e., ETICS should have hydrophobic surfaces, decreasing moisture accumulation within the system.

The three acrylic-based systems (ETICS_2, ETICS_4 and ETICS_5) showed traces of mould growth on their surfaces after one year of outdoor exposure. In fact, these systems have greater surface roughness when compared to the silicate-based or lime-based ETICS, facilitating dirt accumulation which contributes to mould growth [27,64]. These systems also showed the highest aesthetic alterations (i.e., greater global colour difference after ageing), due to significant dirt deposition observed on their surfaces. Additionally, the results of the theoretical indices 2 and 3 indicated a higher risk of mould growth for ETICS_2 (with MW thermal insulation) and ETICS_4 (with an aerogel-based thermal mortar). On the other hand, the lowest mould growth risk (i.e., lowest indices 2 and 3 with the monitored results) was obtained for the acrylic-based system ETICS_5 with an EPS-based thermal mortar. It is worth noting, however, that capillary water absorption results were significantly higher after ageing in the case of ETICS with a thermal mortar as insulation. Given the importance of the capillary water absorption on the bio-colonisation, there is a possibility of higher long-term mould growth on ETICS_4 and ETICS_5, when compared to ETICS_2.

In a study of this nature there are several factors that cause uncertainties. When considering the mould indices results, it can be observed that significant differences were obtained using the simulation or monitoring data as input, especially in the case of indices 2 and 3. Such differences are mainly due to simplifications and/or assumptions considered in the numerical simulations (e.g., the set of outdoor climate data used in the simulations or the fact that the effect of wind-driven rain was not validated in WUFI software for inclined elements). Moreover, some of the input data used in the simulations were obtained from previous studies, technical datasheets and WUFI database. Another limitation of the present study is related to the RH sensors. In accordance with the study of Johansson et al. [10], these sensors were placed as close as possible to the surface, but not completely attached due to their sensitivity to condensation. Finally, this study considers the influence of favourable and unfavourable T and RH conditions (i.e., fluctuating conditions) to test three theoretical indices in order to provide an indication of the risk of mould growth. Results were complemented and validated by assessing the long-term bio-colonisation, capillary water absorption and aesthetic alteration. Nevertheless, further conditions (e.g., soiling, biocide concentration, wind-driven rain, surface roughness, surface pH, etc.) could also have an influence on biological colonisation.

9. Conclusions

To study the influence of the hygrothermal behaviour of five different ETICS (with thermal mortars and insulation boards) on the risk of mould growth, ETICS systems were exposed outdoor for one-year at an urban site in Lisbon (Portugal), monitoring the surface temperature and the surface relative humidity of the systems for nine months. These results, together with others obtained via numerical simulations, were used as input data to test three theoretical indices, which can provide an indication of potential mould growth. Results were complemented and validated by assessing the long-term bio-colonisation, water performance and aesthetic properties of the five ETICS. The systems have different thermal insulation materials (ICB, MW, aerogel-based thermal mortar, and EPS-based thermal mortar), base coats (with cementitious or hydraulic lime binders) and finishing coats (acrylic, silicate, or lime-based).

The fluctuation of surface temperature (ST) and surface relative humidity (SRH) over time significantly affects mould growth on ETICS facades, regardless of the incorporation of biocide in the finishing coat composition. The index 1 (percentage of time with SRH

≥80%) indicated similar potential of mould growth for all systems (~50% of the monitored time and ~58% of the simulated time). However, this index neglects the effect of temperature, thus, it is only meaningful when applied for the study of indoor environments with more constant ST values. Considering the effects of the fluctuating climatic conditions, high values of SRH can be associated with remarkably low values of ST, thus limiting mould growth. Furthermore, the index 2 (percentage of time with SRH = 100%) indicated a higher potential of mould growth for the lime-based ETICS (~25% of the monitored time) and a lower potential for the acrylic-based ETICS with an EPS-based mortar (~4% of the monitored time). The results were significantly lower considering the simulation results as input. Finally, in accordance with the second index, the index 3 (percentage of time with SRH ≥80% and 15 °C ≤ ST ≤ 30 °C) indicated a higher potential of mould growth for the lime-based ETICS (~18% of the monitored time) and a lower potential for the acrylic-based ETICS with an EPS-based mortar (~12% of the monitored time).

The results of the mould growth indices were partially validated by the long-term biological colonisation observed on the surface of the systems. The lime-based system obtained the highest rate of mould growth after one year of outdoor exposure, with one specimen rated with 30 to 60% of contaminated surface and the other with 10 to 30% of contaminated surface. Therefore, the results suggest that indices 2 and 3 are in agreement with field observations and thus can provide an indication on mould growth for the analysed ETICS systems considering the onsite monitoring results. It is worth noting, however, the importance of the capillary water absorption of the systems in preventing long-term mould growth. In fact, results showed that an increase of capillary water absorption after ageing to levels higher than 1 kg/m^2 after 24 h in direct contact with water can also favour mould growth. It can thus be concluded that a combination of unfavourable microclimatic conditions (SRH <80%; ST < 15 °C or ST > 30 °C) and surface hydrophobicity caused by a number of reasons, such as microcracking or surface wear, are fundamental to avoid mould growth on ETICS.

The present study provided significant results to obtain a reliable dataset regarding the performance and long-term durability of ETICS to withstand biological colonisation. This dataset can be used by both the construction industry and the scientific community, offering insights to refine existing and develop new models for predicting mould growth on ETICS facades, thus allowing the design of ETICS with enhanced resistance to biological colonisation. Moreover, recognising the high susceptibility of ETICS facades to bio-colonisation, the present study identified both favourable and unfavourable conditions for biological growth in ETICS with different compositions. These findings can be used to enhance procedures for diagnosing bio-susceptibility and develop future strategies for mitigating bio-deterioration. Future research should consider longer monitoring periods as well as different environmental conditions.

CRediT authorship contribution statement

João L. Parracha: Writing – original draft, Visualization, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Rosário Veiga:** Writing – review & editing, Resources, Project administration, Funding acquisition. **M. Glória Gomes:** Writing – review & editing, Supervision, Resources, Methodology, Conceptualization. **Inês Flores-Colen:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition. **Lina Nunes:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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