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Review

Effects of Climate Change on Rendered Façades: Expected Degradation in a Progressively Warmer and Drier Climate—A Review Based on the Literature

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Abstract: Climate change could have a significant impact on buildings if its effects are not properly recognized. The consequences of climate action should be considered at the design and maintenance planning stage, with the objective of promoting the overall durability of constructions. Portugal, being part of the Mediterranean region, Southern Europe, and the Iberian Peninsula, and sometimes highlighted in projections as a critical area, is an example of a country considerably vulnerable to climate change impacts. The climate is expected to become warmer and drier, with a substantial rise in temperature and fall in precipitation by the end of the century. What implications will these changes have on the degradation of façades? Climate agents, such as temperature, solar radiation, humidity, precipitation, and wind, directly influence the performance of external claddings that protect internal building components. Cement render is the prevalent façade cladding in Portugal and Europe. Research to assess the risks of future climate-induced degradation on rendered façades is relevant in the context of buildings' durability and adaptation to climate change. The objective of the present research was to define expectations about the impact of a progressively warmer and drier climate on the degradation of exterior cement renders, based on an analysis of related literature. Generally, less staining and more cracking are expected. Expectations about salt weathering and loss of adhesion are more uncertain and need further research.

Keywords: climate change; façade cladding; cement render; climate agents; degradation expectations

Citation: Barrelas, J.; Silva, A.; de Brito, J.; Tadeu, A. Effects of Climate Change on Rendered Façades: Expected Degradation in a Progressively Warmer and Drier Climate—A Review Based on the Literature. *Buildings* **2023**, *13*, 352. https://doi.org/10.3390/buildings13020352

Academic Editors: Emilio Bastidas-Arteaga and Antonio Caggiano

Received: 13 December 2022
Revised: 12 January 2023
Accepted: 19 January 2023
Published: 27 January 2023

1. Introduction

Climate has a significant impact on the performance of façades [1] and influences the degradation and natural ageing of external building components throughout their service life [2]. Since claddings are the outer layer of the façade system directly exposed to climate loads, such as temperature, solar radiation, humidity, precipitation and wind, and elements in the atmosphere (e.g., pollutants and living organisms), they are more susceptible to degradation. External agents influence the performance of renders [3], and environmental actions are frequently the cause of defects in façade claddings. Climate action is variable and has a cumulative effect over time, which should be considered in the design [4] and maintenance planning of façades, with a view to achieving sustainability for buildings.

Climate change is rapidly evolving at a global scale [5]. Alterations in mean and extreme values of climate parameters and severe weather events, with consequences on the physical environment, are projected [6]. The implications of climate change are expected to be extensive and affect ecosystems, agriculture, health and construction [7]. Climate change leads to alterations in the land and oceans that can alter the natural degradation pattern of buildings and their components. Rising sea levels, thawing permafrost, and fluctuating soil moisture content that result in land erosion, slope instability, landslide phenomena and soil subsidence [8] are likely to affect buildings' foundations, overall structures, and infrastructures [9,10]. The impact on buildings is also due to the direct action of climate agents, such as temperature, solar radiation, humidity, precipitation and wind, on external components like façades and roofs. The service life of building components could be negatively affected, which would imply considerable rebuilding, maintenance work and associated costs [11]. The effects of climate change on the built environment can become serious if the evolution of climate is not properly considered at the design [5] and maintenance planning stage.

The Mediterranean region and Southern Europe are particularly susceptible to climate change risks [12], as are some sub-regions, such as Iberia [13]. Climate change is expected to have an impact on the durability of existing buildings and components [10,14], which in some regions, could be severe in the absence of adaptation measures [5]. The vulnerability of buildings, components and materials to climate change-induced hazards is considered a key uncertainty and research priority by the Intergovernmental Panel on Climate Change (IPCC) [15]. Façade claddings are involved because they are directly exposed to climate action and are extremely important in the protection and overall durability of constructions [2,16].

Painted render is the prevalent façade cladding in Portugal and generally across Southern Europe [17]. Indeed, cement renders account for approximately 62% of the façade claddings throughout Europe [18]. The climate in Portugal is expected to remain temperate, but summers are likely to become hot and dry by the end of this century [19]. Less precipitation and higher temperatures are projected throughout the year, with more intensity during the warm season. Climate change projections are commonly presented by regions that include several countries or land areas grouped according to the coherency of climate-related aspects [20]. Detailed projections for Portugal generally coincide with projections for the Mediterranean region and Southern Europe. The durability of rendered façades subjected to such changes could be seriously affected, since climate agents trigger and influence the development of degradation mechanisms in renders, with consequences on their service life and maintenance costs [21].

The purpose of the present research was to define expectations about the impact of a progressively warmer and drier climate in the context of climate change on the degradation of external cement renders, based on the agents' gradual action over time. The following methodology was used: (i) gather detailed climate projections for the end of the century, including relevant severe weather events; (ii) study the effect of climate agents on degradation mechanisms, which cause the main defects in rendered façades; and (iii) establish logical connections between (i) and (ii), in order to define expectations about the impact of climate projections on the degradation of external cement renders. The research was based on a literature review. Projections were detailed for Portugal, which, being part of the Mediterranean region and Southern Europe, represents these regions, particularly the areas with a tendency towards a warmer and drier climate [19]. This paper includes the following sections: Section 2 includes regional and detailed projections; Section 3 covers the characterisation of cement renders in terms of properties and climate-induced degradation; Sections 4 and 5 discuss expectations for the future degradation of rendered façades and present the main conclusions, respectively.

2. Climate Change Projections

2.1. Mediterranean Region and Southern Europe

The reference regions used in IPCC reports are often adopted by studies on climate change regional modelled projections. The Mediterranean (MED) is one of the three regions that together allow the characterisation of the main European climate types [20]. It includes the whole of Iberia and the total area or coastal land of several countries in Southern Europe, the Middle East and Northern Africa. Southern Europe is a sub-region of Europe, within a total of five sub-regions, also used by the IPCC. Southern Europe sub-region results from aggregating climate zones in such a way as to include geographical and ecological aspects regardless of political limits [22]; it is defined by more restricted limits than the MED and generally fits within it.

The Mediterranean region has been subjected to considerable drying throughout the past century. Projections based on several models and scenarios consistently support precipitation decrease in this region [23]. Significant drying is likely to affect most of the Mediterranean coast, and Iberia is one of the highlighted areas. Precipitation reduction in Southern Europe is likely to be more evident during the dry season [24,25]. Mean precipitation reduction and dryer summers have rendered the Mediterranean region particularly vulnerable to climate change impacts [12]. Inter-annual rainfall variability projected for the northern Mediterranean is probably involved in the intensification of droughts [8,25]. This variability, as well as a possible increase in precipitation in the northern land area of the Mediterranean region during the wet season, could also favour the occurrence of floods [25]. Southern Europe could also be one of the areas most affected by coastal floods [26].

Temperature warming in the MED is very likely to continue to increase over the twenty-first century, with more intensity in the summer [24]. Projections indicate an increase of 0.5–2 °C or 3.5–4 °C (relative to the period 1986–2005) by mid-century, depending on the scenario. Temperatures could rise 3.5–5.5 °C by the end of the century [25]. Other projections present a seasonal temperature increase of 3–5 °C in the winter and 5–7 °C in the summer, within a period of approximately one century [27]. The increase in the maximum summer temperature is likely to be greater in places that suffer from drying caused by lower precipitation levels, such as parts of Iberia [25]. Hot extremes are expected to heighten in a considerable part of Europe [28]. The intensity, length and frequency of heat waves are very likely to increase until the end of the century in the Mediterranean region [24,29].

Climate change observed rates for the majority of variables in the Mediterranean region exceed global trends [30]. The warming rate in this region is likely to be 20% greater than the global rate and to exceed the latter by 50% in the summer, in land areas to the north of the bay. Projections for summer temperature increase, combined with precipitation reduction, indicate the Mediterranean region as a hot spot of climate change for the twenty-first century. The significant vulnerability of the region to negative environmental effects is particularly serious for some land areas, including the Iberian Peninsula [13].

2.2. Portugal: A Hot and Dry Summer Temperate Climate

Portugal being part of the MED, the Southern Europe region (the northern area of the country is included in the Atlantic Europe sub-region) [20,22] and the Iberian peninsula, sometimes highlighted in projections as a critical area, is an example of a country significantly vulnerable to climate change impacts.

Portugal's climate is usually characterized by "moist mild winters and dry warm/hot summers" [31]. It is classified in the "Updated World Map of Köppen-Geiger" as warm temperate with (i) dry and hot summers (Csa) from mid-country to the south, and (ii) dry and warm summers (Csb) from mid-country to the north, approximately [32,33]. The climate of Southern Europe and Iberia is mostly classified as temperate, with some exceptions, in particular a noticeable arid zone in Spain [33]. A more recent version (1980–2016) of the global Köppen-Geiger climate classification map has been compared with a version of the map considering climate change projections (2071–2100) [19]. The earlier climate classification (Csa and Csb) for Portugal was maintained. However, in the most recent version, the Csb area in the north became a smaller fraction [19] close to the Spanish border, compared to older versions [32,33]. The country is already characterized more by hot summers than warm summers. In the map with climate change projections, Csa is the only classification remaining, which means that the whole country is likely to be characterized by hot summers [19].

In Portugal, the mean temperature has risen nearly 0.3 °C per decade since the 1970s, and the five warmest years recorded occurred after the 1990s [6]. This tendency has been followed by projections that indicate substantial temperature changes. Higher minimum and maximum temperatures are expected year-round, with emphasis on the latter in the summer and autumn [34]. Warming is projected to be more significant inland than on the coast. Maximum temperatures could rise 3–8 °C in the summer and autumn, with the highest values associated with some interior areas of the country, and 2–4 °C in the winter and spring. Temperatures above 30 °C are likely to occur more often and the number of cold nights could fall to once a year [31]. The amount of extremely hot days inland in spring and summer is expected to be significant [34]. Heat waves are likely to occur more often and be more intense, increasing to an average of three events per year by the end of the century. Heat waves could last from 19 to 22 days, which is considerably longer than the most common historically registered five days [31]. As heat waves are expected to become progressively stronger until the end of the century, cold spells are likely to decrease in frequency, duration, and intensity by 2046–2065 [35].

The country has seen noticeably dry conditions since the 1980s, including two severe droughts in the present century. The tendency for a drier climate has been observed from the middle to the end of the twentieth century in the south [36]. The period 2001–2010 is considered to be the driest decade in the country since 1932 [6]. Nevertheless, some extremely wet winters have been recorded since the beginning of the century [36]. In the past 30 years, winters have been both wetter and drier, depending on the year, due to the increase in the annual variability of winter precipitation [6]. Projections show a yearly decrease of around 5% in the northwest and 20% in southern areas of Portugal, for the period 2071–2100, occurring mainly in the spring, summer and autumn [37]. Summer precipitation could decline by 30% compared with the pre-industrial period 1881–1910, according to a scenario of a 2 °C increase [38]. A decrease of approximately 15% and 30% in the number of wet days is expected in the northwest and south, respectively. Generally, the changes could be more severe in the south of the country. However, a reduction in the number of days with precipitation above 10 mm is expected for the whole territory. Notwithstanding the general drying projected, some precipitation events could become stronger [37] and winter rainfall more intense, for briefer periods [6].

Portugal's considerable vulnerability to climate change impacts is largely due to rising temperature and heat extremes combined with precipitation decline. This aggravates summer dryness and contributes to hydro-meteorological-related hazards, particularly droughts and forest fires [31]. The country is also susceptible to floods triggered by strong precipitation events and a mean sea level rise [36].

The level of confidence in projections for mean and extreme winds is generally low. Declining trends have been observed since the 1970s over Europe, as well as an increasing trend in central MED [8]. A general decrease in onshore wind energy density (WED) (which "measures the energy contained in the winds, i.e., the kinetic energy flux associated with the winds, being proportional to the third power of wind speed" [39]) is projected for a substantial area of Southern Europe, including Iberia, by the end of the century. In Portugal, considerable sub-regional variability of WED was observed during the period 1971–2000. Coastal and orographic elevated areas are characterized by higher values. Seasonal variability is more evident inland than on the coast. The average is higher in winter than it is in warmer months, reaching the lowest values in September. Despite the considerable uncertainty of projections, WED will probably decrease by the end of the century, especially in the autumn and in (i) northern and central-eastern orographic elevated areas, and (ii) south-western coastal areas of Portugal. A less significant increase in WED could also occur in the central western area. WED projections show a considerable sub-regional variability of annual and seasonal averages [39].

The general climate projections for Portugal by the end of the century are summarized in Table 1.

Table 1. Summary of climate projections for Portugal by the end of the century.

Climate Agent	General Projections	Main Reference
Temperature	Rise ▲ Heat waves intensification	[31]
Precipitation	Decline ▼ Rainfall events intensification	[37]
Wind (WED)	Decline ▼	[39]

3. Climate-Induced Degradation of Rendered Façades

3.1. Characteristics of the Cladding

The common cement render is a composite material that results from a mixture of binder (e.g., Portland cement), aggregates (e.g., sand), water, and additives, which enhance specific properties of the render. Renders are usually applied in two or three layers, each with a slightly different composition, which could prevent the continuation of a defect (e.g., crack) throughout the whole thickness of the render [18,40]. The amount of binder usually decreases from the layer closer to the substrate to the outer layer. This enhances the deformation ability of the latter, which is important to respond to installed tensile stress common in cement renders (e.g., due to shrinkage), and subsequent protection of the more rigid internal layer [41]. Lime, which also has binding properties, can be added to the mix to replace part of the cement. These mixed binder mortars are generally characterized by better workability of the fresh render, improved deformation ability of the hardened render, and less susceptibility to the appearance of cracks. Simple cement renders are stronger and have a tendency to stiffness, shrinkage and cracking [40]. Mixed binder mortars are especially useful in the repair and rehabilitation of façades where lime is used in the original mortars, which is more common in old buildings. Adding lime often improves the compatibility with existing renders and construction solutions, which could prevent cracks and detachment of the cladding.

The characteristics (e.g., sand size grading) and relative quantities of the different ingredients composing the render's mix can be adapted according to performance requirements. The composition of the mix influences the properties of the render while it is fresh and, consequently, after hardening. These properties are critical for the cladding's durability [42]. Good workability of the fresh render is beneficial for its application and adhesion to the substrate, which is crucial for the cladding's performance throughout service life [2]. Workability could be improved by adding fine aggregates or more water to the mix (additions and admixtures also have an influence). However, the render's composition must remain well balanced, since excessive water could lead to ineffective curing and the render's premature degradation (e.g., cracking and cohesion problems) [18]. The cement must be able to hydrate properly during curing, the effectiveness of which depends on the ability of the fresh render to retain water in the mix for the necessary amount of time. A reasonable curing process, which improves the mechanical strength of the hardened render, could be achieved by adding water-retaining agents to the mix [43]. Additives can help to delay early desiccation, improve hydration [2] and avoid using too much water in the mix, which, by having a significant part of its volume lost during curing, could represent substantial shrinkage. These aspects affect the curing contraction process, which often leads to early degradation. Shrinkage can also occur over the render's service life by carbonation. The effects of shrinkage phenomena should be reduced as much as possible, so that durability is improved [40].

The properties of the hardened render that determine its performance during service life are the following: adherence to the substrate, mechanical and superficial strength, deformation ability, behaviour to water, and chemical resistance [16]. Adhesion to the substrate could be improved by a high content of binder and fine elements, since they are able to penetrate with water into the substrate pores and crystallize, ensuring a proper bond [2,40]. Once again, the planning of the mix's composition must be well balanced, because if the render is too rich in cement and fine elements the vulnerability to cracking by shrinkage increases, as well as the probability of further detachment. Adhesion to the substrate also influences cracking by conditioning the distribution of stresses in the render [40]. Good adhesion depends also on the characteristics of the substrate (e.g., texture, absorption capacity), render/substrate compatibility and application conditions [2,44]. The render's mechanical resistance and deformation ability determine its effectiveness to withstand installed stress from internal or external sources or actions, without failure. The render's characteristic tensile strength and dynamic modulus of elasticity are crucial in preventing cracking, subsequent water penetration and loss of adhesion. Superficial strength determines the ability of the render to endure impact and friction actions on its surface. It tends to be lower in the case of poor cohesion [16].

The render's behaviour in reaction to water is conditioned by its porosity, characterized by the pore size, shape, distribution and interconnections. It influences the render's permeability to water and water vapour, and absorption capacity by capillarity. A good render is expected to uniformly absorb rainwater, retain it in its porous structure and allow its circulation and release by evaporation, under favourable weather conditions [40]. The durability of the render greatly depends on the characteristics of its porous structure, since they determine the (i) wetting and drying pattern, (ii) vulnerability to water, frost and salt weathering [45], (iii) susceptibility to carbonation [46], and (iv) general mechanical and hygrothermal performances [47]. Requirements regarding the render's porosity are not established and reference values (e.g., ratio between the volumes of pores within the mortar and overall volume) in the literature vary, being lower in cement renders than in cement-lime or lime renders [48]. Slight alterations in the mix's composition are likely to promote changes in porosity and subsequent water (e.g., carrying damaging elements) internal transportation, ductility, brittleness and overall durability [21,46]. The render's degradation throughout service life, especially when due to salt weathering, carbonation and biological growth, also depends on its chemical resistance. The content of soluble salts and the pH value of the render could indicate its propensity to develop these degradation mechanisms. The less contaminated with soluble salts the initial mix, which influences the condition of the hardened render, and the more stable the pH at around 11–12 pH, the better [40].

The render's surface is generally flat and characterized by a non-smooth finish. The texture is uniform and its roughness can vary according to the specifications of the project. Current renders are finished with a paint coating, the colour and characteristics of which influence the aesthetics and performance of the cladding. Dark colours could be more prone to degradation (e.g., cracking by thermal shock) and should be cautiously used on façades [40]. They absorb more solar radiation, which promotes higher surface temperatures and lower humidity levels, especially on southern façades in the northern hemisphere [49].

3.2. Degradation Mechanisms and Climate Agents

Climate agents, such as temperature, precipitation, wind and solar radiation, directly interact with façade claddings and trigger degradation mechanisms, causing defects. They affect the service life of rendered façades, with consequences for maintenance actions and costs [21]. Environmental actions are the main source of defects in rendered façades, and causes related to wind-rain action, humidity and the general presence of water are quite frequent [50]. Environmental degradation is a complex phenomenon that results from the exposure of façades to climate action and elements present in the atmosphere, such as pollutants and living organisms [51]. A degradation mechanism is frequently triggered and developed under the simultaneous action of different agents. A defect could emerge from a combination of several causes [21] or specific conditions. It could also lead to new defects or aggravate existing ones [18]. The actions of climate and other degradation agents are not only intertwined, they are also characterized by intrinsic variability and randomness, and their effects are cumulative over the years [52–54].

The render's loss of performance generally starts with staining and cracking degradation mechanisms and evolves to loss of cohesion and adhesion defects, until severe conditions are reached (Figure 1) [18,51]. The degradation of exterior renders usually begins at a young age [18], sometimes prematurely (e.g., cracking by shrinkage), probably as a consequence of (i) inadequate environmental exposure conditions during the application and curing process and/or (ii) design or execution errors. This could affect the performance of renders early on and their expected functionality in terms of preventing water penetration, protecting external walls and promoting the durability of constructions [16].

(**a**) (**b**) (**c**)

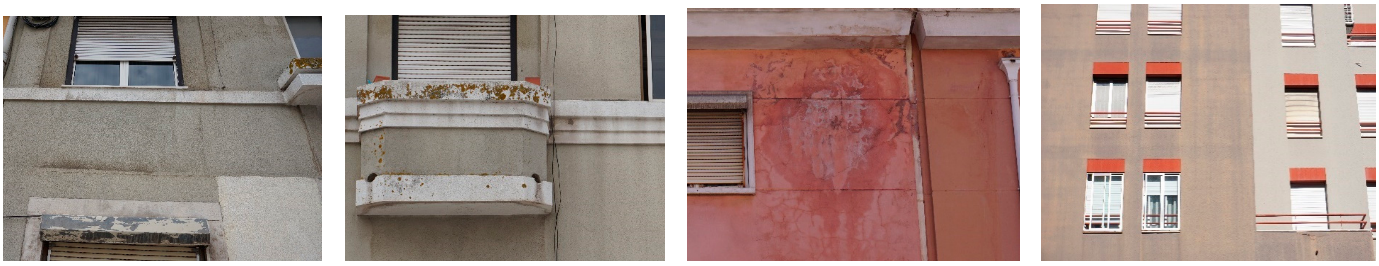
Figure 1. Main types of defects: stains (**a**), cracks (**b**), and loss of cohesion and adhesion (**c**).

The condition of a rendered façade, in the absence of maintenance, tends to worsen with age at a considerably stable rate, until approximately 30 years when it begins to increase, possibly due to the cumulative effect of climate action over time. The degradation level of older renders also tends to vary within a wider range, comparatively to younger ones, which could be the result of the diversity of environmental exposure conditions that different façades are continuously subjected to throughout service life [18]. The sensitivity of rendered façades to environmental agents is considerable (e.g., service life likely reduces with proximity to the sea and high exposure to humidity) [55]. The average estimated service life is 21 years, although it varies depending on several factors, such as climate conditions. For a temperate climate with hot and dry summers, according to the Köppen-Geiger classification, which is expected to be dominant in Portugal by the end of the century, the end of service life could be reached after approximately 24 years [56].

The following sub-sections of this paper focus on the contribution of climate to the triggering and development of the degradation mechanisms, based on pollution, living organisms, soluble salts crystallization (e.g., efflorescence, cryptoflorescence) and dimensional alterations, among others [3], which lead to the main defects found in rendered façades: stains, cracks, and loss of adhesion.

3.2.1. Stains

Several types of stains occur on renders due to physical and chemical phenomena, namely related to dirt (e.g., dust or particles from air pollution) accumulation and washing, biological growth, efflorescence [57], and discolouration (Figure 2). Each type of stain is associated with particular degradation mechanisms (Table 2). Nevertheless, wind and precipitation play a significant part in triggering staining in renders. The wind carries dirt that accumulates on the surface of the cladding and horizontal components of the façade, thus soiling the render. The prevailing wind and the distance from the pollution emission source influence the deposition rate of particles, coverage area and soiling intensity. The deposition of particles is favoured when the wind can carry them directly to the façade. Its main direction and strength, as well as local obstructing elements (e.g., buildings' geometry, trees), affect the airflow and concentration of pollution particles in it [58]. Living organisms (e.g., fungi and lichens) necessary for biological growth stains can also be transported by wind. Rainwater can also carry dirt [59] and living organisms.



(**a**) (**b**) (**c**) (**d**)

Figure 2. Different types of stains: dirt (**a**), biological growth (**b**), efflorescence (**c**), and discolouration (**d**).

The importance of wind in the development of stains and further defects on renders exceeds its role as a transportation medium for particles in the air. The impact of precipitation on façades is influenced by wind. Rainwater reaching and penetrating the render is commonly associated with the simultaneous occurrence of wind and rain. Wind influences the direction of raindrops towards the façade, being critical to its wetting process [60] and a determinant of the runoff path [51,55]. Water flowing down the surface of the render (e.g., when not absorbed due to pores reaching saturation limit [61]) drags dirt, which is either washed off or retained after the drying process [59]. The course of descending water leaves visible marks and influences the façade's staining pattern.

Wind-driven rain wets the render, which remains damp for a certain period. Rainwater in contact with the surface gradually penetrates the render's porous structure, with the help of wind pressure. The superficial water evaporates faster than that retained inside the pores. The latter could leave temporary and visible moisture stains after migrating to the surface. Rainwater in the ground, during or after a precipitation event, and in touch with the render, could be absorbed through capillarity, thereby wetting the façade's lower area. Temperature, which on the surface of the cladding is influenced by solar radiation exposure, has a crucial role in the cladding's drying process. Long precipitation periods and slow drying could enhance moisture stains and lead to subsequent degradation associated with the (i) accumulation of dirt, (ii) growth of biological organisms, and (iii) emergence of efflorescence [57]. Renders' vulnerability to staining is highly dependent on the drying speed. If a wet façade dries slowly, damp in the cladding or moisture on its surface remains there for longer. The latter works as an adhesive for particles, which is favourable to both soiling and biological growth stains. These stains are likely to become more evident as wetting and drying cycles consecutively occur, in the absence of maintenance actions [59].

Efflorescence staining implies the initial existence of soluble salts (e.g., sulphates, chlorides, nitrates, carbonates) in the render, whether present in the mix or later carried into the porous structure. Rainwater triggers the dissolution of these salts, by penetrating the pores. Soluble salts are only able to circulate inside the porous structure once they are dissolved in water [62]. As the render dries, water carrying the dissolved salts migrates to the surface where it evaporates. This process culminates in the salts' crystallization as a white deposit on the surface [63]. Aspects such as composition and diffusion properties of the render, amount of soluble salts present, period of water/salt contact, and evaporation rate influence the emergence of efflorescence [64,65]. Generally, efflorescence stains are harmless to the render's porous structure [62]. Carbonation stains are different from other efflorescence, despite the similarities in terms of appearance and degradation mechanisms. These stains are caused by the dissolution of calcium hydroxide in the render's composition, which reacts in contact with carbon dioxide, both being diffused in the thin layer of water covering the render's surface. This leads to the precipitation of calcium carbonate salts, while superficial water evaporates to form white incrustations that are insoluble [63,66,67]. This feature differentiates carbonation stains from other efflorescence, which are soluble in water. The first also reacts quite distinctively to a phenolphthalein solution [57].

Table 2. Impact of climate action on staining degradation mechanisms in rendered façades.

Stains	**Degradation Mechanisms**		
	Actions	**Climate Agents**	**Favourable Factors or Conditions**
Dirt	Dirt or pollution particles:		
	- transport and deposition	wind wind-rain action	- wind strength - wind direction towards the façade
	- adherence	wind-rain action temperature	- wind direction towards the façade - wet render/moist surface - long moisture cycle - cold temperature - lack of sun exposure
	- washing	wind-rain action	- wind direction towards the façade - water runoff
	- accumulation	wind wind-rain action temperature	- long and consecutive moisture cycles (implied continuation of "transport and deposition")
Biological growth	Living organisms:		
	- transport and deposition	wind wind-rain action	- wind strength - wind direction towards the façade
	- adherence - growth	wind-rain action temperature	- wind direction towards the façade - wet render/moist surface - long moisture cycle - cold temperature - lack of sun exposure
	- accumulation	wind wind-rain action temperature	- long and consecutive moisture cycles (implied continuation of "transport and deposition")
Efflorescence	Soluble salts (existing in the render or penetrating it in rainwater):		
	- dissolution	wind-rain action humidity	- wind direction towards the façade - wet render / water in the pores - high relative humidity
	- crystallization and deposition	wind humidity temperature	- fast drying process of the wet render - water migration towards the surface - evaporation of water in the surface - wind flow - relative humidity decrease - temperature increase
Discolouration	Chemical components (existing in the render or in the coating):		
	- leaching	wind-rain action	- wind direction towards the façade
	- reaction to pollutants	wind wind-rain action temperature	(implied "adherence"and "transport and deposition" subsections)
	- photodegradation	solar radiation	- significant exposure to UV radiation

Note: Temperature encompasses the temperature of the render at a microclimate level, which is directly influenced by solar radiation. The temperature of the render could reach values above the air temperature when the latter is high [68].

Sunlight is one of the commonest direct causes of colour changes in painted render façades [69] since ultraviolet radiation has a particular impact on the photo degradation of the materials' chemical components [4]. Nevertheless, rainwater also promotes the leaching of pigments and adherence of pollution particles, which could lead to chemical reactions and colour changes [69]. Ageing cycles based on the simulation of exposure to rainwater combined with temperature (e.g., heat and cold), followed by ultraviolet radiation, have shown significant colour alterations [70].

3.2.2. Cracks

Different types of cracks appear on rendered façades, namely mapped or oriented (Figure 3), generally caused by phenomena of a mechanical nature [57]. Nevertheless, damaging internal stresses, which could lead to cracking, occur in the render due to the following non-mechanical-related phenomena: desiccation and hydration during the curing process, carbonation, crystallization of dissolved salts, and freeze-thaw (Table 3). The presence of rainwater and alterations of temperature and humidity are triggering factors for these phenomena, as well as for dimensional or movement-related stresses based on temperature gradient within the render or hygrothermal behaviour differences between distinct materials.

(**a**) (**b**) (**c**)

Figure 3. Different types of cracks: mapped (**a**), and oriented (**b**,**c**).

Cracking starts at a premature age in renders, because of the curing process during which the fresh render loses volume and shrinks. This could occur due to the evaporation or absorption by other elements (e.g., substrate) of water in the mix and to the binder's hydration process, as the render dries and hardens [40]. Elevated temperature, low relative humidity and high wind velocity could negatively affect curing by increasing the evaporation rate, allowing the water to drain too rapidly from the fresh render and affecting its durability after hardening [43,71]. The inability of the render to deform without restrictions, for instance, due to the resistance of the substrate to shrinkage, induces tensions (e.g., tensile stress) in the cladding that often result in mapped cracking [57,71]. Carbonation shrinkage, based on chemical reactions triggered by exposure to CO_2, which occurs during curing and throughout service life, could also lead to fine superficial cracking. These cracks emerge due to differential shrinkage between the surface and the deeper layers, considering gradual CO_2 penetration over time [71–73]. Carbonation can accelerate the process of shrinkage during curing, but isolating its contribution from other simultaneous phenomena (e.g., desiccation, hydration) is practically impossible [73]. The carbonation rate and depth are influenced not only by intrinsic factors (e.g., cement's composition) but also by extrinsic ones, such as CO_2 concentration in the atmosphere [74], relative humidity, precipitation and temperature [75], which vary according to the local environmental exposure conditions [76]. After curing, the existence of water in the render's pores triggers carbonation chemical reactions, by promoting the dissolution and interaction of hydration products and CO_2 [77]. Low relative humidity tends to be associated with low carbonation rates [76]. High and constant humidity in the environment and the render are associated with relatively superficial carbonation [74]. Exposure to high temperatures can contribute to increasing the carbonation rate and depth [78].

The combined action of water and temperature has a significant contribution to the degradation of rendered façades [80]. It could lead to cracks in the render by (i) acting specifically on the cladding and triggering thermal shock phenomena, or (ii) affecting the whole building or some of its components, including the cladding, and triggering movements of hygrothermal nature. Cracks are often caused by thermal cycles [3] and temperature gradients [47] within the render. Heat/cold and heat/rain ageing cycles have shown that internal temperature variations and thermal shock lead to cracking [80]. Abrupt temperature fluctuations, explained by amplitude and rate of variation over a short time range, affect the durability of rendered façades. Thermal gradients occur between the heated exposed surface of the render and its interior due to sudden cooling (e.g., effect of rainwater). An expansion phenomenon occurs during the heating phase, whereas shrinkage is observed after cooling. This shrinkage combined with the render's characteristically low tensile strength significantly influences the cracking process [81].

Table 3. Impact of climate action on cracking degradation mechanisms in rendered façades.

Cracks	Degradation Mechanisms		
	Actions	**Climate Agents**	**Favourable Factors or Conditions**
Mapped cracking	Fresh render's curing process:		
	- shrinkage	wind humidity temperature	- high wind velocity - low relative humidity - high temperature - excessive speed of evaporation of water in the mix
	Hardened render:		
	- shrinkage by carbonation	wind-rain action humidity temperature	- wet render/water in the pores, unless if excessively or constantly - relative humidity around 40–60% [78] - high temperature
	Hardened render:		
	- expansion by alkali-aggregate reaction	wind-rain action humidity temperature	- wet render/water in the pores - internal relative humidity >80% [79] - swelling of alkali-silica gel - high temperature
Render level cracking	Hardened render:		
	- expansion	temperature	- considerable exposure to UV radiation - warm temperature
	- shrinkage by thermal shock	wind-rain action temperature	- wet render - cold temperature - temperature variation and gradient within the render
Oriented cracking	Hardened render:		
	- movement of hygrothermal nature	temperature	- temperature and damp variations in the render and/or in related building components; differential hygrothermal behaviours - dimensional change - expansion with warm temperature - shrinkage with cold temperature (implied influence of "wind-rain")
Por level cracking	Soluble salts (existing in the render or penetrating it in rainwater):		
	- transport and deposition (of salts in air pollution)	wind wind-rain action humidity	- wind strength - wind direction towards the façade - high relative humidity
	- dissolution	wind-rain action humidity	- wind direction towards the façade - wet render/water in the pores - high relative humidity
	- crystallization and deposition	wind humidity temperature	- fast drying process of the wet render - water migration in the porous structure - evaporation of water in the pores - relative humidity decrease - temperature increase
	Water in the render:		
	- freeze-thaw	temperature	- wet render/water in the pores - transformation of liquid water into ice crystals and subsequent melting

Note: Temperature encompasses the temperature of the render at a microclimate level, which is directly influenced by solar radiation. The temperature of the render could reach values above the air temperature when the latter is high [68].

Oriented cracking can be caused by thermal-induced movements that affect the building in general or just some structure elements (e.g., terrace slab) and differential responsive movements of the façade's components [57,61]. Temperature and damp level changes lead to dimensional variations and stresses of a hygrothermal nature between different materials, which promote cracking [4,55]. This is observed when cracks follow the joints between the various elements of the substrate if it is heterogeneous (e.g., concrete, bricks and mortar). The incompatibility of Young's modulus and the coefficient of thermal expansion between render and substrate negatively influences cracking [57]. If the deformation ability of the render is not enough to accommodate interfacial tensions between the render and adjacent building components (e.g., substrate), cracking occurs [40].

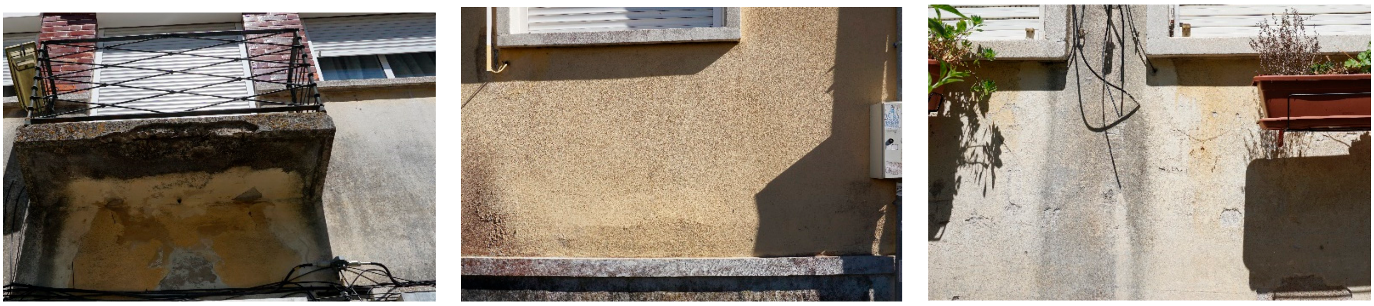
Cracks can also result from the crystallization of dissolved salts. Despite all the similarities between the degradation mechanisms of cryptoflorescence and efflorescence, the main difference is significant. The first occurs below the surface of the render, within the pores, and has more damaging effects [82]. When this chemical phenomenon of expansive nature occurs inside the porous structure, instead of on the surface, as in the case of efflorescence, it induces internal pressures that could damage the matrix and lead to cracking [3,83,84]. The place where the salts crystallize is determined by evaporation speed and how the porous structure allows water to circulate [85]. Soluble salts responsible for this type of attack on rendered façades are often present in the render or adjacent building components, and soil, groundwater or seawater [86]. Air pollution is also an external source of mainly sulphates and nitrates, the deposition of which could occur under dry or wet (e.g., acid rain) circumstances [83,87]. High relative humidity is frequently associated with high deposition velocity, which also depends on wind speed [87]. Generally, rainwater and air humidity have a triggering effect on renders' salt-related attacks [86].

High relative humidity and frequent exposure to rainwater are favourable conditions to alkali-aggregate reactions. This could occur if the render contains both the necessary quantity of alkalis, in its composition or by exposure, to enable it, along with reactive aggregates [88]. The reaction is due to the interaction between a basic pore-filling solution, composed mainly of alkali hydroxides, and considerably soluble or unstable fine aggregates (e.g., silica), which are sensitive to the solution's alkalinity level. The reaction is expansive (e.g., formation of an alkali-silica swelling gel) and induces tensile stresses that result in mapped cracking [3,88–90]. A high damp level is necessary for the swelling process of the gel resultant from the alkali-silica reaction [91]. Generally, the rate of the reaction and the resulting final expansion increase with relative humidity and temperature. The higher the temperature, the faster the alkali-aggregate reaction and the more significant the induced expansion [91].

Temperature action affects the hygrothermal behaviour of building components, as well as the render's curing and drying process. Furthermore, a sufficiently low temperature could freeze water retained in the porous structure. The transformation of liquid water into ice crystals entails a volume increase, which could induce enough pressure on the pores and cause cracks [92]. Successive freeze-thaw cycles, caused by temperature variations, increase the render's vulnerability to degradation [93]. Cracking undermines the aesthetic and protection functions of the render, affects its mechanical performance and facilitates the penetration of external water and salts. This exacerbates the cladding's susceptibility to degradation and promotes subsequent damage, such as loss of adhesion [93]. The probability of water-related degradation mechanisms occurring increases, as does the severity of defects.

3.2.3. Loss of Adhesion

Loss of adhesion defects encompass (i) detachment from the substrate in localized areas, which represents renders' durability threshold; (ii) bulging, which also implies a separation from the substrate, usually happening before the complete detachment; and (iii) loss of bond within the render, manifested as spalling and crumbling, which implies disconnection between component elements, increased fragility and disaggregation (Figure 4) [18,57]. Detachment could be caused by mechanical phenomena [57]. Nevertheless, climate agents have a significant triggering effect on adhesion problems because of their influence on hygrothermal stresses and chemical transformations (e.g., crystallization of soluble salts) (Table 4) [60,94]. Rainwater, temperature and humidity variations contribute to the development of these phenomena, as in the case of cracking.



(**a**) (**b**) (**c**)

Figure 4. Different types of loss of adhesion: detachment (**a**), bulging (**b**) and crumbling/spalling (**c**).

Bulging is described as a loss of adhesion on the render/substrate interface, where the bond between them becomes ineffective while the cladding suffers displacement towards the exterior [57]. Poor adhesion results from climate action during application and throughout the render's service life, among other factors [44]. Stress induced by successive hygrothermal expansions of the render could become unbearable over time and lead to its deformation and movement. Damaging hygrothermal behaviour can be caused by environmental exposure factors, such as wind-rain action (hitting the façade and wetting the render), high temperature and intense thermal variations. Water retained in the render's pores, depending on their storage capacity, could increase its weight and negatively contribute to adhesion defects [60].

The degradation mechanism related to the dissolution and crystallization of salts that cause cracking could also lead to cohesion and adhesion defects [3,83]. The development of cryptoflorescence, based on the growth of crystals inside the render's pores, which expand and disrupt the matrix, could result in crumbling, spalling and bulging [86,94]. Bulging could be described as swelling outwards that only occurs on the surface of the render, due to dilatation caused by the crystallization of salts [94], in addition to the previous definition [57]. Detachment of the render's outer layer could also be caused by the crystallization of salts [95], as could the detachment of render from substrate. The latter requires damaging crystals to form on the interface, which is often associated with the evaporation of rising damp coming from the inner part of the wall and crystallization occurring close to the substrate surface, due to slow water migration towards the exterior [96]. However, rainwater that reaches the substrate through the render could also lead to its complete detachment, under favourable porosity properties and climate conditions. Salts penetrate the render by several means influenced by climate action, such as pollution particles transported by wind and rain, flood water driven by capillarity, and sea spray carried by wind and fog [97]. Sulphates and chlorides, which can shorten the service life of rendered façades by destroying the cladding's porous structure, are found in sea spray, typical in coastal areas. Strong wind velocity is a favourable condition for their presence in the atmosphere. Wind velocity and direction, as well as relative humidity, precipitation and temperature, which could increase the mass of the particles in sea spray, influence the deposition speed [98].

Relative humidity has an important role in the dissolution and crystallization cycles of some salts, which could exist or be deposited in the render, the hygroscopic properties of which allow them to dissolve in the presence of high relative humidity, above 70%. These hygroscopic salts crystallize when humidity decreases, increasing in volume and inducing tension in the pores [57]. The repetition of these cycles, which tends to occur in the case of exposure to favourable relative humidity variations, likely causes crumbling and loss of cohesion, aggravating the degradation of rendered façades [62]. High relative humidity and other conditions that favour the alkali-aggregate reaction leading to cracking could also result in loss of adhesion problems, such as spalling [3,88]. The same could be said about the freeze-thaw phenomenon, which, besides cracking, could also lead to spalling [93].

Table 4. Impact of climate action on loss of adhesion degradation mechanisms in rendered façades.

Loss of Adhesion	**Degradation Mechanisms**		
	Actions	**Climate Agents**	**Favourable Factors or Conditions**
Crumbling and spalling	Soluble salts (existing in the render or penetrating it in rainwater):		
	- transport and deposition (of salts in air pollution and sea spray)	wind wind-rain action humidity temperature	- high wind velocity - wind direction towards the façade - high relative humidity - flooding (for capillarity driven salts)
	- dissolution	wind-rain action humidity	- wind direction towards the façade - wet render/water in the pores - high relative humidity
	- crystallization and deposition	wind humidity temperature	- fast drying process of the wet render - water migration in the porous structure - evaporation of water in the pores - relative humidity decrease - temperature increase
	Hardened render:		
	- expansion by alkali-aggregate reaction	wind-rain action humidity temperature	- wet render/water in the pores - internal relative humidity >80–85% [90] - swelling of alkali-silica gel - high temperature
	Water in the render:		
	- freeze-thaw	temperature	- wet render/water in the pores - transformation of liquid water into ice crystals and subsequent melting
	Fine particles:		
	- washing	wind wind-rain action	- wind direction towards the façade
	Prior triggering defects: cracks and detachment of the external layer of the render		
Bulging	Hardened render:		
	- wetting	wind-rain action	- wind direction towards the façade
	- deformation of hygrothermal nature	temperature	- wet render/damp in the pores - temperature and damp variations - dimensional expansion - high temperature - weight increase by damp in the pores
	The degradation mechanism based on the dissolution and crystallization of salts is applicable		
	Prior triggering defects: cracks		
Detachment	The degradation mechanism based on the dissolution and crystallization of salts, between render layers or on the interface render/substrate, is applicable The degradation mechanism based on the hardened render's deformation of hygrothermal nature is applicable Prior triggering defects: bulging and cracks		

Note: Temperature encompasses the temperature of the render at a microclimate level, which is directly influenced by solar radiation. The temperature of the render could reach values above the air temperature when the latter is high [68].

Loss of bond within the render could also occur by erosion, due to the direct action of wind and rain on the surface. The washing of fine particles leads to disaggregation and loss of mass. Cohesion problems are more usual in the case of old renders, reduced amount of cement in the mix, or exposed underlying layer after prior detachment of the external one. The latter is generally the most resistant to environmental exposure [57]. Besides preceding partial detachments, existing cracks are a favourable pre-condition for adhesion problems. Cracks route rainwater into the render, which then spreads through the porous structure [60]. They are often found at the initial phase of detachments [3]. Cracks could be particularly hazardous when creating a path for water to infiltrate from outside down to the substrate, which could result in defects based on the dissolution and crystallization of salts and loss of adhesion at the render/substrate interface [18].

4. Expected Degradation of Rendered Façades in a Progressively Warmer and Drier Climate—Discussion

Table 5 summarizes the expectations on the impact of climate agents on degradation mechanisms and subsequent defects in rendered façades, based on climate change projections for Portugal. The information in Table 5 results from the methodology described in the last paragraph of the introduction. The discussion of the table content is developed in Sections 4.1–4.3. The graphical codes presented at the end of Table 5 have been created to facilitate reading of the table content. The colour green indicates that the projection, whether representing an increase or a decrease associated with a specific climate agent, will likely not accelerate the development of the degradation mechanism. The colour orange indicates the opposite. The projections summarized in Table 5 reflect the information in Section 2.2.

4.1. Stains

Generally, fewer stains are expected to occur in the future. Long periods of exposure to rainwater, which increase the probability of staining to progress [57], tend to occur less. Decreases in precipitation and wind intensity, despite the uncertainty of projections for the latter, as their weakened combined action, do not favour the transport, deposition, adherence and accumulation of particles or living organisms. The render is likely to stay wet less often and for shorter periods. This is generally beneficial in terms of degradation, since water is often considered the main causative agent of defects in renders [3,16]. The chance of rainwater and damp being associated with the emergence of defects in painted rendered façades is significant [57]. Warmer temperatures also contribute to drier renders. Whereas these climate projections are most certainly unfavourable for the emergence of dirt and biological growth stains, the temperature increase adds complexity to the assessment of expectations on efflorescence.

Table 5. Expectations on the impact of climate agents on degradation mechanisms and subsequent defects in rendered façades, based on climate change projections for Portugal.

Defects		Climate Agents' Projections	Expectations	
Stains	Dirt	wind▼ wind-rain action▼ temperature▲	Dirt and pollution particles ↓ less transport and deposition ↓ less adherence due to reduction of moisture from rainwater on the surface shorter moisture cycles ↓ less washing due to reduction of water runoff ↓ less accumulation due to shorter and less consecutive moisture cycles	↓
	Biological growth	wind▼ wind-rain action▼ temperature▲	Living organisms ↓ less transport and deposition ↓ less adherence and growth due to reduction of moisture from rainwater on the surface shorter moisture cycles ↓ less accumulation due to shorter and less consecutive moisture cycles	↓
	Efflorescence	wind▼ wind-rain action▼ humidity▼▼ temperature▲	Soluble salts ↓ less dissolution due to reduction of rainwater in the render shorter moisture cycles ↕ less or more crystallization and deposition due to ↓ reduction of dissolution probability ↑ faster drying process and evaporation	↕−

Table 5. *Cont.*

Defects		Climate Agents' Projections	Expectations	
Stains	Discolouration	wind ▼ wind-rain action ▼ temperature ▲ solar radiation ▼	Chemical components ↓ less leaching potential ↓ less reaction to pollutants due to reduction of transport, deposition and adherence of particles ↓ less photo degradation	↓
Cracks	Mapped cracking	wind ▼ wind-rain action ▼ humidity ▼▼ temperature ▲	Fresh render curing process ↑ more shrinkage due to faster evaporation of water from the mix Hardened render ↕ less or more shrinkage by carbonation due to ↓ less dissolution of chemical componds due to reduction of rainwater in the render ↑ deeper CO_2 penetration due to reduction of rainwater in the render ↑ deeper and faster CO_2 penetration by temperature warming Hardened render ↕ less or more expansion by alkali-aggregate reaction due to ↓ less swelling of alkali-silica gel due to reduction of rainwater in the render ↑ more ultimate thermal induced expansion	↕+
Cracks	Oriented cracking	temperature ▲	Hardened render ↑ more differential movements of hygrothermal nature due to increase of thermal expansion increase of dimensional change by intense warming	↑
Cracks	Render level cracking	wind-rain action ▼ temperature ▲	Hardened render ↑ more thermal expansion and dimensional change by intense warming ↓ less shrinkage due to decrease of cooling by wind-rain action decrease of temperature gradient within the render	↕+
Cracks	Pore level cracking	wind ▼ wind-rain action ▼ humidity ▼▼ temperature ▲	Soluble salts ↓ less transport and deposition ↓ less dissolution potential due to reduction of rainwater in the render shorter moisture cycles ↕ less or more crystallization and deposition due to ↓ reduction of dissolution probability ↑ faster drying process and evaporation Water in the render ↓ less freeze-thaw potential	↕−
Loss of adhesion	Crumbling and spalling	wind ▼ wind-rain action ▼ humidity ▼▼ temperature ▲	Soluble salts ↓ less transport and deposition ↓ less dissolution potential due to reduction of rainwater in the render shorter moisture cycles ↕ less or more crystallization and deposition due to ↓ reduction of dissolution probability ↑ faster drying process and evaporation Hardened render ↕ less or more expansion by alkali-aggregate reaction due to ↓ less swelling of alkali-silica gel due to reduction of rainwater in the render ↑ more ultimate thermal induced expansion Water in the render ↓ less freeze-thaw potential Fine particles ↓ less washing	↕−
Loss of adhesion	Crumbling and spalling		Prior triggering defects: cracks and detachment of the outer render layer	+

Table 5. *Cont.*

Defects		Climate Agents' Projections	Expectations	
Loss of adhesion	Bulging	wind-rain action▼ temperature▲	Hardened render ↓ less wetting ↑ more deformations of hygrothermal nature due to increase of thermal expansion ↓ less damp weight in the render	↕+
		wind▼ wind-rain action▼ humidity▼▼ temperature▲	The degradation mechanism based on the dissolution and crystallization of salts is applicable	↕−
			Prior triggering defects: cracks	+
	Detachment	wind▼ wind-rain action▼ humidity▼▼ temperature▲	The degradation mechanism based on the dissolution and crystallization of salts is applicable	↕−
		wind-rain action▼ temperature▲	The degradation mechanism based on the hardened render's deformation of hygrothermal nature is applicable	↕+
			Prior triggering defects: cracks and bulging	+

▼▲ projection/contribution for the development of the degradation mechanism: ▼decrease/negative; ▲ increase/negative; ▼ decrease/positive; ▲ increase/positive; ↓↑↕ conditions for the emergence of the defect: ↑ favourable; ↓ unfavourable; ↕ favourable and unfavourable/difficult to project; + — weighting factor: + favourable; — unfavourable. Note 1: Temperature encompasses the temperature of the render, at a microclimate level, which is directly influenced by solar radiation. The temperature of the render could reach values above the air temperature, when the latter is high [68]. Note 2: Wind-rain action projections refer to precipitation projections. It does not include intense rainfall events during brief periods, in winter. Note 3: Humidity projections were qualitatively determined by the authors for the purpose of the present study, considering the influence of temperature and precipitation projections, due to the lack of specific projections for humidity. Generally, humidity could decrease due to the projected rise of temperature and decline of precipitation. Note 4: Solar radiation projections are discussed on the third paragraph of Section 4.1.

Efflorescence emerges as the render dries and it depends on the drying rate, which is influenced by climate agents, such as temperature, relative humidity and wind [82]. The crystallization of a salt-saturated solution tends to occur when porous materials dry fast enough and the drying rates are high [99]. This phenomenon is unlikely to occur if the solution is kept in relative humidity conditions above the crystallization threshold characteristic of the salts that it contains. Additionally, for some salts, the variation of temperature is the main factor influencing crystallization, which could occur even under nearly constant relative humidity [100]. The behaviour of climate agents fluctuates outdoors and it is not possible to control them and keep them constant, hence wetting and drying cycles are inevitable, as are damaging drying rates [99]. Efflorescence intensity varies seasonally, depending on the contribution of yearly climate action. Despite tending to occur more frequently in spring and autumn [65,101], efflorescence could be observed during visual inspections on site in these seasons and in summer, after rainy periods [102]. This suggests that exposure to rainwater is necessary for efflorescence to emerge in façades subjected to warm temperatures. Therefore, in terms of expectations, if the render's wetting depends on wind-rain action, the probability of salts dissolving and the subsequent appearance of efflorescence in the spring, summer and autumn could be low by the end of the century, in Portugal, considering the projected precipitation decrease. However, in the case of effective rainfall events, the probability of higher drying rates and subsequent crystallization is considerable, based on the increase in maximum temperature and the number of extremely hot days in spring and summer, and is more accentuated inland. Moreover, efflorescence has been detected during the wet season when the temperature increases and relative humidity decreases [103]. This could indicate that efflorescence would be expected to start emerging more during winter, when the precipitation decline is not as steep if the temperature rises enough. Nevertheless, a lower winter temperature may be a favourable condition for the crystallization of specific salts [100]. Therefore, warming projections could affect the salt weathering of renders, but possibly not in all its manifestations since crystallization depends both on climate action and on the type of salt.

Discolouration caused by degradation mechanisms based on wind-rain action is expected to occur less in the future. The uncertainty of projections for solar radiation is high. Medium confidence level projections show a slight reduction of ultraviolet radiation in Portugal by the end of the century due to ozone recovery [104]. However, it is difficult to know whether such slight decreases could positively affect discolouration staining in renders. In addition, this degradation mechanism is more associated with dark and saturated coloured renders exposed to longer periods of solar radiation, which is highly dependent on orientation [57].

The general expectations of less staining in rendered façades in the future are more likely to be met in some areas of the country, according to detailed projections. Staining degradation mechanisms could be especially hindered in the (i) southern region, due to a more accentuated precipitation decline, and (ii) elevated ground areas in northern and central-eastern parts of the country and south-western coastal areas, due to a significant reduction of wind intensity. If the projected warming helps to worsen staining by salt weathering, this type of defect could occur less in the littoral zone, due to the less pronounced temperature increase.

4.2. Cracks

Generally, more cracks are expected to appear in the future. Temperature rise, as well as wind and relative humidity conditions that promote desiccation, favour premature mapped cracking if water from the mix evaporates too quickly during the curing process. Early degradation could occur more if climate conditions since the fresh render's application are not thoroughly acknowledged so that the mix can be adjusted and severe heating conditions prevented during curing.

Mapped cracking by carbonation and alkali-aggregate reaction is more difficult to anticipate. Despite temperature increase being a favourable condition for the development of these degradation mechanisms, the presence of water in the render's porous structure is necessary. In Portugal, the render is likely to remain in dry conditions for longer periods by the end of the century, which could prevent the triggering of (i) after-curing carbonation, which is unlikely to occur in dry conditions [77], and (ii) alkali-silica reaction, which is unlikely to occur if the relative humidity is lower than 50% [91]. In the case of carbonation, however, high water content (for instance, due to rainwater exposure), not only triggers carbonation chemical reactions but simultaneously delays the CO_2 diffusion rate [78] and decreases the penetration depth [76]. Therefore, the projected precipitation decrease could be favourable for this degradation mechanism, by allowing its faster and deeper development in the future if the optimum relative humidity of 40–60% [78] is still reached and the dissolution of hydration products and CO_2 is enabled. Additionally, higher temperatures accelerate the penetration of CO_2, despite the warming slowing the dissolution process [77], which could also be favourable to carbonation cracking by the end of the century. In the case of the alkali-aggregate reaction, internal relative humidity above 80% is considered necessary for the alkali-silica gel to swell [79], which could occur less in the future due to precipitation decrease. Additionally, the evolution of the gel's expansion process can be linked to wetting and drying cycles and is possibly associated with seasonal behaviour. A long period and repetition of cycles could be necessary for this degradation mechanism to cause substantial damage when the reactivity of the aggregates is low [105]. This suggests that cracking from alkali-aggregate reaction could take longer to emerge in the future, since consecutive cycles are expected to occur less. However, an alkali-silica reaction could start developing under relatively lower damp levels, and the gel could expand if the temperature is favourable (e.g., 59% and 60 °C) [79]. Therefore, the projected warming could contribute to exacerbating the rate and ultimate expansion caused by this type of reaction in the future, even under drier conditions, if the render's pore-water condition is above the internal relative humidity threshold.

Temperature increase is also favourable to oriented cracking if differential hygrothermal movements and expansion of building components create stresses not compatible with the render's deformation ability. Thermal expansion is one of the main degradation mechanisms triggered by climate action that affects building components. Thermal fluctuations within a short period (e.g., day and night temperature range), which are likely to be aggravated by temperature warming, could exacerbate cracking mostly in façades directly exposed to solar radiation, which depends on orientation [106]. As well as these façades, other parts of the building, such as parapets around flat roofs in contact with the terrace slab, are especially vulnerable to temperature variations, and hence, are more prone to cracking [61]. The projected increase in the maximum temperature could lead to hazardous temperature ranges. More intense and longer heat waves could even subject building components to unprecedented stresses by thermal expansion and damaging differential movements. The temporary nature of these events could be exceedingly damaging, considering the subsequent temperature change and possible sudden decrease.

Expectations regarding cracking at the render level throughout service life are more difficult to define. Temperature warming could enhance the thermal expansion of the render. However, a drop in precipitation and wind intensity reduces the chance of a temperature gradient within the cladding's thickness and shrinkage by sudden cooling. The projected precipitation decline for Portugal by the end of the century is greater at the time of the year when rendered façades would be subjected to higher temperatures. Nevertheless, the maximum temperature that the render reaches is of great importance for cracking by thermal shock. Therefore, the consequences of this degradation mechanism could be more severe in warm climates [80], such as that in Portugal, when effective cooling also occurs, either by the effects of wind and rain or temperature fluctuations.

The assessment of expectations for cracking caused by cryptoflorescence throughout service life is complex. The reasons are similar to the ones described for efflorescence, since both degradation mechanisms are based on the crystallization of soluble salts. In Portugal, the projected decline in precipitation and wind intensity is likely to reduce the probability of salts being transported and deposited, and then penetrating into the render and dissolving, since claddings become wet less regularly and for briefer periods. Temperature significantly influences the render's drying rate, which is a determining factor for the crystallization site. Rapid drying could promote the development of cryptoflorescence if the water migrating towards the surface is prevented from reaching it faster than the drying rate [107,108]. The projected temperature warming is favourable to rapid drying, likely leading to the crystallization of salts below the surface and consequent unbearable stresses for the porous structure, which ends up cracking. If the render's wetting depends on wind-rain action, cryptoflorescence could occur more in winter, when the precipitation decline is less accentuated, if the temperature warming is enough. However, significantly higher temperatures are expected mainly from spring to autumn, coinciding with the period of main precipitation reduction and low dissolution probability, which may not favour cryptoflorescence.

Cracking that occurs at the pore level caused by freeze-thaw cycles is likely not to be significantly damaging for rendered façades in Portugal in the future. The general temperature increase and projected reduction of cold spells do not favour the cooling of the render and the freezing of water retained in its porous structure, which are the freeze-thaw cycle phases when damage generally occurs [109].

The general expectations of more cracking in rendered façades by the end of the century could become more evident in the interior part of the country, where temperature warming is projected to be higher. Central and northern inland areas could be more favourable to the emergence of cracks caused by degradation mechanisms that also require the direct contribution of wind-rain action (e.g., to enhance temperature gradient within a heated render or to trigger salt weathering), since precipitation decrease in these areas is not expected to be as accentuated as in the south of Portugal.

4.3. Loss of Adhesion

Temperature warming contributes to exacerbating deformations of hygrothermal nature in rendered façades that could cause bulging and detachment. Simultaneously, as described for cracking, its action could be favourable to (i) alkali-aggregate reaction that may cause loss of adhesion problems, such as spalling, as well as to (ii) cryptoflorescence that may lead to crumbling, spalling, bulging and detachment. On the other hand, wind and rain reduction is generally unfavourable for the degradation mechanisms behind loss of adhesion problems, since it lessens the probability of façades being wetted. It balances the possible negative effects of temperature increase, which inhibits clear conclusions.

Cracking could be a weighting factor that favours bulging and detachment since it is a prior triggering defect and is generally expected to occur more in the future. The resulting cracking from thermal expansion is a path to water penetration and subsequent degradation [106]. Therefore, it promotes salt weathering and pore saturation, loading and stressing renders in already vulnerable conditions and possibly leading them to their durability threshold. Salt weathering also causes crumbling and spalling, for which the presence of cracks could also be a favourable prior defect. Wind pressure, which promotes rainwater penetration in façades, could be low and still be enough to move water into the render if existing cracks are sufficiently wide [110]. Therefore, the projected decline in wind intensity may not be enough to prevent water penetration in the render, considering the possible existence of significant cracks. The areas of the country where the loss of adhesion defects could be more prone to occur tend to coincide with the ones identified for cracking.

4.4. Potential Influencing Aspects Not Detailed in the Study

The expectations about the impact of climate change on the future degradation of rendered façades in Portugal do not cover the influence of specific factors in depth, such as (i) the alterations in the pattern of winter precipitation, and (ii) local environmental conditions and microclimate.

The projected intensity increase of rainfall in briefer periods could affect all of the renders' degradation mechanisms triggered by wind-rain action. It could have more washing and leaching potential, thereby enhancing dirt stains (e.g., in façades with prior deposition of particles) and discolouration, respectively, in winter. Rainwater-increased washing ability could also promote crumbling. Additionally, water from heavy precipitation could remain on the ground if drainage is poor, and trigger degradation mechanisms in lower parts of façades, due to splashing on the surface and rising damp in the render [61]. The projected strong precipitation events in winter could also be favourable to an effective dissolution of salts if the water is able to penetrate deep in the pores and lead to a fast saturation, which could be facilitated by the presence of cracks. Nevertheless, the impact of strong precipitation events on salt weathering depends on aspects such as the period of water/salt contact necessary for dissolution and the characteristics of the porous structure, which determine the render's response to rainwater action. Permeability to water and the absorption capacity of the render depend on the pores' distribution, size, shape [45,47] and connectivity. These aspects also influence the circulation of water in the render [48], the period of retention, and the time needed for its release, which are crucial factors for salt weathering induced by climate action.

The microclimate is crucial for the degradation phenomena, which could vary between different façades of the same building since it depends on orientation [111,112]. The development of a rendered façade's degradation mechanism is often based on transitions of state (e.g., from dry to wet and vice versa) and depends on climate fluctuations (e.g., temperature and humidity), considering their frequency, speed and intensity. These aspects may vary according to the façade's orientation, since this determines the exposure to solar radiation and consequently the render's temperature, the speed of the drying process [51,60] and potential UV weathering. This is why in Portugal, north-oriented façades tend to be more vulnerable to staining, given the absence of direct sunlight, lower temperatures and longer wet cycles. South-oriented façades, on the other hand, could be more susceptible to cracking and discolouration, due to significant exposure to solar radiation [113]. Currently, the south tends to be associated with less degradation than the north.

Could the condition of south-oriented façades become worse than north-oriented ones by the end of the century, if the expected increase of cracking due to exposure to higher temperatures and the decrease of staining due to exposure to less wind-rain action are both considered? Could a strong but brief precipitation event be more damaging to the durability of renders than milder rainfall for a longer period? The assessment of expectations on the future degradation of rendered façades, including precipitation patterns and microclimate particularities, is a complex issue and needs further research.

5. Conclusions

The result of the present research is an overview of the expectations of the degradation of rendered façades in a progressively warmer and drier climate. Expectations are defined through educated guesses based on links established between climate change projections for Portugal, contextualized in the MED and Southern Europe, and the impact of climate agents on degradation mechanisms and resulting defects of rendered façades. The study mainly covered the impact of climate agents' gradual action over time (e.g., temperature, precipitation, and wind), and excluded direct maintenance activities.

The future degradation of rendered façades in Portugal is expected to be characterized by less staining and more cracking, mainly because wind-rain action intensity is likely to decrease and temperature warming is likely to rise, respectively. The contribution of the projected temperature increase to salt weathering is more uncertain. Future loss of adhesion problems is therefore difficult to anticipate, since salt weathering could cause a broad spectrum of defects within this category and expectations on other degradation mechanisms are generally unclear. Despite the possible damage caused by salt weathering, less crumbling and spalling could occur in the future due to the reduced chance of freeze-thaw in winter and washing of fine particles throughout the year. Bulging and detachment could occur more with the contribution of temperature increases to thermal expansion and subsequent deformations. Loss of adhesion problems could also be enhanced in the future by the expected increase in cracking.

Generally, the impact of climate change on the degradation of rendered façades in a progressively warmer and dryer climate may not be substantial. The projected precipitation decrease and drying trend could help to lessen gradual climate-induced degradation by the end of the century, since water is a crucial agent in the triggering and development of defects [114].

The expectations for the emergence of salt-related defects in rendered façades are not conclusive and would benefit from further research, considering the paramount importance of salt crystallization to the degradation of porous materials [83]. More research on the joint contribution of temperature and humidity to alkali-silica gel swelling [79] and after-curing carbonation could also be useful to clarify the future impact of these phenomena on cracking and spalling.

The composition of the mix influences the properties of the hardened render, which establish its performance throughout service life, and can be objectively defined. Other aspects, such as surface texture and colour, are also important for the render's responsiveness to climate action. Detailed expectations of climate change effects on degradation mechanisms could be considered at the stage of planning the render's composition and finishing, with the objective of preventing damage, extending service life, and lessening future maintenance needs in rendered façades.

The conclusions of the present research could apply at a regional level, to the MED and Southern Europe, particularly in vulnerable areas where the climate tends to become warmer and drier [19], and where climate change projections generally coincide with those for Portugal. The results could be useful to further research on the service life and maintenance planning of rendered façades within the context of buildings' durability and adaptation to climate change.

Author Contributions: Conceptualization, J.B., A.S., J.d.B. and A.T.; methodology, J.B.; software, J.B.; formal analysis, J.B.; investigation, J.B., A.S., J.d.B. and A.T.; writing—original draft preparation, J.B.; writing—review and editing, J.B., A.S., J.d.B. and A.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the FCT (Portuguese Foundation for Science and Technology) through the project BestMaintenance-LowerRisks (PTDC/ECI-CON/29286/2017) and the PhD programme PD/BD/150397/2019. The authors gratefully acknowledge the support of FCT, CERIS and Itecons.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The authors gratefully acknowledge the support of CERIS and Itecons.

Conflicts of Interest: The authors declare no conflict of interest.

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