

## Article

# Natural Weathering of Bio-Based Façade Materials

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Received: 9 May 2020; Accepted: 3 June 2020; Published: 5 June 2020



**Abstract:** Although there is a global awareness that the exploitation of non-renewable materials is unsustainable, there has been limited interest in fully utilizing natural, renewable resources like wood and its products because of the service durability concerns. One such issue is the aesthetical degradation of wooden facades due to the impact of weathering. This research was carried out as an international cooperation project to ascertain the weathering resistance of bio-based façade materials under the Estonian climate. In total, 120 bio-based façade materials obtained from 31 different companies, universities and research institutions from 17 countries were investigated. The specimens were placed on an exposure rack, inclined at an angle of 45° located at 59°23′50.6″ N 24°39′24.0″ E and then subjected to accelerated natural weathering for 2 years. Parameters such as precipitation, UV index, temperature and relative humidity were measured during the period of the natural weathering. The influence of the weathering on the colour change and cracks on the surface of test specimens was evaluated using Minolta Chroma Meter CR-121 (Konica Minolta INC., Tokyo, Japan) and Avongard Check Width Gauge (Avongard Ltd., Gloucestershire, UK), respectively. The results showed that the untreated natural wood façade materials presented the least resistance to weathering, while 63 of the tested materials developed checks. The outcome of this study is essential to the optimization of software-simulating changes in the appearance of façade materials in outdoor conditions.

**Keywords:** natural weathering; bio-based materials; wood; colour change; checks

## 1. Introduction

Forestry accounts for 30% of the Earth's land resources in Europe, but only about 1.6% of wood is used as a construction material [1]. This limited application of wood is traced to the issue of durability during service [2]. Through further research, innovation and development of a new approach, wood properties have been enhanced to provide a significant increase in their strength. However, there is a lack of awareness or sufficient information available [3]. Recent publications present the benefits that can be achieved by using bio-based materials [4,5]. For changing the consumer's behaviour, more information about the service life prediction, cost of service and aesthetical performance of wooden façade materials is collected and provided in several recent research papers [2,5,6]. The major factor affecting wooden façade material during service is weathering that causes the deterioration affecting the aesthetics and structural integrity of the covering. Weathering of wood material is influenced by parameters such as solar radiation, water, atmospheric temperature, humidity, oxygen, microorganisms and so on that can alter the material appearance [7]. However, the rate of weathering depends on the durability of the wood species [8], finishing type, technical design, climatic conditions, duration and direction of exposure as well as the inclination of the material surface [6,9]. It is essential to adopt proper construction design and adequate protection from water entrapment to minimise the effect of weathering. Moreover, coatings, impregnation, chemical and thermal modification of wood or wood with higher natural durability should be used for outdoor construction [3,8,10–14].

Our study aimed to evaluate the accelerated 2-years weathering resistance of 120 bio-based façade materials in the Estonian climate. There was international collaboration in this research to provide knowledge about the fundamental properties of novel bio-based building materials. Furthermore, the obtained results could be used to develop optimised simulation software and validate the developed models of the weathering of building façades.

## 2. Materials and Methods

### 2.1. Façade Materials

The 120 façade specimens were obtained from 31 companies and 17 countries, the majority of which are in Europe with some from Central America and New Zealand. The samples measured 150 mm × 75 mm × 20 mm in length, width and thickness, respectively. Specimens were categorised based on the type of modification into 7 groups (Figure 1). The bulk of the samples were from impregnated wood materials (Beech and Beech chips (4), Fir (3), Poplar (6), Spruce (6), and Pine (10)), which were treated with either AATMOS (3-(2-Aminoethylamino) propyl trimethoxysilane), TA (Timbercare Aqua), Fluorosilane, DMDHEU (1.3-dimethylol-4.5-dihydroxyethyleneurea), Knittex, Madurit (aqueous unetherefied and etherified melamine resins for impregnation—amine salt) or Fixapret (modified dimethyloldihydroxyethylene urea) impregnation. The 25 hybrid modified materials used were either chemically impregnated or thermally modified before surface coating or further impregnation. Examples of such materials in this group are Accoya (acetylated and surface-coated wood [15]), impregnated softwood coated with biofilms, thermally modified wood (oak) coated with wax and so on. Only 7 composite materials Tricoya (coated, acetylated medium density fibre (MDF) board [16]), wood–plastic composite (WPC), ceramics and bamboo (*Bambuseae*)-coated particleboards and 5 chemically modified samples were provided for the test.

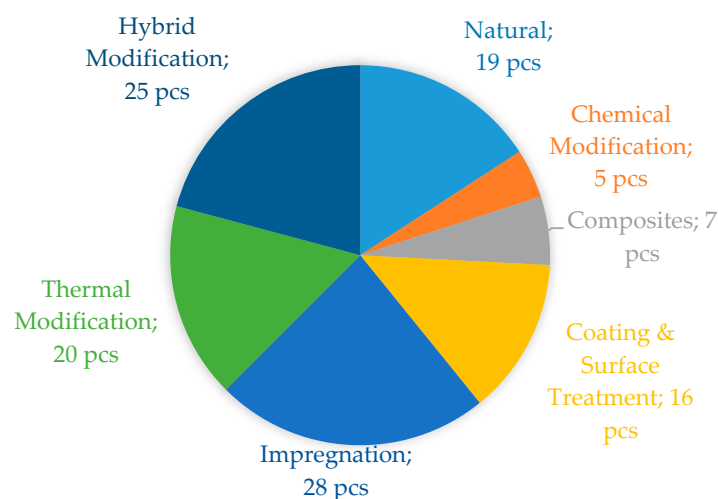


Figure 1. Groups of materials evaluated. [4,17].

### 2.2. Site Description

The effect of weathering on the materials was evaluated in Tallinn. We commenced the experiment in Tallinn on March 14th in 2017 and concluded on March 26th in 2019 (2 years). The weathering site was at Laboratory of Wood Technology in Tallinn University of Technology (59°23′50.6″ N 24°39′24.0″ E) on an exposure rack inclined at a 45° angle (according to EN ISO 2810 [18]) and facing the south (Figure 2), to aid water drainage and good exposure to the sun, respectively.



**Figure 2.** Specimen set-up (southern exposure, 59°23′50.6″ N 24°39′24.0″ E).

### 2.3. Evaluation Method

Material assessment was done in accordance with the guidelines stipulated by COST FP1303 [2] for colour change and formation of checks, which are in line with EN ISO/CIE 11664-4 [19] and EN ISO 4628 [20], respectively. The colour measurement was performed using Minolta Chroma Meter CR-121 based on the International Commission of Illumination (CIE—Commission Internationale de l'éclairage)  $L^*a^*b^*$  (Lab) colour space method, also known as CIELAB. The  $L^*$  axis represents the light and dark scale of a specimen (i.e.,  $L = 100$  and  $L = 0$ , respectively). Axis  $a^*$  shows specimen colour in the scale of red ( $a = 100$ ) and green ( $a = -100$ ), while axis  $b^*$  shows the scale of yellow ( $b = 100$ ) and blue ( $b = -100$ ) [21]. The colour coordinates were measured from three predefined points on the surface of the specimens to ensure uniformity. The mean value was then used to characterise the colour change for each of the samples. In addition, all of the specimens were captured every month using a Canon EOS 450D camera, while Checks were evaluated using Avongard Check Width Gauge. Checks were evaluated after the first 3 months of weathering. Equation (1) below shows the mathematical expression for determining the colour change in the colour space referred to as Units of Measure (U/M).

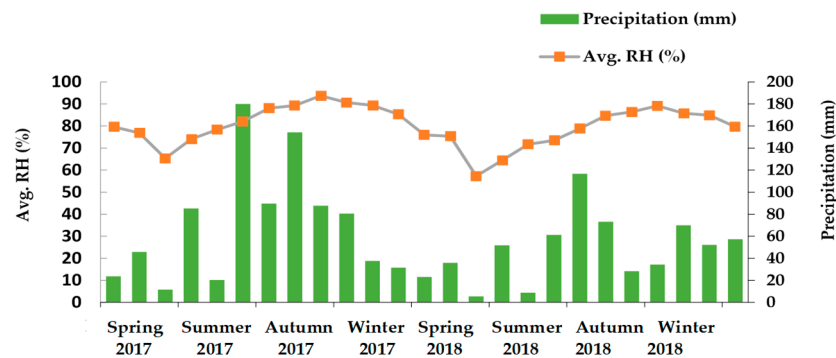
$$\Delta E = \sqrt{(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2} \quad (1)$$

where  $\Delta L$ ,  $\Delta a$  and  $\Delta b$  are the colour change in  $L^*$ ,  $a^*$  and  $b^*$  axes, respectively. For reference,  $\Delta L = (L_1 - L_2)$ , where  $L_1$  is colour coordinate after latest measurements in the  $L^*$  axis and  $L_2$  is colour coordinate before the exposure in the  $L^*$  axis.

## 3. Results

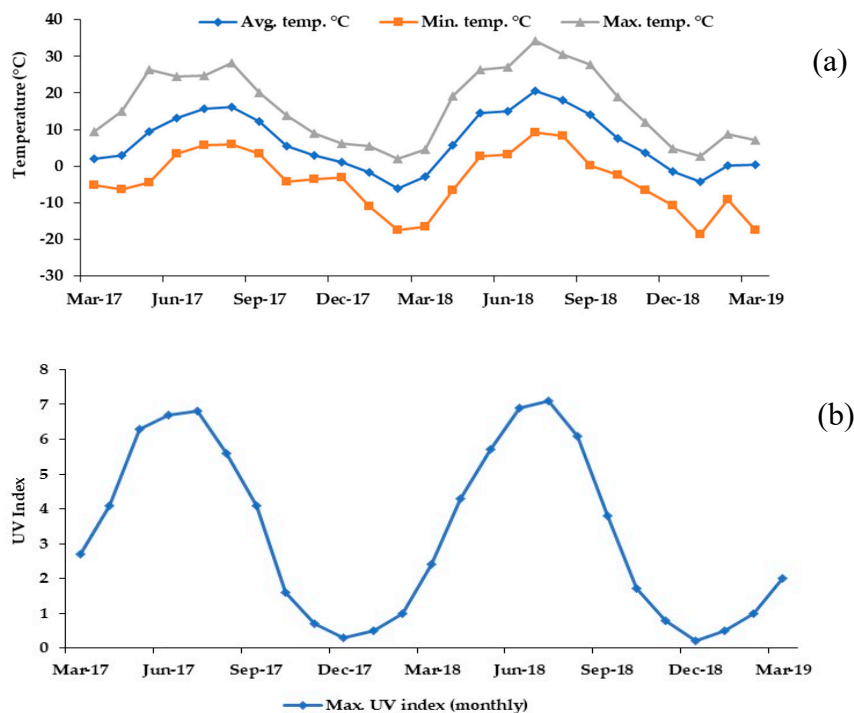
### 3.1. Weather Conditions

Estonian Weather Service Station situated in Harku provided the weather data during the tests. The considered parameters were precipitation, UV index, average, maximum and minimum air temperature and average relative humidity (RH), all changing with the four seasons. The precipitation and relative humidity data presented in Figure 3 shows, on the average, low amounts of precipitation during the spring and summer of both years. However, the highest monthly value (180 mm) was in August of 2017, while the lowest was in May 2018 (5.5 mm), which corresponds to 57.3% of RH, the lowest for both years. On average, the highest RH (82.7%) in the first year of weathering was more than that in the second (77.3%).



**Figure 3.** Precipitation and relative humidity during 2-year weathering.

The lowest air temperature recorded was  $-17.5\text{ }^{\circ}\text{C}$  in February 2018, while the highest was  $34.2\text{ }^{\circ}\text{C}$  in July of the same year (Figure 4a). The average temperature ranged from  $-6\text{ }^{\circ}\text{C}$  (February 2018) to  $20.4\text{ }^{\circ}\text{C}$  (July 2018). The UV index (Figure 4b) was highest in the summer period of both years (6.8 and 7.1 in 2017 and 2018, respectively) while the lowest recorded index was in December 2018 (0.2).



**Figure 4.** The air temperature (a); UV index (b) during the 2-year weathering as obtained from Estonian Weather Service Station situated in Harku.

### 3.2. Appearance and Colour Change of Specimens after 2 Years of Weathering

Figure 5 shows how the 120 test specimens' appearances changed during the 2-year weathering period. It can be seen that the effect of weathering was severe for those materials under the Estonian climate. Visually, only about 20 of the materials appeared to maintain their original colour at the end of the study.

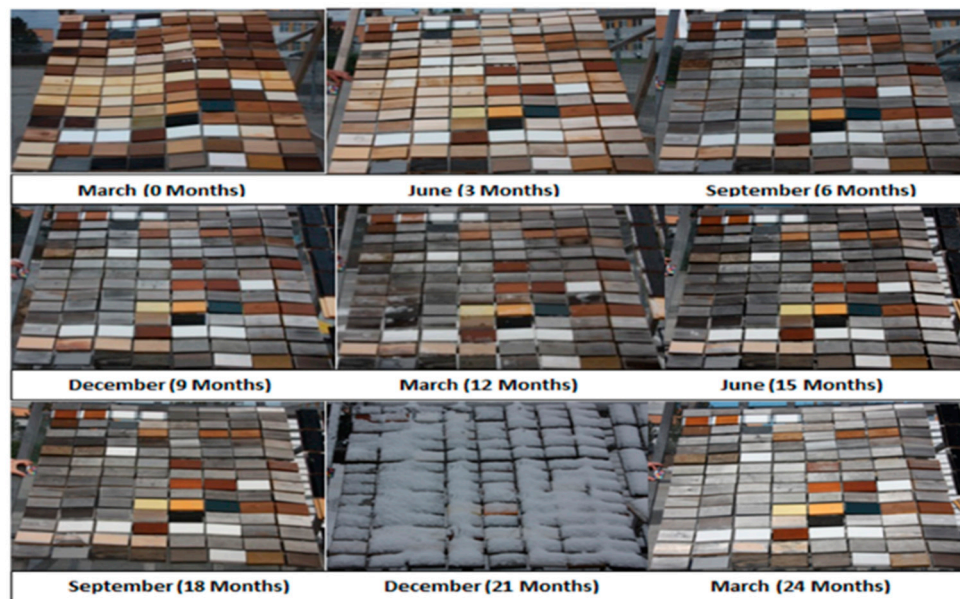


Figure 5. Experimental samples during natural weathering in Tallinn (2 years).

Table 1 shows the colour changes of all the natural wood and bamboo specimens at the end of the 2-year weathering period. It can be seen from Table 1 that all test specimens showed relatively low resistance to colour change with an overall mean outcome of  $25 \pm 7$  U/M. However, the average colour change of the bamboo specimens was  $17 \pm 3$  U/M, which was significantly lower than that of the wood specimens ( $26 \pm 7$  U/M). Additionally, the hardwood species appear to show better colour retention with an average  $\Delta E$  of  $21 \pm 5$  U/M compared to  $32 \pm 1$  U/M of the softwood samples.

Table 1. Colour changes of natural specimens.

Wood Specimens	Scientific Name	$\Delta E$ (U/M) After 2 Years
Norway Spruce	<i>Picea abies</i>	$35.7 \pm 1.7$
Pine (Heartwood, dried 50–70 °C)	<i>Pinus radiata</i>	$33.6 \pm 3.7$
Pine	<i>Pinus radiata</i>	$31.3 \pm 4.6$
Larch with Laser Graver	<i>Larix</i> sp.	$31.0 \pm 2.9$
Southern Yellow Pine	<i>Pinus echinata</i>	$30.7 \pm 3.4$
Natural Pine	<i>Pinus sylvestris</i>	$30.4 \pm 2.8$
Silver Fir	<i>Abies alba</i>	$30.0 \pm 1.4$
Softwood	-	$29.0 \pm 1.5$
Plantation Teak (Class P_B)	<i>Tectona grandis</i>	$28.6 \pm 2.3$
Plantation Teak (Class A)	<i>Tectona grandis</i>	$26.9 \pm 2.0$
Plantation Teak (Class B)	<i>Tectona grandis</i>	$24.2 \pm 0.7$
Plantation Teak (Class C)	<i>Tectona grandis</i>	$21.8 \pm 3.7$
Oak	<i>Quercus petraea</i>	$20.8 \pm 4.1$
Beech	<i>Fagus sylvatica</i>	$19.4 \pm 2.9$
Bamboo Cladding	<i>Bambuseae</i>	$18.9 \pm 4.7$
Natural Beech	<i>Fagus</i> sp.	$18.5 \pm 2.7$
Bamboo Decking	<i>Bambuseae</i>	$15.3 \pm 0.8$
Poplar	<i>Populus tremula</i>	$14.6 \pm 1.6$
Ceris Oak	<i>Quercus cerris</i>	$13.8 \pm 2.2$

In the results shown in Table 2 for the chemically modified specimens, the overall average was  $13 \pm 4$  U/M. It can be seen that the type of chemical treatment influences the material performance more than the type of wood species. There was no significant difference for acetylated pine and alder, but acetylated beech appears to show a better outcome. Furfurylation treatment showed a significantly better outcome ( $10 \pm 4$  U/M) than acetylation ( $16 \pm 1$  U/M). Diverse composite samples



were compared. Hence, it will be inaccurate to present an overall outcome. Nonetheless, the results show that composites of wood and plastics are 3 times more likely to retain the original colour compared to those of only wood-based materials (average  $\Delta E = 21 \pm 3$  U/M). Coated, acetylated medium-density fibreboard and bio-ceramics specimens showed very good colour retention after weathering, with mean values of  $4 \pm 0.3$  U/M and  $5 \pm 1$  U/M, respectively.

**Table 2.** Colour change of chemically modified and composite specimens.

Chemically Modified Specimens	$\Delta E$ (U/M) after 2 Years	Composites	$\Delta E$ (U/M) after 2 Years
Acetylated Radiata Pine	$16.5 \pm 1.3$	Particleboard and Bamboo	$23.2 \pm 1.4$
Acetylated Alder	$16.4 \pm 0.8$	Fiberboard	$18.5 \pm 5.3$
Acetylated Beech	$14.3 \pm 1.0$	Wood Plastic Composites	$7.4 \pm 1.2$
Kebony (Furfurylated)	$12.4 \pm 1.1$	Bio-Ceramics	$4.5 \pm 1.0$
Scots Pine Kebony (Furfurylated)	$6.8 \pm 3.4$	Tricoya. Opti finish	$4.5 \pm 0.3$
		Tricoya for cladding.	$4.1 \pm 1.0$
		Pigmented White	$4.0 \pm 1.5$
		Tricoya White	$4.0 \pm 1.5$

Table 3 presents the results for the surface-coated and impregnated materials. Similarly, the different types of treatment and specimens offer different outcomes, leading to high error margins ( $\pm 8$ ) for the coated specimens. The average colour change was 13 U/M. Overall, spruce coated material showed better colour stability ( $6 \pm 0.7$  U/M) compared to the other coated wood-based materials (pine and oak). For the outcome of impregnated materials, three groupings were made according to the type of wood and the similarity of the impregnating chemicals. The result was significantly better for impregnated pine, with an average value of  $30 \pm 4$  U/M, compared to impregnated spruce ( $32 \pm 4$  U/M) and poplar ( $34 \pm 4$  U/M). Additionally, when we compared the method of chemical penetration, forced impregnation produced a better result than soaking. Considering the type of chemicals, copper ethanalamide (CEA)-impregnated softwood presented the best outcome ( $10 \pm 2$  U/M).

**Table 3.** Colour change of surface coated and impregnated wood-based specimens.

Surface Coated Specimens	$\Delta E$ (U/M) after 2 Years	Impregnated Specimens	$\Delta E$ (U/M) after 2 Years
Pine. nanocoated	$27.4 \pm 1.2$	Spruce. AATMOS soaked	$39.0 \pm 1.3$
Natural Oak. Waxed	$22.9 \pm 0.6$	Spruce. TA Impregnated. + Fluorosilane	$38.8 \pm 4.0$
Larch Lightly Burned	$18.4 \pm 4.2$	Poplar. TA Impregnated. + Fluorosilane	$37.5 \pm 3.1$
Pine. Aqua Coating	$17.9 \pm 2.4$	Poplar Soaked AATMOS	$37.1 \pm 0.8$
Natural Oak Coated	$17.4 \pm 3.7$	Spruce. TA Fluorosilane soaked	$34.2 \pm 1.6$
White Treatment Solas	$14.0 \pm 0.2$	Spruce. Impregnated. AATMOS	$33.9 \pm 1.6$
Softwood. Coated	$12.1 \pm 2.6$	Pine. Soaked AATMOS	$33.5 \pm 1.9$
Pine. Grey Coating	$9.3 \pm 1.4$	Pine. Impregnated + Soaking in Fluorosilane	$32.6 \pm 1.7$
Pine. White Coating	$9.3 \pm 2.6$	Poplar. Impregnated AATMOS	$32.2 \pm 3.4$
Natural Spruce. Oiled	$9.3 \pm 0.5$	Pine. Impregnated AATMOS	$31.6 \pm 4.6$
Hardwood. for Windows (coated)	$9.1 \pm 1.2$	Spruce. Fluorosilane	$30 \pm 1.5$
Larch Carbonised	$8.8 \pm 4.0$	Beech. Silicone	$29.8 \pm 3.9$
Softwood. Water Base	$8.5 \pm 1.7$	Poplar. Impregnated + Fluorosilane	$29.6 \pm 2.5$
Softwood. Solvent Base	$7.9 \pm 0.3$	Poplar. Fluorosilane	$28.6 \pm 1.7$
Spruce. Coated	$5.5 \pm 0.7$	Spruce. Impregnated + Fluorosilane	$28.6 \pm 2.7$
Softwood. for Windows	$1.6 \pm 0.3$	Poplar. Impregnated. + Soaking in Fluorosilane	$28.5 \pm 1.4$
		Pine. DMDHEU	$27.8 \pm 1.6$
		Fixapret	$25.0 \pm 3.2$
		Pine. TiO <sub>2</sub>	$24.2 \pm 0.2$
		Silver Fir	$23.4 \pm 4.2$
		Silver Fir. treated	$21.5 \pm 0.9$
		Beech. impregnated	$20.7 \pm 3.1$

Table 3. Cont.

Surface Coated Specimens	$\Delta E$ (U/M) after 2 Years	Impregnated Specimens	$\Delta E$ (U/M) after 2 Years
		Silver Fir	$20.5 \pm 1.6$
		Madurit	$20.3 \pm 3.1$
		Beech. PBS	$19.6 \pm 1.7$
		Knittex	$18.3 \pm 0.2$
		Beech. PLA	$11.3 \pm 0.9$
		CEA impregnated Softwood	$10.1 \pm 1.7$

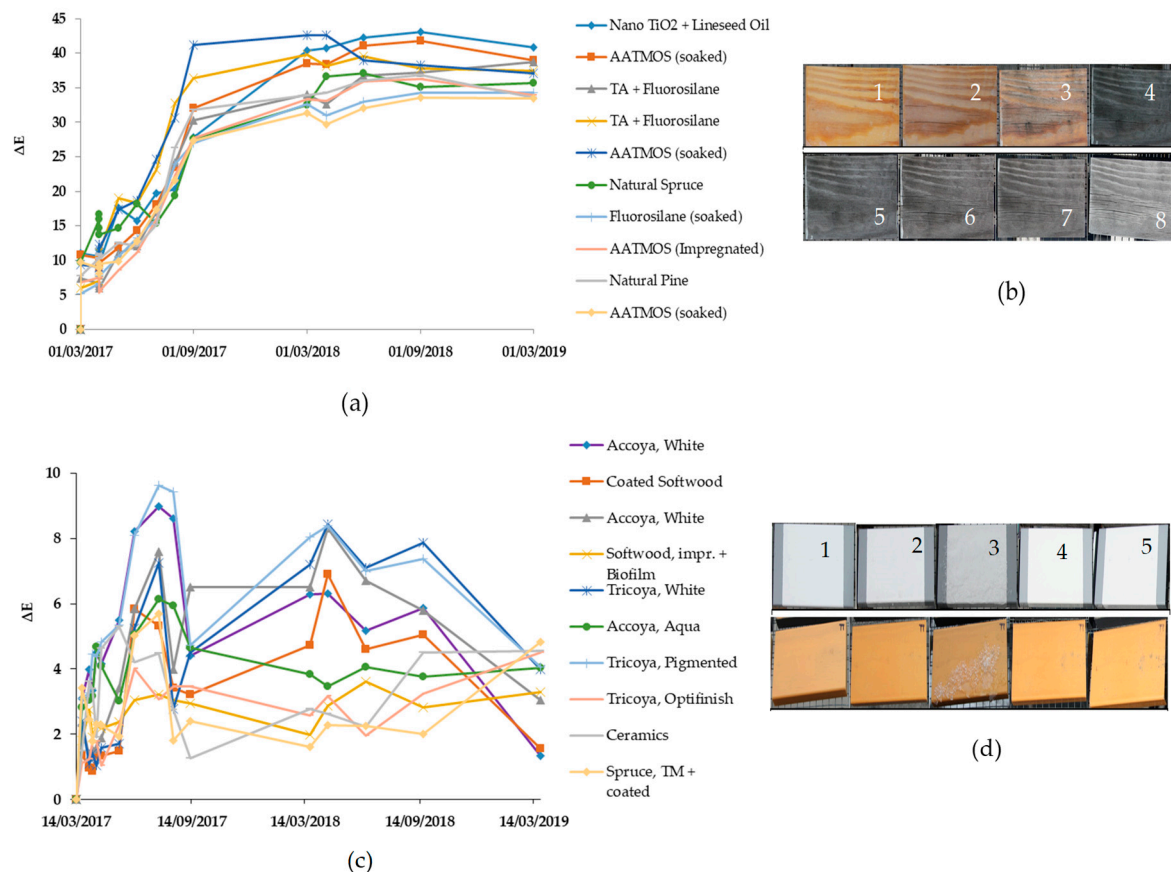
Table 4 shows the values of the colour change for thermally modified, and hybrid treated specimens. The mean value of the colour change ( $18 \pm 5$  U/M) was the second highest of all the groups of material after that of samples from natural wood. Many of the samples observed were from thermally modified spruce and pine. Although there was no significant difference in test results between these two wood types, the test results showed that overtreatment with heat could enhance colour stability as we can see from the outcome presented by overtreated spruce ( $7 \pm 2$  U/M). The samples from thermally modified poplar also showed similar results to those of the aforementioned wood types. The weakest colour stability was from thermally modified wood frakes ( $22 \pm 4$ ), while TM oak and ash showed comparable outcomes with  $\Delta E$  values of  $13 \pm 0.2$  U/M and  $13 \pm 3$  U/M, respectively. On the contrary, the average outcome presented by hybrid samples was  $13 \pm 9$  U/M, with the acetylated + surface coated wood (pigmented white) displaying the optimum colour stability ( $1.3 \pm 0.3$  U/M) of all the 120 samples examined. It appears that the type of hybrid treatment influenced the colour stability more than the kind of material used. For illustration,  $\Delta E$  varies from 1 to 18 U/M for the acetylated wood with different types of coatings and from 7 to 41 U/M for pine with a different combination of solution/coatings treatment. In comparison, no significant difference can be seen between spruce ( $14 \pm 2$  U/M) and pine ( $14 \pm 4$ ) test pieces having similar treatments (TM + coating).

Table 4. Colour change of thermally modified and hybrid treatment specimens.

Thermally Modified Specimens	$\Delta E$ (U/M) after 2 Years	Hybrid Modified Specimens	$\Delta E$ (U/M) after 2 Years
Frake. TM	$25.4 \pm 2.2$	Pine. Nano TiO <sub>2</sub> + Linseed Oil	$40.8 \pm 2.2$
Radiata Pine. TM	$24.2 \pm 1.9$	Spruce. TM + Oil	$25.2 \pm 1.9$
Pine. TM	$23.8 \pm 3.1$	Poplar. Madurit + TM	$22.9 \pm 1.8$
Spruce. TM	$23.1 \pm 1.2$	Accoya (Poseidon)	$20.8 \pm 3.0$
Spruce. TM	$22.0 \pm 1.4$	TM Oak + Coated	$19.7 \pm 5.6$
Spruce. TM	$21.9 \pm 2.6$	Accoya (Hydro-Oil)	$17.9 \pm 1.4$
Poplar. TM	$20.0 \pm 1.1$	Softwood. TM + Wax	$14.8 \pm 1.6$
Ayous. TM	$19.3 \pm 1.8$	Pine. TM + Coating	$14.3 \pm 4.0$
Frake. TM	$19.2 \pm 1.7$	Spruce. TM + Coating	$14.2 \pm 2.3$
Pine Thermo D 212 °C	$18.7 \pm 2.1$	Oak. TM + Wax	$13.4 \pm 0.5$
Spruce Thermo D 212 °C	$18.6 \pm 4.9$	Radiata Pine. Silicate	$13.2 \pm 2.5$
Sycamore. TM	$17.4 \pm 1.4$	Radiata Pine. TM + Coating	$12.1 \pm 0.8$
Pine. TM	$17.0 \pm 0.4$	Pine. Treated + Triazole	$11.1 \pm 1.6$
Poplar. TM	$16.7 \pm 2.3$	Spruce TM + FeSo <sub>4</sub>	$10.4 \pm 1.8$
Thermally Treated Obeche	$15.4 \pm 2.3$	Ayous TM + Coating	$10.3 \pm 0.8$
Pine. OHT	$14.8 \pm 2.2$	Accoya (Dark)	$10.2 \pm 0.7$
Ash Thermally Treated	$13.5 \pm 2.6$	Accoya (Matt)	$9.2 \pm 3.8$
Thermally Modified Oak	$12.6 \pm 0.2$	Radiata Pine. Water	$8.6 \pm 0.5$
Softwood. TM	$12.0 \pm 1.3$	Frake. TM + Coating	$7.8 \pm 0.8$
TM Spruce. Over treated	$7.1 \pm 1.8$	Pine. Triazole + Treated	$7.0 \pm 4.0$
		TM Spruce. Coated	$4.8 \pm 1.0$
		Accoya (Aqua)	$4.0 \pm 0.9$
		Softwood. Biofilm	$3.3 \pm 0.4$
		Accoya (White)	$3.0 \pm 0.2$
		Accoya (Pigmented White)	$1.3 \pm 0.3$

Figure 6a shows the colour change for the 10 most weathered specimens. Mostly affected were natural wood (pine and spruce) and chemically (AATMOS and Fluorosilane) impregnated materials. Image of Nano TiO<sub>2</sub> + linseed oil impregnated wood taken during 3-month intervals is presented in Figure 6b with Pallet 1 and 8 showing the pictures taken before weathering in March 2017 and after in March 2019. As can be seen from Figure 6, the colour was fairly stable in the first 3 months,

followed by a more rapid change in the latter stages (October 2017 (pallet 4) to March 2018). Figure 6c displays the results of the 10 most colour-stable samples, which consist principally of acetylated + surface coated wood, coated + acetylated medium density fibreboard, surface-coated woods, ceramic material and hybrid (TM and coated spruce). Figure 6d presents a more explicit image of the colour change of accoya (matt and pigmented white) taken during 6-month intervals (Pallet 1, the first image before weathering and Pallet 5, the image after weathering in March 2019), very good colour stability is observed throughout the weathering period.



**Figure 6.** (a) Ten specimens with the most colour changes, (b) image of titanium dioxide (TiO<sub>2</sub>)-impregnated + linseed-oil-treated wood taken at 3-month intervals, (c) 10 specimens with the least colour changes and (d) image of accoya (matt and pigmented white) taken at intervals of 6-month until the end of weathering [17].

### 3.3. Material Surface Checks

Figure 7 presents the materials with the longest total checks obtained from aggregates of widths exceeding 0.1 mm, while Figure 8 shows an image of the noticeable splits that occurred on the surface of pine nano TiO<sub>2</sub> impregnated pine after the 2-year weathering time. Before the weathering, 21 of the samples, especially oak and some tropical hardwood, previously showed some amounts of visible checks on the surface that were not counted during the evaluation. After 3 months, there were 40 materials with surface checks, and at the end of the research, most checks were from natural wood and impregnated and thermally modified specimens.



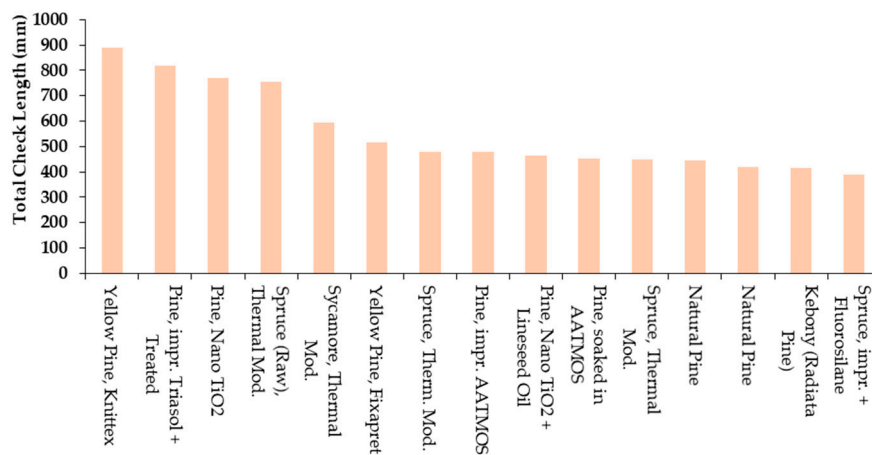


Figure 7. Materials with the longest total checks after 24 months of weathering.

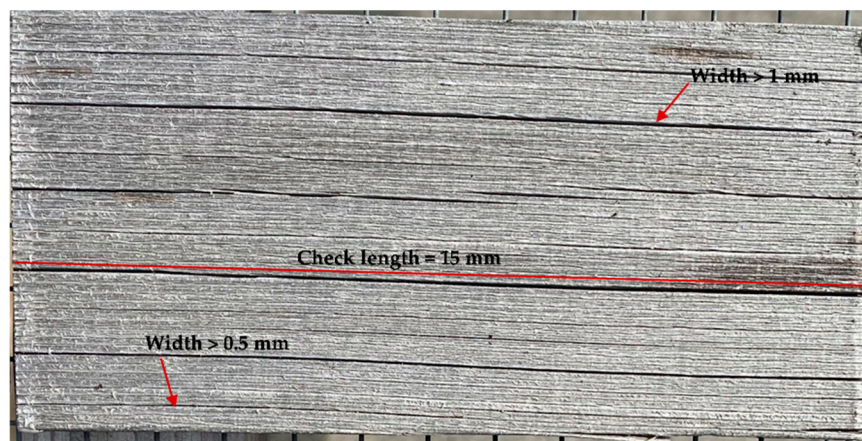


Figure 8. Visible cracks of nano TiO<sub>2</sub>-impregnated pine after 2 years of weathering.

#### 4. Discussion

The fluctuation in climatic conditions makes it problematic for materials to maintain their original condition. Material degradation during weathering is increased by almost two times by the set-up of the specimens on the exposure rack (45°) compared to a vertical (90°) set-up [9]. Overall, results showed that the use of untreated wood as façade material should be discouraged. Spruce, larch and pine showed low colour stability during weathering tests [22]. This outcome was expected because these wood species are naturally classified as moderate to low durability [8]. The colour change ( $\Delta E$ ) result for spruce (34.1 U/M) obtained after 1 year of weathering was like the  $36 \pm 2$  U/M obtained in our study. However, it may be difficult to relate results from different studies because of the distinct geographic location and environmental conditions. A major reason for the colour changes in natural wood is attributed to delignification [22]. For TM wood façade materials, resistance to colour change of TM spruce (7 U/M) was the best, while 11 out of the 20 TM façade test specimens also showed good colour stability (below the measured average of  $18 \pm 5$  U/M). When comparing untreated wood and TM wood, past research confirms that thermal modification enhances colour stability [11]. Impregnated materials showed higher colour degradation, with just three of the 28 specimens, CEA-impregnated softwood, poly-lactic acid (PLA)-treated beech and Knittex-treated yellow pine, presenting some resistance to colour deterioration. Copper-based preservatives are known to decrease photodegradation of wood [23], which is attributed to a reduction in delignification during weathering [24]. Although PLA-treated beech and Knittex-treated pine showed some measure of resistance to colour change, there was a stable shift in the  $b^*$  axis with the material becoming bluish (by  $-10$  U/M), which is assumed to be due to leaching of decomposed lignin and extractives [22]. Chemical impregnation of wood by

AATMOS and flourosilane primarily resists biological degradation (insects and fungi), decay and water damage, but they do not give as much improvement to colour stability [25,26]. This may be the reason for their slightly poor performance. All the chemically modified specimens offered better outcomes than previously mentioned samples with Kebony modified materials that showed the best stability. This result is in accordance with Rowell et al. [7] and Temiz et al. [24], whose studies have shown that chemical modification by acetylation promotes colour stability. Nanocoated pine (27 U/M) and waxed oak (23 U/M) were the only two surface-painted materials of the 16 examined exhibiting above-average colour degradation. Oil and water-based solvent coatings showed no significant variation. The film thickness, covering the biomaterial, plays an important role in its ability to resist colour change [27]. Since no information about the thickness of the various coatings was provided, it is difficult to draw a direct comparison between the performances of the coated samples. Composite materials from particleboard and fibreboards covered with bamboo presented minimal colour stability. The exposure of a wood-based composite material to both light and water, as well as a high wood content (no information given about composite fractions), aid deterioration in colour [7]. The favourable result from coated, acetylated, medium-density fibreboard is due to the acetylation [24,25], followed by surface-coating of the medium density fibre boards. Hybrid modification, on the other hand, generally enhanced colour stability except for nano TiO<sub>2</sub>- and linseed-oil-modified pine. The hybrid modification combining a series of treatment (Chemical, impregnation or thermal) with material surface coating are most suitable. Specimens of the Accoya like the coated + acetylated medium density fibreboards showed outstanding resistance to colour change. The least colour-stable specimen was Poseidon-coated acetylated wood ( $21 \pm 3$  U/M), while the most resistant to change was pigmented white (1.3 U/M). The poor outcome by nano TiO<sub>2</sub> (an ultraviolet screen) and linseed-oil-modified pine could be due to the use of TiO<sub>2</sub>, which does not show much integration with pine wood, and, though it is confirmed to improve colour stability when used alone, no particular improvement is obtained when combined with other methods [28,29]. Even linseed oil is proven to reduce colour changes in the wood [29]. Assessment of the degree of cracking on the test specimens showed that development of surface checks was more rapid during the first year. This is due to the moisture-induced swelling of photodegraded wood particles on the surface of the material [7]. Sixty-three (63) of the tested materials, mainly natural, impregnated and thermally modified wood developed checks after the experimental period. Knittex-impregnated yellow pine developed the longest total checks (890 mm), while pine, spruce and oak samples showed significant amounts of surface checks as well. Although impregnation with chemicals reduces water uptake and enhances dimensional stability in wood, It often increases susceptibility to checking [13].

## 5. Conclusions

In the weathering resistance test, 120 bio-based materials were assessed. Due to the high colour degradation and cracking the untreated wood is not the best alternative material for façades. Additionally, impregnation and thermal modification of natural wood do not significantly improve resistance to the weathering when compared with results obtained from untreated wood. However, a combination of methods like thermal modification or other forms of wood modification with subsequent surface coating should be considered to enhance the colour stability of façade materials. Consequently, the successful approach to maintain the aesthetical conditions of wood building façade details is to use hybrid treatment of wood materials involving acetylation and surface coats or to use wood–plastic composites where the wood content does not significantly limit the colour stability of the material.

**Author Contributions:** Conceptualization, T.P., H.K.; methodology, K.V., H.K.; validation, P.A., H.K.; formal analysis, K.V., P.A.; investigation, K.V.; resources, T.P.; data curation, K.V.; writing—original draft preparation, K.V., P.A., H.K.; review and editing, P.A., J.K.; supervision, H.K., T.P. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the Republic of Estonia according to the administrative contract number 1.1-6.2/19/93 for wood technology professor.

**Acknowledgments:** Authors would like to acknowledge companies who provided samples: ABODO (New Zealand), Accsys Technologies (Netherlands), Bern University of Applied Sciences (Switzerland), BioComposites Centre (UK), CAMBOND (UK), Centre for Sustainable Products (UK), Drywood Coatings (Netherlands), EDUARD VAN LEER (Netherlands), FirmoLin (Netherlands), GraphiTech (Italy), Houthandel van Dam (Netherlands), ICA Group (Italy), IMOLA LEGNO (Italy), Kebony (Norway), KEVL SWM WOOD (Netherlands), Kul Bamboo (Germany), Latvian State Institute of Wood Chemistry (Latvia), Lulea University of Technology (Sweden), NOVELTEAK (Costa Rica), Politecnico di Torino (Italy), RENNER ITALIA (Italy), Solas (Italy), SWM-Wood (Finland), Technological Institute FCBA (France), TIKKURILA (Poland), University of Applied Science in Ferizaj (Kosovo), University of Gottingen (Germany), University of Life Science in Poznan (Poland), University of Ljubljana (Slovenia), University of West Hungary (Hungary), and WDE-Maspel (Italy).

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

## References

- Hill, C. *Wood Modification: Chemical, Thermal and Other Processes*; John Wiley and Sons, Ltd: Chichester, UK, 2006; pp. 1–18.
- Sandak, A.; Sandak, J.; Petrillo, M.; Grossi, P. Strengthening the confidence in bio-based building materials – BIO4ever project approach. Presented at Final COST FP1303 Meeting “Building with Bio-Based Materials: Best Practice and Performance Specification”, Zagreb, Croatia, 6–7 September 2017.
- Petrillo, M.; Sandak, J.; Sandak, A.; Grossi, P.; Kutnar, A. Life cycle assessment of bio-based façades during and after service life: maintenance planning and re-use. Presented at 9th European Conference on Wood Modification, Arnhem, The Netherlands, 17–18 September 2018.
- Sandak, A.; Sandak, J.; Brzezicki, M.; Kutnar, A. *Bio-Based Building Skin*; Springer Open: Singapore, 2019; Available online: <https://doi.org/10.1007/978-981-13-3747-5> (accessed on 25 May 2019).
- Sandak, A.; Sandak, J.; Grossi, P.; Petrillo, M. Simulation and modelling tool for the evaluation of the façade performance—BIO4ever project approach. FACADE 2018. Presented at Final Conference COST Action TU1403 “Adaptive Facades Network”, Lucerne, Switzerland, 26–27 November 2018.
- Sandak, J.; Sandak, A.; Grossi, P.; Petrillo, M. Simulation and visualization of aesthetic performance of bio-based building skin. Presented at IRG49 Scientific Conference on Wood Protection, Johannesburg, South Africa, 29 April–3 May 2018. IRG/WP 18-2063.
- Rowell, R.M. *Handbook of Wood Chemistry and Wood Composites*, 2nd ed.; CRC Press/Taylor & Francis: Boca Raton, FL, USA, 2012; pp. 152–199.
- Reinprecht, L. *Natural Durability of Wood. Wood Deterioration, Protection and Maintenance*; John Wiley & Sons, Ltd: Chichester, UK, 2016; pp. 14–16.
- Evans, P.D. The influence of season and angle of exposure on the weathering of wood. *Holz als Roh- und Werkstoff: Eur. J. Wood. Wood. Prod.* **1996**, *54*, 200. [CrossRef]
- EN 350-2. *Durability of Wood and Wood-Based Products*; European Committee for Standardization: Brussels, Belgium, 1994.
- Tomak, E.D.; Ustaomer, D.; Ermeýdan, M.A.; Yildiz, S. An investigation of surface properties of thermally modified wood during natural weathering for 48 months. *Measurement* **2018**, *127*, 187–197. [CrossRef]
- Coulson, J. *Wood in Construction*; John Wiley & Sons Ltd: Chichester, UK, 2014; pp. 57–78.
- Sandberg, D.; Kutnar, A.; Mantanis, G. Wood modification technologies—A review. *iForest* **2017**, *10*, 895–908. [CrossRef]
- Bulian, F.; Graystone, J.A. *Wood Coatings: Theory and Practice*, 1st ed.; Elsevier Radarweg: Amsterdam, The Netherlands, 2009; pp. 2–13.
- Accoya. Available online: [https://www.accoya.com/wp-content/uploads/2015/09/WIG\\_EN\\_lowres.pdf](https://www.accoya.com/wp-content/uploads/2015/09/WIG_EN_lowres.pdf) (accessed on 8 April 2020).
- A New Breed of MDF an Extremely Durable and Stable Wood Panel. Available online: [www.tricoya.com](http://www.tricoya.com). [https://tricoya.com/wp-content/uploads/2017/11/Tricoya\\_Main\\_Brochure\\_s16\\_FW\\_reduce\\_size-NORTH-AMERICA.pdf](https://tricoya.com/wp-content/uploads/2017/11/Tricoya_Main_Brochure_s16_FW_reduce_size-NORTH-AMERICA.pdf) (accessed on 8 April 2020).
- Visnapuu, K. Natural Weathering of Bio-Based Facade Materials. Master’s Thesis, Department of Materials and Environmental Technology, Tallinn University of Technology, Tallinn, Estonia, June 2019.
- EN ISO 2810. *Paints and Varnishes—Natural Weathering of Coatings—Exposure and Assessment*; European Committee for Standardization: Brussels, Belgium, 2004.

19. EN ISO/CIE 11664-4. *Colorimetry—Part 4: CIE 1976 L\*a\*b\* Colour Space*; European Committee for Standardization: Brussels, Belgium, 2011.
20. EN ISO 4628-4. *Paints and Varnishes – Evaluation of Degradation of Coatings – Designation of Quantity and Size of Defects, and of Intensity of Uniform Changes in Appearance – Part 4: Assessment of Degree of Cracking*; European Committee for Standardization: Brussels, Belgium, 2016.
21. Brischke, C.; Humar, M.; Meyer, L.; Bardage, S.; Bulcke, J.V. *Performance of Bio-Based Building Materials*; COST Action FP 1303 – Cooperative Performance Test Instructions for participants: Brussels, Belgium, 2014.
22. Oberhofnerová, E.; Pánek, M.; & García-Cimarras, A. The effect of natural weathering on untreated wood surface. *Maderas-Cienc. Tecnol.* **2017**, *19*, 173–184. [[CrossRef](#)]
23. Turkoglu, T.; Baysal, E.; Toker, H. The Effects of Natural Weathering on Color Stability of Impregnated and Varnished Wood Material. *Adv. Mater. Sci. Eng.* **2015**, 1–9. [[CrossRef](#)]
24. Temiz, A.; Yildiz, U.C.; Aydin, I.; Eikenes, M.; Alfrdsen, G.; Colakoglu, G. Surface roughness and color characteristics of wood treated with preservatives after accelerated weathering test. *Appl. Surf. Sci.* **2005**, *250*, 35–42. [[CrossRef](#)]
25. Broda, M.; Bart, M.; Frankowski, M. Durability of wood treated with AATMOS and caffeine – towards the long-term carbon storage. *Maderas-Cienc. Tecnol.* **2018**, *20*, 455–468.
26. Nanoprotect. Nanoprotect Wood Product System. Available online: [http://files.nanoprotect.de/System\\_Holzprodukte\\_englisch.pdf](http://files.nanoprotect.de/System_Holzprodukte_englisch.pdf) (accessed on 25 May 2019).
27. Grüll, G.; Tscherne, F.; Spitaler, I.; Forshuber, B. Comparison of wood coating durability in natural weathering and artificial weathering using fluorescent UV-lamps and water. *Eur. J. Wood. Wood. Prod.* **2014**, *72*, 367. [[CrossRef](#)]
28. Ozgenc, O.; Hizioglu, S.; Yildiz, U.C. Weathering Properties of Wood Species Treated With Different Coating Applications. *Bioresources* **2012**, *7*. [[CrossRef](#)]
29. Shen, H.; Zhang, S.Z.; Cao, J.; Jjang, J.; Wang, W. Improving anti-weathering performance of thermally modified wood by TiO<sub>2</sub> sol or/and paraffin emulsion. *Constr Build Mater.* **2018**, *169*, 372–378. [[CrossRef](#)]



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