

# **Encapsulation for Enhanced Stability of Perovskite Solar Cells**

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Perovskite solar cells (PSCs) are a promising photovoltaic technology because of their affordability and high efficiency, yet their long-term stability remains a major challenge. To be able to improve the lifetime and therefore commercial viability of PSCs it is important to understand the factors affecting the stability of the cells, such as exposure to moisture, light and oxygen.

The use of suitable encapsulants could potentially play a crucial role in improving the stability of perovskite solar cells. However, commonly used encapsulation techniques cannot be directly applied to perovskite solar cells, as they differ greatly from, for example, silicon-based solar cells and their degradation mechanisms. This thesis outlines the factors that are important to consider when choosing suitable encapsulants for PSCs. The specific properties of perovskite, including its sensitivity to environmental factors, should be considered when encapsulating the cells. Additionally, to ensure that the manufacturing costs remain low, it is important that the encapsulation process is both simple and easily applicable in industrial scale.

The experimental section of this thesis provides insight on the durability of the encapsulants for real-life applications using the damp heat and light soaking test. Damp heat test provided information on the ability of the encapsulants to withstand extreme conditions, in this case high temperatures and humidity. Light soaking, in turn, allowed to evaluate the durability of the materials in the long term against visible and UV illumination in addition to elevated temperature. The discoloration of the samples was observed through photography, which was indicative of the degradation as well as the durability of the samples to the various factors affecting their stability.

**Key words:** Perovskite solar cells, encapsulation, stability

Kandidaatin tutkielma

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Perovskiittiaurinkokennot ovat lupaava aurinkosähköteknologia niiden edullisuuden, tehokkuuden ja hyvien optisten ominaisuuksien vuoksi. Kennojen kaupallistumista sekä käyttöikää rajoittaa kuitenkin vielä niiden heikko stabiilisuus. Jotta stabiilisuutta voitaisiin parantaa, on tärkeää ymmärtää stabiilisuuteen vaikuttavien tekijöiden, kuten kosteuden, hapen ja valon vaikutuksia kennoihin.

Perovskiittikennojen kapseloimisen ajatellaan olevan yksi tehokkaimmista tavoista parantamaan kennojen stabiilisuutta ulkoisia tekijöitä vastaan. On kuitenkin monia tärkeitä asioita, joita tulisi huomioida perovskiittikennojen kapselointiaineita valittaessa. Esimerkiksi yleisempiin piipohjaisiin aurinkokennoihin käytettyjä kapselointimenetelmiä ei voida hyödyntää perovskiittikennoihin sellaisenaan, sillä näiden ominaisuudet, kuten hajoamismekanismit, eroavat merkittävästi toisistaan. Perovskiitti on myös materiaalina erityisen herkkä eri ympäristövaikutuksille, joka tulisi huomioida kennoja kapseloidessa. Lisäksi olisi tärkeää, että kapselointimenetelmät olisivat yksinkertaisia sekä helposti toteutettavissa, jotta valmistuskustannukset pysyisivät alhaisina myös teollisessa mittakaavassa.

Tutkielman kokeellisessa osuudessa saatiin tietoa kapselointiaineiden soveltuvuudesta todellisiin käyttökohteisiin kosteuslämpökokeen sekä tehostetun valoaltistuksen avulla. Kosteuslämpökokeella saatiin tietoa siitä, miten kapselointiaineet kestävät ääriolosuhteissa, kuten korkeassa ilmankosteudessa ja lämpötilassa. Tehostettu valoaltistus puolestaan auttoi arvioimaan materiaalien kestävyyttä pidemmällä aikavälillä sekä näkyvää että UV-valoa vastaan. Samalla saatiin tietoa materiaalien kestävyydestä korkeissa lämpötiloissa. Näytteissä tapahtuvia värinmuutoksia seurattiin sekä kosteuslämpökokeessa että valoaltistuksessa valokuvauksen avulla. Näin saatiin tietoa eri kapselointiaineiden kulumisesta sekä siitä, kuinka hyvin ne kestivät eri ympäristötekijöiden, kuten kosteuden, valon ja korkeiden lämpötilojen vaikutuksia.

**Avainsanat:** Perovskiittiaurinkokennot, kapselointi, stabiilisuus

# Table of Contents

<b>Abbreviations</b>	<b>5</b>
<b>1 Introduction</b>	<b>6</b>
<b>2 Perovskite Solar Cells</b>	<b>8</b>
<b>2.1 Structure of perovskite solar cells</b>	<b>8</b>
<b>2.2 Working principle of perovskite solar cells</b>	<b>10</b>
<b>3 Stability of Perovskite Solar Cells</b>	<b>11</b>
<b>3.1 Internal and external factors affecting the stability</b>	<b>11</b>
3.1.1 Internal instability of the cells	11
3.1.2 External factors affecting the stability of the cells	12
<b>3.2 Existing stability protocols and reporting of the data</b>	<b>14</b>
<b>4 Encapsulation</b>	<b>15</b>
<b>4.1 Required features for encapsulants</b>	<b>15</b>
4.1.1 Chemical and permeability requirements	15
4.1.2 Mechanical requirements	16
4.1.3 Optical and electrical requirements	17
<b>4.2 Encapsulation techniques</b>	<b>17</b>
<b>4.3 Literature review of encapsulants</b>	<b>19</b>
<b>5 Experimental Section</b>	<b>22</b>
<b>5.1 Sample preparation</b>	<b>22</b>
<b>5.2 Damp heat test for the encapsulants</b>	<b>23</b>
<b>5.3 Light soaking test for the encapsulants</b>	<b>23</b>
<b>5.4 Photographing the samples</b>	<b>24</b>
<b>6 Results and discussion</b>	<b>25</b>
<b>Conclusions</b>	<b>35</b>
<b>References</b>	<b>37</b>

## **Abbreviations**

**PSC** Perovskite solar cell

**PCE** Power conversion efficiency

**HTL** Hole transport layer

**ETL** Electron transport layer

**FTO** Fluorine doped tin oxide

**ITO** Indium tin oxide

**TCO** Transparent conductive oxide

**MA** Methylammonium

**FA** Formamidinium

**ISOS** International Summit on Organic Photovoltaic Stability

**IEC** International Electrotechnical Commission

**WVTR** Water vapor transmission rate

**OTR** Oxygen transmission rate

**EVA** Ethylene vinyl acetate

**PDMS** Polydimethylsiloxane

**PIB** Polyisobutylene

**TPU** Thermoplastic polyurethane

# 1 Introduction

We are approaching a global energy challenge as increasing energy demand is faced by limited availability of energy sources. Renewable energy sources will become essential, as fossil fuels, such as coal and oil, are not only harmful to the environment, but their availability is also limited [1]. It is therefore important to develop renewable energy sources in a way that enables them to potentially replace fossil fuels in the future. Solar energy is considered to be one of the leading renewable energy sources to meet future energy needs due to its easy accessibility and affordability [2].

Perovskite solar cells (PSCs) have been attracting a lot of attention in recent years due to their low cost, good optical properties and high power conversion efficiency (PCE) among other promising features [3]. The PCE of perovskite solar cells has demonstrated fastest growth of any photovoltaic technology: it has increased from 3,8% in 2009 to up to 26,1% in 2024 [4]. In addition to the high PCE, the use of more affordable fabrication processes and materials has enabled the development of PSCs to be even more appealing and cost-effective compared to other sources of solar energy [5]. Other photovoltaic technologies, such as crystalline silicon or thin-film technologies, tend to have significantly higher manufacturing costs compared to PSCs. This is because their manufacturing may include energy intensive processes, such as high-vacuum or high-temperature processes [6].

Despite the high power conversion efficiency, commercialization of PSCs is still limited by the cells' comparatively poor long-term stability. Currently, the longest reported lifetime of PSCs is about one year. Comparing this to the conventional silicon solar cells with a lifetime expectancy up to 25 years, there is still plenty of improvement to be made concerning perovskite solar cell stability [7]. The materials used in perovskite solar cells are susceptible to detrimental changes when exposed to environmental conditions, such as humidity, illumination and oxygen, which in turn reduce the lifetime of unencapsulated cells [8].

The limited information available on degradation mechanisms makes it challenging to understand and overcome such mechanisms [9]. However, the effects of oxygen, humidity and light on the stability and performance of the cells can be reduced by proper encapsulation. Encapsulants act as a protective layer of the cells against these external factors and can protect the cells from mechanical stress and contaminants [5], [8]. Encapsulation is therefore

considered to be an effective way of improving cell stability [8] which is why this thesis is focused on testing potential PSC encapsulants.

This thesis provides a literature review into the theory behind PSC encapsulation and some of the currently used encapsulant materials, followed by experimental section where damp heat and light soaking tests were used to test the most suitable encapsulant for perovskite solar cells. The test results provided information on the effects of the above-mentioned environmental factors, such as moisture, oxygen and illumination on the encapsulants. Finally, the results of these experiments were compared with one another and with the corresponding findings in the literature.

## 2 Perovskite Solar Cells

### 2.1 Structure of perovskite solar cells

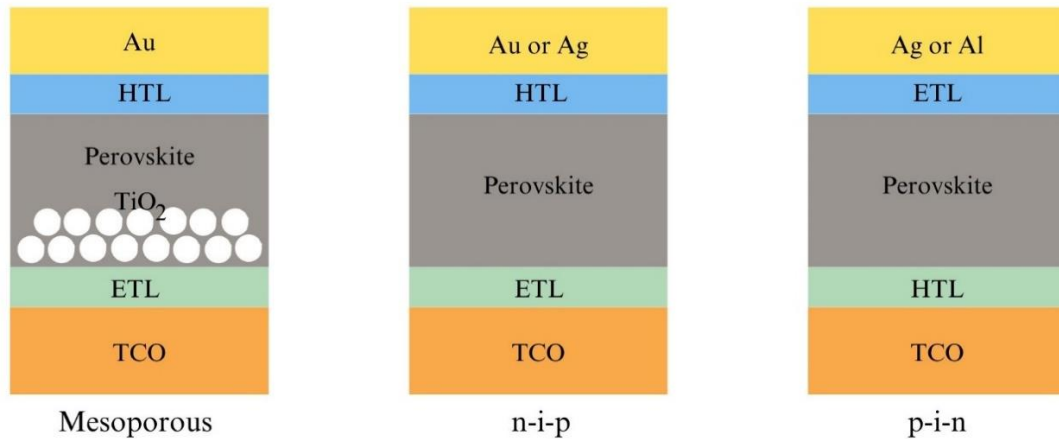


Figure 1. Mesoporous, regular n-i-p and inverted p-i-n structure of PSCs. [10]

Perovskite solar cells are photovoltaic devices that convert sunlight into electricity. PSCs consist of an active layer between a hole transport layer (HTL) and an electron transport layer (ETL) (Figure 1). The HTL layer functions as an electron-blocking layer, where materials such as Spiro-OMeTAD, Copper (I) iodide or P3HT (Poly(3-hexylthiophene-2,5-diyl)) are often used [5], [11]. The ETL layer typically consists of materials like titanium dioxide, zinc oxide or tin (IV) oxide [5], [11], [10]. The top and back electrodes, anode and cathode, can be transparent depending on the type of the perovskite solar cell [11], [12]. The top electrode, known as the anode, is usually fluorine doped tin oxide (FTO) or indium tin oxide (ITO) deposited on a glass substrate [11]. Cathode materials in PSCs are often materials such as gold, aluminum or silver [13].



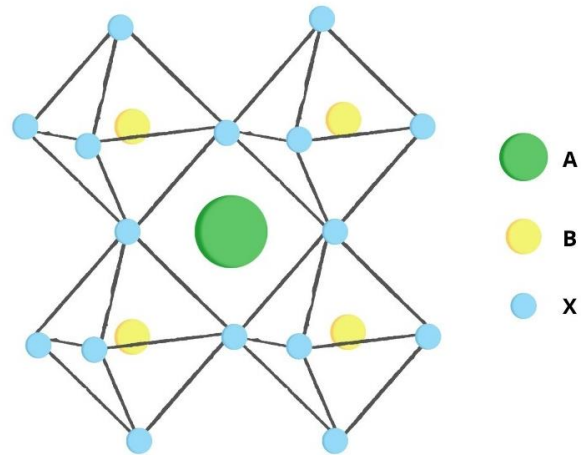


Figure 2. Perovskite structure, where A and B are the cations and X is the anion. [14]

The key component of perovskite solar cells is the active layer made of metal halide hybrid perovskite materials, which form the light-absorbing layer of the cells. The general structure of perovskites is three dimensional  $ABX_3$ , where A and B are cations and X is an anion [5],[14], as shown in Figure 2. The most common cation used as the A cation of the structure is methylammonium ion  $CH_3NH_3^+$  but other cations have also been used, such as cesium  $Cs^+$ , formamidinium  $NH_2CH = NH_2^+$  and ethyl-ammonium  $CH_3CH_2NH_3^+$  [5],[8],[14]. The B cation of the perovskite structure is usually a metal cation, such as  $Pb^{2+}$ ,  $Ge^{2+}$  or  $Sn^{2+}$ . In turn, X is a halide ion, for instance  $Br^-$ ,  $Cl^-$  or  $I^-$  [5],[8]. Alternative ions affect the structure of perovskite and, thereby, also the stability, efficiency and operation of the cells. The most commonly used perovskite in PSCs is methylammonium lead iodide perovskite ( $MAPbI_3$ ) [15]. Other light absorbers are also used, such as formamidinium-lead-iodide ( $FAPbI_3$ ).

Perovskite solar cells have a number of different structures, including n-i-p, p-i-n and mesoporous structures (Figure 1). Other structures also exist, such as tandem cells, where two or more absorbers are placed on top of each other. The so-called regular structure, that is, n-i-p structure is usually composed of a cathode, HTL and ETL layers, perovskite and as the anode the transparent conductive oxide (TCO) (Figure 1). The transparent conductive oxide of the n-i-p structure is either ITO or FTO. The mesoporous structure is similar to the n-i-p structure, but in addition to the electron transfer layer (ETL), there is another a layer of  $TiO_2$  as another electron transfer layer [16] (Figure 1). Similarly, for a mesoporous structure, the TCO is either FTO or ITO. The promising features of mesoporous structures are that a higher PCE, low hysteresis and reduced recombination of the carriers has been achieved compared to the n-i-p structure [17], [18]. The PCE increased from 13.21% to 15.51% after the addition of the mesoporous  $TiO_2$  layer to the cells [18]. The high temperatures required to manufacture

these mesoporous structures, however, often exceeds 450°C, which significantly increases the manufacturing costs [16].

The p-i-n structure is inverted compared to the n-i-p structure, as seen in Figure 1. Here, the HTL and ETL layers have switched places and the transparent conductive oxide is typically Indium tin oxide (ITO) [19]. The inverted p-i-n structure has its advantages, including good stability and easy processing with lower temperatures [11], [16]. With the inverted structure, it has also been reported that hysteresis is minimal compared to the regular (n-i-p) structure [16]. However, with the inverted structure, the PCE is not as high as with the regular n-i-p structure due to the band alignment between the HTL and perovskite [16]. Further improvements in this could potentially increase the PCE to the same level as with the regular (n-i-p) structure [16].

## 2.2 Working principle of perovskite solar cells

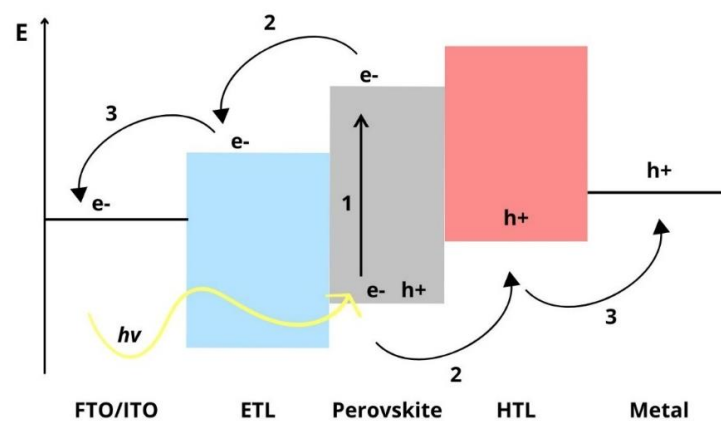


Figure 3. The working principle of PSCs. [10]

When sunlight reaches the active layer of the cell, the perovskite, it causes the valence electrons to excite to the conduction band. For this to happen, the energy of the photons must be greater than the band gap energy of the active layer. This creates excitons, also known as electron-hole pairs. [11]

The internal potential between the electrode and cathode causes the electron-hole pairs to separate. The holes move to the anode and the electrons to the cathode, through the HTL and ETL respectively, as seen in Figure 3. Once the holes and the electrons have reached the electrodes, they are then collected and transferred to the external circuit through electrical conductors, therefore generating electrical current. [11]

### 3 Stability of Perovskite Solar Cells

#### 3.1 Internal and external factors affecting the stability

##### 3.1.1 Internal instability of the cells

Stability can be divided into two main aspects, either external or internal factors. Internal factors affecting the stability of the cells are mainly related to the characteristics and properties of perovskite itself. The internal stability may be significantly affected by contaminants that may have entered the device, for example during the manufacturing process or through the operation of the cells [5]. Therefore, encapsulation of the device is also an important part of improving the internal stability of the cell, to ensure that contaminants do not enter the cell and thus affect its performance [5]. The internal factors affecting the stability are typically categorized into three different aspects, which are thermal, chemical and structural stability of the cells [8].

As mentioned above, the chemical stability of perovskite can be affected by the defects that can enter the perovskite layer during the fabrication or operation of the devices. Such defects include vacancies and interstitials. These can affect the charge generation and transport properties of the cells. In order to avoid these negative effects, the passivation of these defects has been studied, as well as optimizing the material composition of the perovskite to minimize their impact. [8]

Structural instability, which refers to undesired changing or breaking of the perovskite crystals, can negatively affect the optoelectronic properties of the perovskite and, consequently, the performance of the cell [5]. One of the sources for structural instability are phase transformations which are dependent on ion suitability for the perovskite structure. The suitability of an ion can be evaluated with the Goldschmidt tolerance factor. The Goldschmidt tolerance factor ( $t$ ) can therefore provide information about the structural stability and can be calculated with the following equation (1):

$$t = \frac{r_A + r_X}{\sqrt{2}(r_B + r_X)} \quad (1)$$

where  $r_A$ ,  $r_B$  and  $r_X$  are the radii of the A, B and X ions [20]. Perovskite material retains its cubic structure when  $0.9 \leq t \leq 1$ . So, the lower the value of  $t$ , the more asymmetric the

perovskite structure and more likely it is that changes in the perovskite structure may occur, which in turn can negatively affect the performance of the cell. [8],[5]

Thermal stability is another important part of ensuring the longest possible lifetime for PSCs. High temperatures can cause decomposition or phase transitions in perovskite, which can lead to changes in the structure and properties of the perovskite materials [8]. These can negatively affect the performance of the cells. To enhance the thermal stability of perovskite, alternative A-cations to the widely used methylammonium (MA) have been researched [21], [22]. For instance, the use of formamidinium (FA) has demonstrated promising results, showing that FA-based perovskites have better resistance to high temperatures than MA-based perovskites [23]. The use of FA however is, not without its challenges: despite its high temperature resistance, it is very sensitive to humidity [5],[24]. Hence, further research into alternative A-cations is still needed. In addition to this, other possible ways to improve the internal stability of the cells include modifying the perovskite structure with alternative ions or adding inorganic cations [25],[26] to the structure [8].

### 3.1.2 External factors affecting the stability of the cells

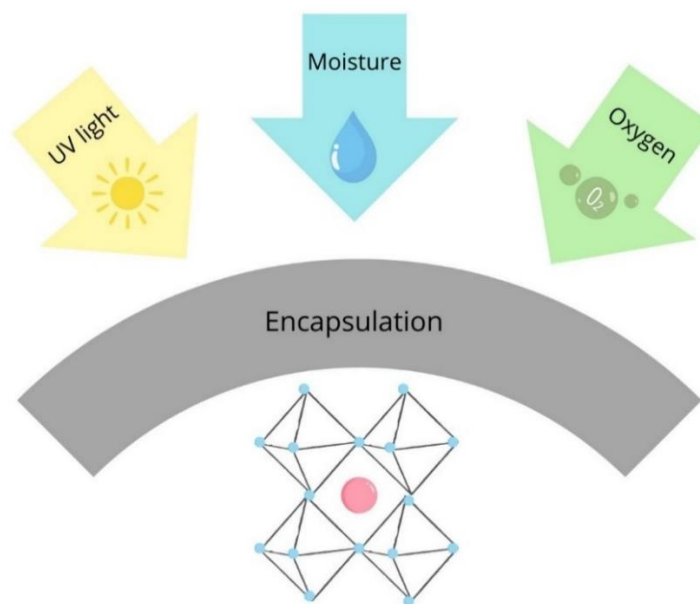


Figure 4. The role of encapsulation on the external factors affecting the stability of perovskite solar cells. [8]

PSCs are vulnerable to a variety of environmental factors, of which humidity, illumination and oxygen are perceived to be the most crucial. High relative humidity, that is, above 50%, can cause moisture to permeate into the perovskite and cause changes to the crystal structure [8]. This can result in the formation of hydrogen bonds with the organic cations on the

perovskite, which in turn can lead to significant degradation of the cells [5],[8]. In addition, the presence of water in the cells can cause the formation of hydroiodic acid (HI) when water protonates iodide. As a decomposition product, harmful lead iodide  $\text{PbI}_2$  can be formed in the cells [8],[27].

Oxygen can be expected to affect the cells either in the charge transport layers (ETL and HTL) or in the active layer. Degradation in the charge transport layer mainly affects the carrier mobility and recombination rather than the carrier generation. So even if oxidation occurs in these layers, it does not necessarily mean that the cells will be immediately degraded. Some of the organic materials used in the charge transportation layers may even require some level of oxidation to function in the cells as intended. [27]

The active layer of the cells, which is the perovskite layer, does not show significant oxidation if the cells are not exposed to light. Oxygen combined with light however, can lead to photo-oxidation of the perovskite. Iodide vacancies in the perovskite layer can further enhance this reaction. Oxygen may be bound to these iodide vacancies and can diffuse into the perovskite, leading to the formation of superoxide ions. Reactions of superoxide significantly increases the degradation of the perovskite. The unwanted combination of oxygen and light in the cells could be addressed, for example, by controlling vacancy density by adding dopants such as cadmium [28] to the structure. [5], [8], [27]

In the future, perovskite solar cells should be able to withstand the effects of light for many years to achieve the same lifetime as silicon-based solar cells. However, it is known that the effect of light alone can cause ion migration, halide segregation, compositional degradation and other effects on perovskite cells. These can have both reversible and irreversible effects on the stability and efficiency of the cells. As an example of the reversible reactions that occur in the cells, researchers have studied the Hoke effect, where phase segregation of halide ions occurs in perovskite when exposed to light. Due to the Hoke effect, the materials in the cells return to their normal compositional distribution when no longer exposed to light. The irreversible reactions in the cells include permanent compositional changes in the perovskite, which have been found to cause degradation in the cell efficiencies over time. However, there is still limited knowledge of the effects of these reactions and therefore research on this area is important for achieving more stable and reliable PSCs. [5], [8], [27]

### **3.2 Existing stability protocols and reporting of the data**

Although PSCs have shown promising results in a variety of areas, there is still a lack of definite knowledge on the degradation mechanisms of the cells. Despite the increased focus on stability in recent years, it would be important to have comparable and reproducible results across the various research groups in order to obtain more reliable results on the stability and aging of perovskite solar cells. [5], [7], [9]

There are standards set by the International Electrotechnical Commission (IEC) for silicon-based solar cells but they are not directly applicable to PSCs, as the cell structures and material properties differ significantly. The current ISOS (International Summit on Organic PV Stability) protocols have been used for PSCs, as their degradation behavior is closer to organic photovoltaic cells. For example, the effects of temperature and moisture are thought to be somewhat similar for both types of solar cells. However, there is still room for further development and improvement for the ISOS protocols in order to address the specific characteristics of PSCs even better. The use of these protocols is primarily intended for measurements on a laboratory scale, allowing the comparability of measurements made in different laboratories, thus contributing to the reliability of results and publications. The ISOS protocols, however, are not comparable to the previously mentioned IEC standards, as the protocols are only addressing generally accepted test conditions and procedures. ISOS protocols are not a standardized qualification test, like IEC standards, and is therefore not applicable for industrial use. [7], [29]

Therefore, to improve the reliability and reproducibility of the measurement results, there should be more detail on the conditions under which degradation measurements are carried out on. Factors such as, illumination, humidity or the number of cells is rarely mentioned in reports. [9]

## 4 Encapsulation

### 4.1 Required features for encapsulants

When choosing an encapsulant, consideration should be given to its price, environmental impact and how easy it is to use. If the encapsulation of the cells does not involve complex or energy-intensive processes, the manufacturing costs will also remain low. Encapsulants that are easy to use would reduce the number of errors in the encapsulation process, thus increasing reliability and making the encapsulation process easily reproducible.

Consideration of the environmental impact of encapsulation is also important. In addition to minimizing lead leakage from the cells, it is worth considering the recyclability of the encapsulant and, for example, ensure that the encapsulant itself is not harmful to the environment. It is therefore essential that consideration is given to whether it is possible to recycle and possibly reuse the encapsulants. This could reduce the environmental impact of encapsulants and the need for new materials. The ease of separating the encapsulant from the cell at the end of its operational life is another factor to consider when choosing an encapsulant in terms of recyclability.

#### 4.1.1 Chemical and permeability requirements

Traditional encapsulation methods, such as those used for silicon-based solar cells, should not be applied as such to perovskite solar cells because of their intrinsic properties. Perovskite solar cells have different degradation mechanisms compared to silicon-based cells and are more susceptible to environmental factors, such as moisture or high temperatures.

Encapsulants are mainly used to protect the cells from these environmental factors. Therefore, these materials should have high mechanical strength and insulating properties, preventing the permeation of moisture and oxygen into the device [8], [30]. The permeability of moisture and oxygen can be measured using two parameters: the water vapor transmission rate (WVTR) and the oxygen transmission rate (OTR). These indicate the rate at which moisture or oxygen can permeate through the encapsulant [3]. For WVTR the maximum value is from  $10^{-6}$  to  $10^{-4}$  g/m<sup>2</sup>/day and for OTR the corresponding value is from  $10^{-5}$  to  $10^{-3}$   $\frac{cm^3}{m^2*day*atm}$  [31],[32].

A good encapsulant adheres well to the cells and holds the structure of the cells together. Other features of a good encapsulant are that it is compatible with all parts of the cell. This

means that the encapsulant should be considered inert to other parts of the cells, even at high temperatures. Inertness ensures that reactions do not affect the performance or properties of the PSCs. One of the fabrication steps for cells often involves a wet chemical coating process, which can leave chemical residues on different parts of the cell. Chemical residues can lead to unwanted chemical reactions in the cells, which is why it would be important that the encapsulant is inert and does not react with the residue. Reacting with the cell or the chemical residues could lead to the formation of harmful compounds, which in turn could affect the performance of the cell. [8],[30]

Hence, a good encapsulant does not react with the environment nor the cell, but protects the cell from environmental effects. Furthermore, it is important that the encapsulant prevents, for example, harmful substances such as lead from leaking into the environment. One major factor hindering the commercialization of PSCs is the toxic lead the cells contain. In order to find a solution to this problem, it would be essential to either find a way to replace the lead in the cells or to prevent it from leaking into the environment. Currently, however lead-free PSCs have not achieved as high PCE, which has been limiting their usage [33],[34]. Various encapsulants have been researched to enable end-of-life recovery of lead from the cells, including the use of cation-exchange resin and ultraviolet resin mixed as an encapsulant. This encapsulation technique has shown promising results and has enabled recovery of up to 90% of the lead from degraded cells [35].

#### 4.1.2 Mechanical requirements

A high mechanical strength of the encapsulants allows the device to be able to withstand possible external loads that are beyond control, such as heavy rain or snow. In addition, temperature changes can be significant in the conditions in which the cells will operate in. It would be ideal that the coefficient of thermal expansion is suitable and reasonably close to that of the other parts of the cells. This would therefore prevent the negative effects, such as delamination or mechanical damage, caused by temperature changes. Temperature changes can also cause mechanical stress in the cells and may lead to degradation if the encapsulant is unable to withstand the stress. The ability of encapsulants to withstand the stress due to temperature changes can be studied with thermal cycling. [30]

Lamination is also an important part of many encapsulation techniques, requiring the melting temperature of the encapsulant to be relatively low so that the lamination process does not harm the cells. The shrinkage of the encapsulants must be kept to a minimum to avoid



cracking or degradation of the cells when cooling. Most of the laminated encapsulants that are used are laminated in high temperatures such as 120 °C or as high as 150 °C. If the PSCs are kept at these temperatures for a long period of time, it might cause the perovskite layer to degrade which will negatively affect the performance of the cells. It is therefore important to ensure that the lamination temperature is not the factor that causes the degradation. [30]

#### 4.1.3 Optical and electrical requirements

Depending on where the encapsulant is placed in the cells, there are different optical requirements. If the encapsulant is placed at the back of the cell, it would be beneficial if visible light, that is, light in the wavelength range from 400 to 780 nm, could be reflected back to the active part of the cell. Light in the UV wavelength range, which is from 100 to 380 nm [36], is a common cause for degradation and therefore the desired effect is that the encapsulant allows UV light to pass through so that it does not return to damage the cell. However, if the encapsulant is placed at the front of the cell, the aim is that the encapsulant has a high light transmittance, while absorbing or reflecting the UV light [8]. The use of encapsulants that double as UV absorbers on top of the cells could potentially be a preventing factor against degradation [30].

In addition to the optical requirements, the electrical requirements for encapsulants are that the materials should be well insulating to ensure that leakage current is kept as low as possible [30]. High volume resistance and high dielectric constant enables low leakage current and prevents potential induced degradation [8].

### 4.2 Encapsulation techniques

Various encapsulation techniques have been developed to protect the components of the PSCs. The most common techniques include glass-glass encapsulation, thin film encapsulation and polymer encapsulation. Glass-glass encapsulation means that the cell is placed between two glass sheets that are glued together with an encapsulant. Materials such as EVA, Surlyn™, polyurethane and polyisobutylene have been used in glass-glass encapsulation previously [37]. In this work, this technique was used for applications including EVA, Oppanol® B and Surlyn™. The disadvantage of this technique is that the glass makes it difficult to apply to flexible solar cells, even though the price would be affordable. Moreover, using two glass sheets instead of one makes the cells both heavier and more expensive. [8]

Currently, thin-film encapsulation is perceived as the most promising of these encapsulation techniques. Thin-film encapsulation can be done using methods such as spin coating, atomic layer deposition (ALD) or vacuum deposition. Usually, it is a combination of inorganic and organic multilayers. Thin-film encapsulation has been used with materials such as ALD- $\text{Al}_2\text{O}_3$ , ALD-SnOx/Ag/ALD-SnOx and ALD- $\text{SiO}_2$ /UV-curable epoxy/desiccant [38],[39],[40]. The advantages of thin-film encapsulation include lower fabrication temperatures compared to, for example, polymer encapsulation or glass-glass encapsulation. However, thin-film encapsulation, such as ALD, is an energy and time-consuming process and the equipment needed for the process is rather expensive. Therefore, for commercialization, further thought should be given to how the encapsulation technique could be made as efficient as possible, perhaps at lower temperatures. [8]

Polymer encapsulation, like other encapsulation methods, has its advantages and disadvantages. Firstly, it is well suited to roll-to-roll fabrication processes, in other words, to flexible applications, and fast industrial-scale application, making it an appealing encapsulation option. The use of polymers is also a cost-effective option. It is often carried out by adding polymer layer or many polymer layers on top of the cells. Many polymers can require curing or crosslinking for better adhesion and protection of the cells. Polymers such as poly(methyl methacrylate) (PMMA), Teflon (PTFE), polydimethylsiloxane (PDMS) and paraffin have been used for polymer encapsulation [41],[42],[43]. However, this encapsulation technique also has its problems, as polymers have high WVTR and OTR compared to, as an example, thin-film encapsulation. [8]

In conclusion, when choosing a suitable encapsulation technique, the possible effects on the cells, such as the effects of temperature, needs to be taken into account. It is also worth considering whether the encapsulation technique is suitable for flexible components. In addition, encapsulation should be affordable and easily applicable, so that it does not significantly increase the manufacturing costs of the cells.

### 4.3 Literature review of encapsulants

Table 1. Properties of encapsulants

Encapsulant	Encapsulation technique	WVTR ( g/ m <sup>2</sup> /day)	Flexibility	Thermal durability	Ref.
EVA	Glass-glass encapsulation	28	Not flexible	Can withstand moderate temperatures	[8]
Surlyn™	Glass-glass encapsulation	0.66	Can be used on flexible devices	Can withstand moderate temperatures	[8]
PDMS	Polymer encapsulation	Not available	Can be used on flexible devices	Can withstand high temperatures	[44]
PIB	Polymer encapsulation	0.001 – 0.01	Can be used on flexible devices	Can withstand moderate temperatures	[8]
Epoxy, UV-cured	Polymer encapsulation	0.15	Not flexible	Can withstand high temperatures	[30]
Paraffin	Polymer encapsulation	5.73	Not flexible	Can withstand temperatures below 60°C	[45]
TPUs	Polymer encapsulation	9.68 – 59.61	Can be used on flexible devices	Can withstand high temperatures	[3]

Various encapsulants have been researched to be used in perovskite solar cells. However, comparing them is challenging because of the differences of the testing methods and conditions. One of the most widely used encapsulants for PSCs is ethylene vinyl acetate (EVA). The use of EVA has shown some promising results. In a damp heat test using EVA as an encapsulant with an edge sealant, butyl rubber, the cell withstood conditions of 85% RH and 85°C for 1000 hours without any decrease in PCE [46]. In another study, cells retained up to 95% of the original PCE, when stored for 1000 hours under inert conditions [47]. While EVA has its positive features, such as low price and relatively promising results on stability, there are also some negative ones. For instance, the high lamination temperature of 150°C, required to attach EVA to the cells can have an impact on the performance of the cells [8]. When exposed to moisture or UV, EVA forms a harmful byproduct called acetic acid, which

can accelerate corrosion in the cells and thus affect the operation as well as the performance of the cells [48].

Another widely used encapsulant for PSCs is Surlyn™, which attracted interest because of its lower lamination temperature compared to EVA. Additionally, Surlyn™ does not react with the perovskite of the cell and it can provide high electrical insulation compared to EVA, for instance [8]. Surlyn™ encapsulated cells have retained 85% of the original PCE under 30-60% RH and one Sun illumination for 800 hours [49]. Although the lamination temperature is lower compared to EVA, it is still as high as 120° C, which limits the use of Surlyn™ as an encapsulant. Besides, as Surlyn™ cures, it also releases a byproduct called methacrylic acid [8], [50], which can be harmful to the cells. Surlyn™ and EVA are usually laminated with glass, which limits their usage for flexible applications.

Polydimethylsiloxane (PDMS) has been widely used as an encapsulant in electronic devices. It is affordable, can be used on flexible applications, does not react with the perovskite layer and the lamination temperature of 80° C is significantly lower compared to other materials such as EVA and Surlyn™. PDMS encapsulated cells have been up to 54% more efficient than unencapsulated cells. Moreover, encapsulated cells have shown promising long-term stability for up to 3000 hours. [44]

When comparing polyisobutylene (PIB) with EVA and epoxy in the literature in the damp heat test and thermal cycling, polyisobutylene has shown the best results as an encapsulant. In the damp heat test, at 85% RH and 85°C, there was no significant changes in PIB after 500 hours. During thermal cycling from -40°C to 85°C, the PCE of PIB encapsulated cells remained at the original value after 200 cycles. Furthermore, PIB is a low-cost encapsulant, can be added to the cell at low temperatures and in addition, it is easy to use and can be applied to flexible devices. [51]

Promising results have also been obtained using paraffin as an encapsulant. It is a low cost, easy to use and moisture-repellent option. There was no difference in the photovoltaic properties of paraffin-encapsulated cells after 2160 hours at 70-85% RH [45]. Paraffin has also been used as an encapsulant together with UV-curable adhesive (UVCA). Such devices retained over 80% of the initial efficiency after 1000 hours at 65°C and 40-60% RH [43]. However, paraffin cannot withstand high temperatures and can't be used on flexible applications. [45]

A thermosetting polymer called epoxy has been used both as an edge sealant and as an encapsulant for perovskite solar cells [30]. Devices encapsulated with UV curable epoxy prevented moisture ingress and retained 83% of the original performance beyond 70 days at 30°C and 50% RH [52]. Another study using UV curable epoxy as an encapsulant showed that the device retained 90% of its original PCE after 1000 hours in continuous AM 1.5 light soaking at 85°C and 5% RH [53]. However, at high temperatures (85°C) and with high humidity (80% RH) devices encapsulated with epoxy resin noticeably degraded [54]. One of the disadvantages of epoxy, however, is that it cannot be used as an encapsulant for flexible devices because of its crosslinking [30].

In addition, thermoplastic polyurethanes (TPUs) have been studied for PSC encapsulation. TPUs are an environmentally friendly, flexible and low-cost option. In addition, TPUs can remain stable even in high humidity conditions [55]. Devices encapsulated with TPUs have retained more than 93% of the original PCE in harsh environmental conditions, such as high relative humidity (80% RH), for 1000 hours [3]. In another study, TPU encapsulated cells retained up to 94% of the original PCE [55]. These cells were exposed to ambient light, 28-65% RH and 18-30°C. In this study, these cells were compared to unencapsulated cells, which showed up to 90% loss of performance after 500 hours [55]. Polyurethane has also been used as an encapsulant with glass, allowing cells to retain up to 97.52% of the original PCE at outdoor conditions after 2136 hours [56].

In conclusion, it seems that a variety of encapsulants have been applied to PSCs with promising results. The challenge, however, is that although there are many studies and results on the use of different encapsulants, it is challenging to fairly compare them, as the experiments carried out on the encapsulants differ significantly.

## 5 Experimental Section

Encapsulants that were experimentally tested in this work were paraffin from Farnia, Sylgard®184 (polydimethylsiloxane) from Dow, Surlyn™ from DuPont, Oppanol® B from BASF, polyurethane sealant from Sika®, Gorilla tape® from Gorilla glue company, ethylene vinyl acetate (EVA) from Vistasolar® and different glues from Casco®. The glues used were Marin & Teknik, Silikon, Strong Epoxy Professional, Express Glas and Express Gel.

Table 2. Sample preparation

Sample	Encapsulation technique
Paraffin	Melting at 120°C, applied on top of the microscope slide
Polyurethane sealant	Applied on top of the microscope slide, cured by humidity
Gorilla tape®	Applied on top of the microscope slide
Casco® Marin & Teknik	Applied on top of the microscope slide
Casco® Silikon	Applied on top of the microscope slide, cured by humidity
Casco® Strong Epoxy Professional	Both ingredients in a 50-50 ratio, applied on top of the microscope slide, must be used within 90 minutes
Casco® Express Glas	Applied on top of the microscope slide, UV curing
Casco® Express Gel	Applied on top of the microscope slide
Sylgard® 184 (PDMS)	Applied on top of the microscope slide after mixing the ingredients
EVA	Laminated between two microscope slides at 150 °C
Surlyn™	Laminated between two microscope slides at 120 °C
Oppanol® B	Laminated between two microscope slides at 160 °C

### 5.1 Sample preparation

Preparing the samples began by coating microscope slides with the encapsulants mentioned above. The microscope slides were thoroughly wiped with ethanol before adding the encapsulants. Some of the encapsulants required melting before they were applied on top of the glass. Such encapsulants were paraffin, Oppanol® B, EVA and Surlyn™. EVA and Surlyn™ were both used for two types of samples. First, four samples with Surlyn™ were prepared, so that first two of the samples had Surlyn™ added on top of the microscope slides.

On the other two samples, Surlyn™ was laminated between two pieces of glass slides. When laminating the Surlyn™ and EVA samples pressure was applied in top of both samples to ensure good adhesion to the glass slides. EVA samples were prepared using the same method, where two samples were made with EVA on top of the glass and two samples with EVA laminated between the two glass slides. EVA was laminated between these two microscope slides by heating it on a hotplate at 150°C, while the Surlyn™ samples were encapsulated with the same technique, this time with heating at 120°C. Paraffin was melted in a separate container on a hot plate at 120°C, from which it was applied to the glass slide once melted. Oppanol® B samples were prepared by melting it in a separate container at 160°C after which it was laminated between two glass slides while pressing to ensure good adhesion.

The rest of the encapsulants, that is, Sylgard®184, polyurethane sealant, Gorilla tape®, and the glues were added on the microscope slides after these had been wiped with ethanol. The glues used were Marin & Teknik, Silikon, Strong Epoxy Professional, Express Glas and Express Gel. Epoxy and Sylgard® 184 required mixing before adding them on the microscope slides. Epoxy in a 50-50 ratio and Sylgard® 184 in a 10:1 ratio. Two samples of each encapsulant were prepared, for a total of 28 samples. The samples were then left to cure for about a week. Before the samples were added to the light soaking and damp heat tests, they were photographed so that any discoloration of the samples could be detected.

## **5.2 Damp heat test for the encapsulants**

After photographing the samples, they were placed on a tray where they could be placed in Aralab weather chamber (Model TESTA\_e CT/TT) for the damp heat test. There was one sample of each encapsulant in Aralab. The damp heat test was carried out at 85°C and 85% relative humidity (RH) for 800 hours and for Gorilla tape® for 600 hours. The samples were photographed approximately every week so that any discoloration could be detected.

## **5.3 Light soaking test for the encapsulants**

Light soaking test was carried out on the encapsulants to be able to estimate their long-term durability under visible and UV light in addition to high temperatures. The samples were placed on a tray after photographing and transferred to the aging chamber Atlas XLS+. The samples were photographed weekly and this experiment also lasted 800 hours for all of the samples, except for Gorilla tape® the test took 600 hours. XLS+, like Aralab, had one sample of each encapsulant.

#### **5.4 Photographing the samples**

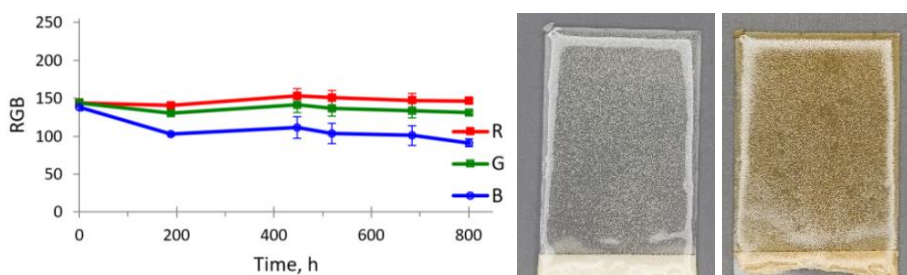
The photographs were taken with a Sony A7 MK2 camera. When photographing the samples, they were moved to a separate photo chamber that had an LED strip illuminating the samples. In this way, ambient light did not reach the photo chamber and thus did not affect the color of the photographs. The camera settings were kept the same for each photo session so that the results remained as reliable as possible. The camera settings were so that the sensitivity was ISO 200 and the shutter speed 1/20s. A color profile was created by using an X-Rite ColorChecker Passport, which ensured that the results were comparable. To further adjust the color profile the photographs were imported to Adobe Photoshop Lightroom Classic where the white balance and exposure were adjusted. The average red, green and blue (RGB) values of the samples were determined with a Python script, where three areas of each sample were selected to create an average color value of each sample. This allowed the comparison of the average RGB values of the samples from the beginning to the end of the experiments, as well as the comparison between the different samples and their average RGB values.



## 6 Results and discussion

The analysis of RGB values provides insight into the degradation of the used encapsulants. In the past, RGB values have been used in perovskite cells to evaluate the durability of the encapsulants, as well as perovskite degradation to  $\text{PbI}_2$  [41]. In this thesis, the average RGB values are used to indicate the degradation of the encapsulants in the damp heat and light soaking tests as a function of time. Some samples were transparent, which is why the starting RGB values for these samples is the background color.

a)



b)

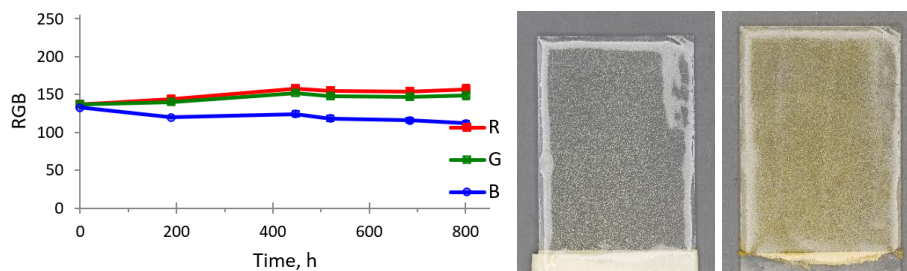


Figure 5a) Average RGB values for epoxy during the light soaking test. On the right side, epoxy sample before and after the light soaking test. b) On the left side, average RGB values for epoxy on the damp heat test. On the right side, epoxy sample before and after the damp heat test.

As can be seen in Figures 5a) and b), the starting values of RGB are around 140 for all colors. However, in both light soaking (Fig. 5a) and damp heat (Fig. 5b) tests, there are significant changes in these values after less than two hundred hours. In particular, the value of the blue color is markedly different from the other values (red and green). In the light soaking test, the average value of blue decreases from the original 140 to as low as 90 (Fig. 5a). On the damp heat test, the average value of blue also decreases from 135 to 111 (Fig. 5b). It can therefore be seen that in both samples there is significant discoloration indicating that the samples are not at the required level of durability against the tested environmental factors, including the light soaking test's illumination and temperature, as well as the damp heat test's high

temperature and humidity. Compared to the corresponding findings in the literature, the results seem to be similar. Epoxy appears to be particularly susceptible to high humidity.

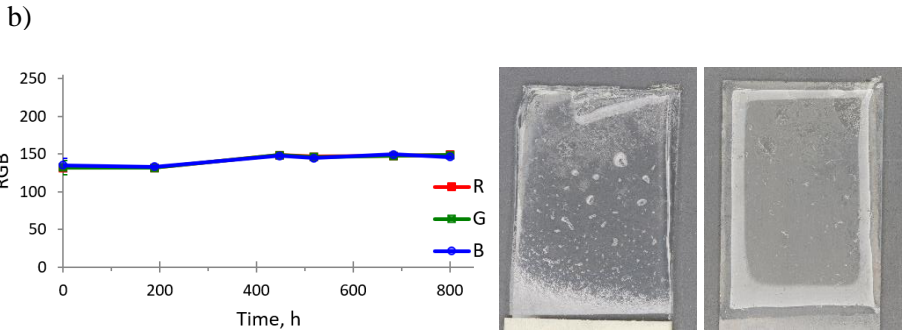
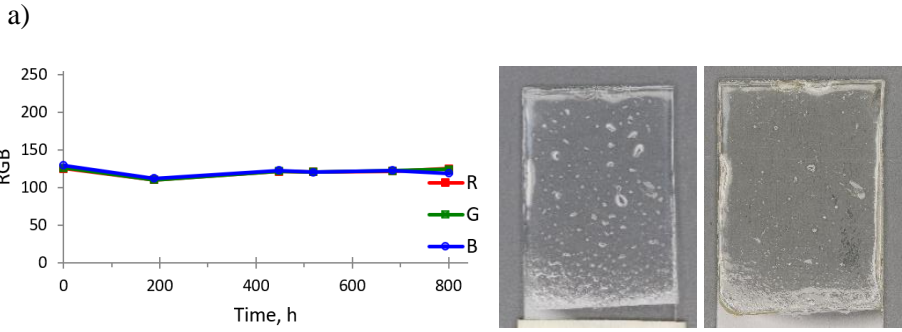
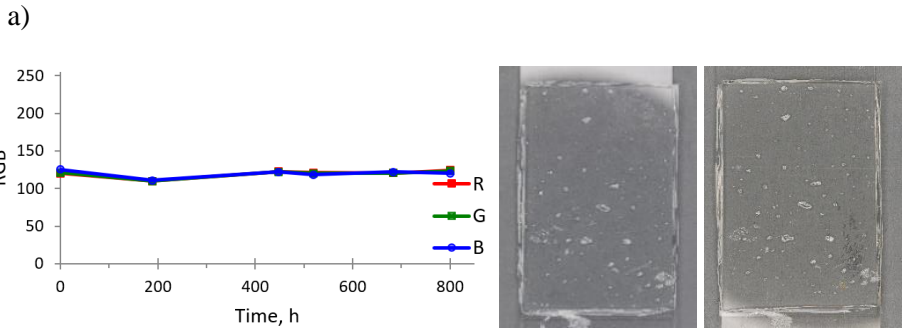


Figure 6a) Average RGB values for EVA on the light soaking test. On the right side, EVA sample before and after the light soaking test. b) Average RGB values for EVA on the damp heat test. On the right side, EVA sample before and after the damp heat test.

Figures 6a) and b) show the average RGB values of both light soaking (Fig. 6a) and damp heat test (Fig. 6b). The average RGB values for EVA on light soaking were around 125 for all of the colors. There are some minor changes in the average RGB values during the test, however, it is not that noticeable. The biggest decrease is in the average value of the blue color, which was around 129 at the beginning and 118 at the end (Fig. 6a). On the damp heat test, the starting average RGB values are around 130 (Fig. 6b). The average RGB values show some increase, with the final values being around 150 for each sample (Fig. 6b). Some changes occur in the RGB values but they are not significantly changed.



b)

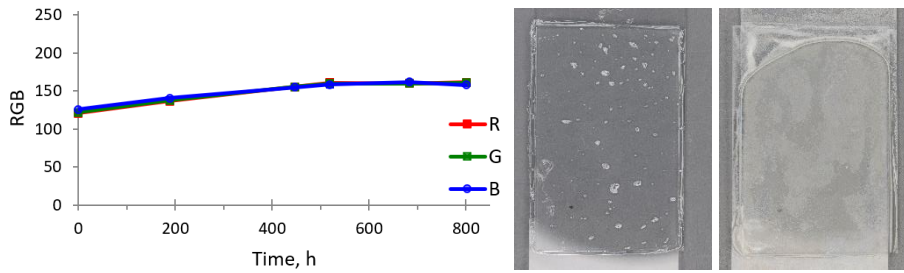
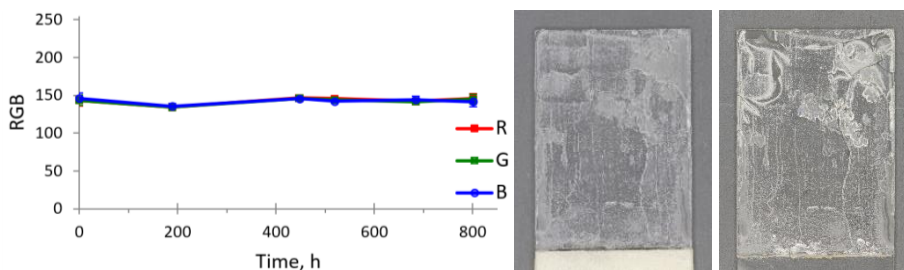


Figure 7a) On the left side, average RGB values for laminated EVA on the light soaking test. On the right side, laminated EVA sample before and after the light soaking test. b) Average RGB values for laminated EVA on the damp heat test. On the right side, laminated EVA sample before and after the damp heat test.

The starting average RGB values for laminated EVA on the light soaking test are around 120 each (Fig. 7a). There are some minor changes in the RGB values as they increase from the initial value of 120 to around 125 (Fig. 7a). On the damp heat test, the starting average RGB values are around 120 (Fig. 7b) and in the end the values are around 160 each. During the damp heat test, the values of laminated EVA therefore showed more changes compared to the light soaking test, indicating that laminated EVA is more susceptible to high temperatures and humidity than the effects of light.

Contrary to the findings in the literature, where EVA-encapsulated cells have shown some excellent results, some degradation of EVA was observed in these tests, as can be seen in the average RGB values of both laminated and unlaminated samples of EVA.

a)



b)

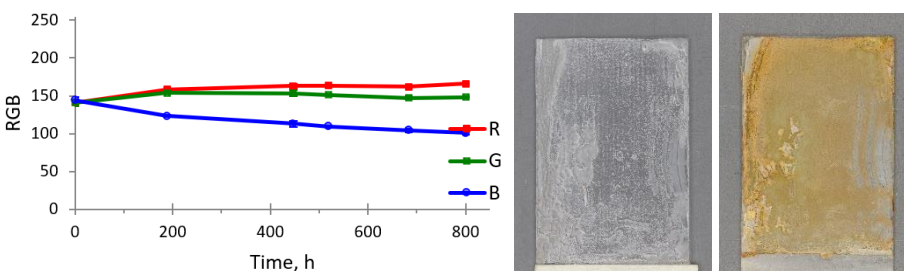
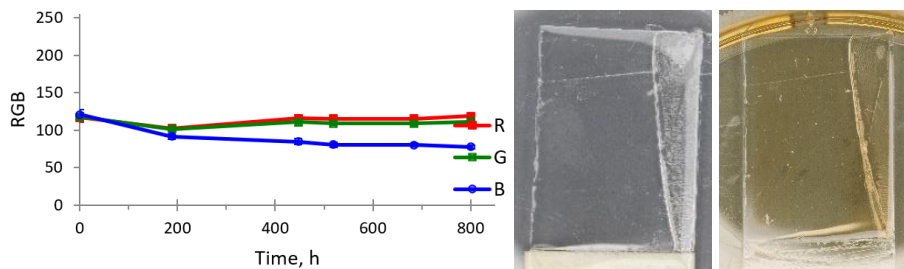


Figure 8a) On the left side, average RGB values for Casco® Gel glue on light soaking test. On the right side, Gel glue sample before and after light soaking. b) On the left side, average RGB values for Gel glue on the damp heat test. On the right side, Gel glue sample before and after the damp heat test.

As can be seen in Figure 8a), the average RGB values of Gel glue does not show significant changes on the light soaking test. The values start from 144 and ends up being around 145 each (Fig. 8a). On the damp heat test, however, the values change considerably (Fig. 8b). The average values of red and green start from 140 and for red it ends up at 165, while green ends up at 148 (Fig. 8b). The average value of blue decreases the most: from 143 to 100. Based on the graphs, it seems that the Gel glue is more stable under illumination than high humidity and temperature.

a)



b)

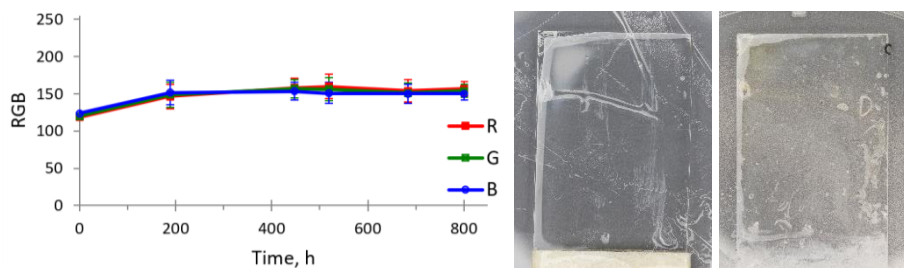
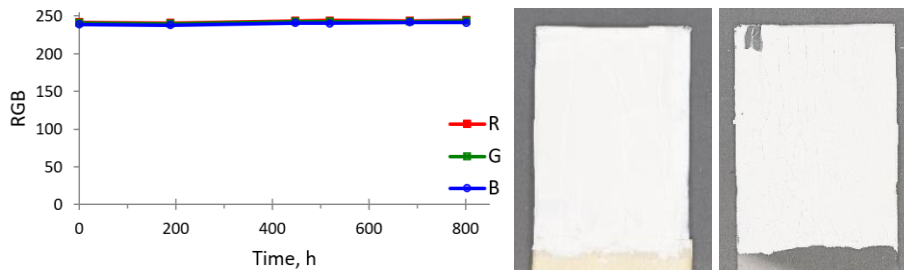


Figure 9a) Casco® Glas glue average RGB values on light soaking. On the right side, Glas glue sample before and after the light soaking test. b) Average RGB values for Glas glue on the damp heat test. On the right side, Glas glue sample before and after the damp heat test.

On the light soaking test, the average RGB values for Glas glue are around 120 at the start (Fig. 9a). Some variation in these values occurs, with blue decreasing to 77, red to 119 and green to 111 (Fig. 9a). On the damp heat test, however, the average RGB values increase from around 120 to values of 150 (Fig. 9b). Therefore, Glas glue does not seem to be very stable in either of the tests, neither in the damp heat nor in the light soaking test.

a)



b)

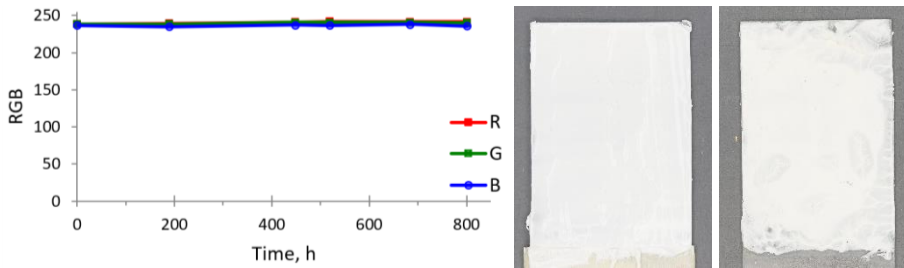
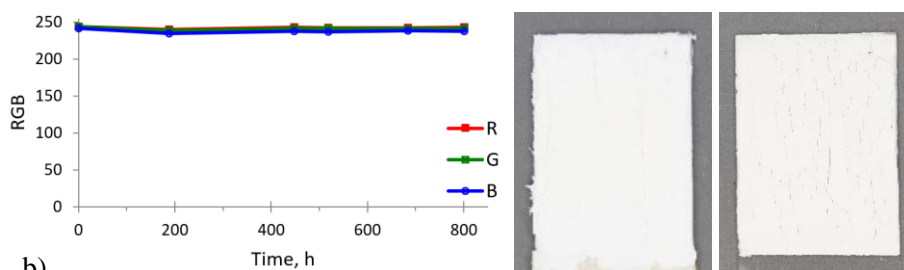


Figure 10a) Casco® Marin & Teknik glue average RGB values during the light soaking test. On the right side, Marin & Teknik glue sample before and after the light soaking test. b) Marin & Teknik glue average RGB values during damp heat test. On the right side, Marin & Teknik glue sample before and after the damp heat test.

As can be seen from Figure 10a), the average RGB values of Marin & Teknik glue remain roughly the same during the light soaking test, starting from 241 and ending up at around 243. The average RGB values also remain relatively stable in the damp heat test, starting at 238 and ending at 240 (Fig. 10b). However, in both samples, there were some factors indicating instability. On the light soaking test, the glue was cracked, and on the damp heat test, it did not cure at all, meaning that the graphs do not give a completely accurate description of the stability of the glue.

a)



b)

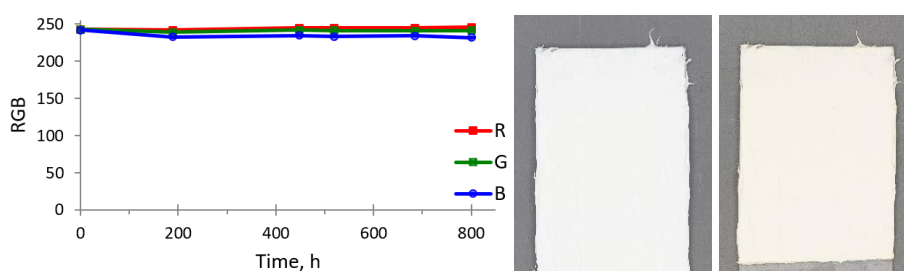




Figure 11a) Polyurethane average RGB values on the light soaking test. On the right side, polyurethane sealant sample before light soaking. b) Polyurethane sealant average RGB values on the damp heat test. On the right side, polyurethane sealant before and after the damp heat test.

On the light soaking test, the average RGB values of the polyurethane sealant sample remain approximately the same, starting around 243 and ending up at 240 (Fig. 11a). On the damp heat test the average values of red and green stay roughly the same, starting at 243 and ending up at around 243 (Fig. 11b). The change is more significant for the blue color, although not by much, as the average value decreases from 241 to 231. The polyurethane sealant also showed some cracking in the light soaking test, but not in the damp heat test, which indicates that it was not very stable in the light soaking test either, even though the values in the graph appear that way. Although polyurethane appears to be one of the most promising encapsulants in the literature, in these experiments the polyurethane sealant began the formation of cracks during light soaking suggesting that the samples were not as stable to the effects of visible and UV light.

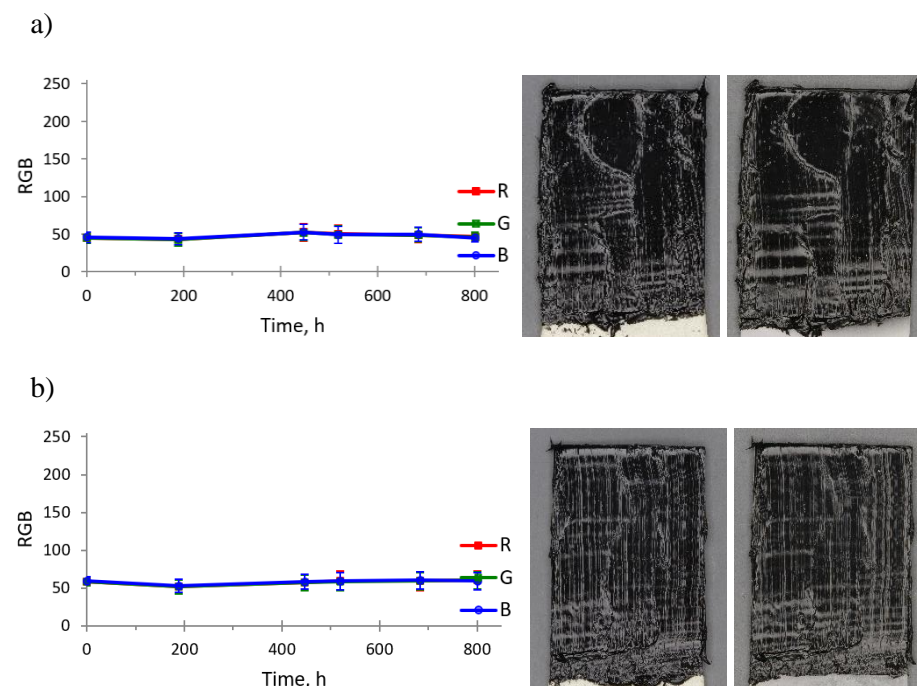
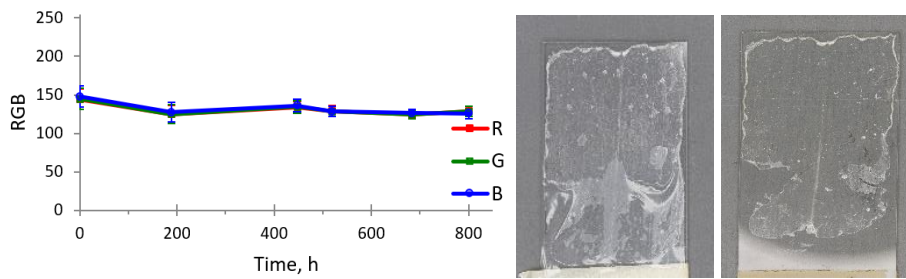


Figure 12a) Silikon average RGB values on the light soaking test. On the right side, Silikon sample before and after the light soaking test. b) Silikon average RGB values on the damp heat test. On the right side, Silikon sample before and after the damp heat test.

As can be seen in Figure 12a), the average RGB values of Silikon remain approximately the same, starting from 45 and ending up at 46 on the light soaking test. Also, on the damp heat test the values seem to remain stable, starting from 59 and ending up on 60 (Fig. 12b). It seems that Silikon remains relatively stable in both the damp heat test and the light soaking test, showing negligible degradation.

a)



b)

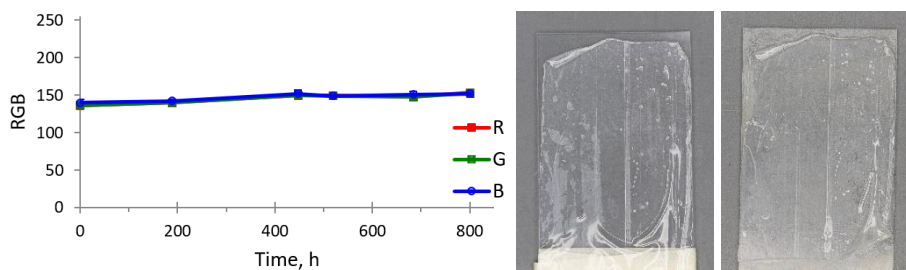
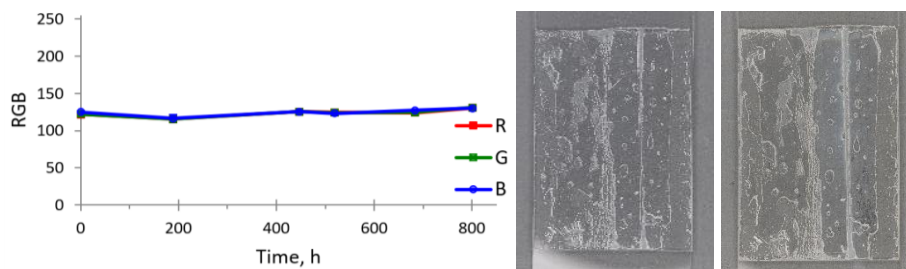


Figure 13a) Average RGB values of Surlyn™ on the light soaking test. On the right side, Surlyn™ sample before and after the light soaking test. b) Average RGB values of Surlyn™ on the damp heat test. On the right side, Surlyn™ sample before and after the damp heat test.

On the light soaking test, Surlyn™ shows a little decrease in the average RGB values, decreasing from around 145 to 127 (Fig. 13a). On the damp heat test, however, the values are increasing from around 137 to 152 (Figure 13b). There are therefore some changes in the values of both tests, but the changes are not very significant. Thus, Surlyn™ is relatively stable both in high humidity and temperatures as well as under exposure to light.

a)



b)

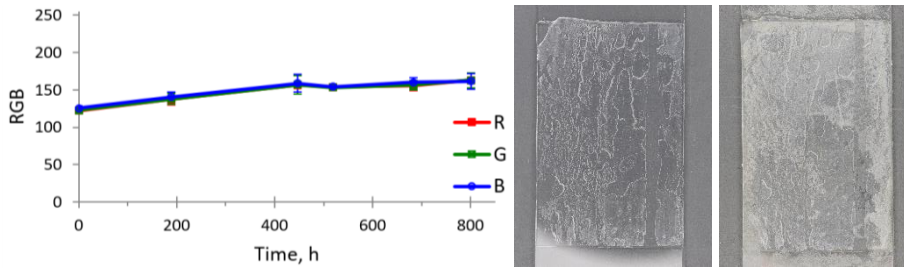
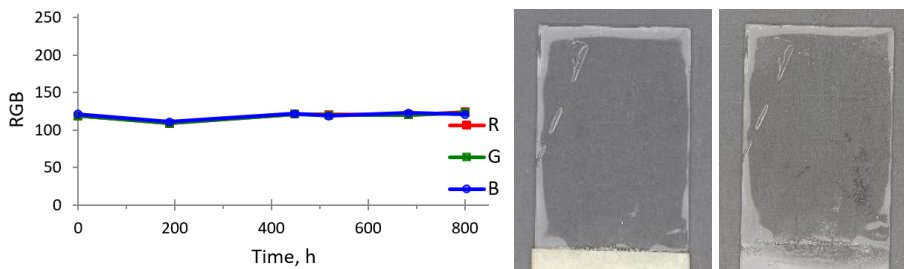


Figure 14a) Laminated Surlyn™ average RGB values on the light soaking test. On the right side, laminated sample of Surlyn™ before the light soaking test. b) Average RGB values for laminated Surlyn™ on the damp heat test. On the right side, laminated Surlyn™ before and after the damp heat test.

As can be seen from Figure 14a), there are some minor changes in the average RGB values of laminated Surlyn™ on the light soaking test. The average RGB values increase from 122 to 130 each. In the damp heat test, the values increase from 122 to 162 (Fig. 14b), indicating that laminated Surlyn™ degrades to some extent under high humidity and high temperature conditions. The changes are less noticeable in light soaking (Fig. 14a), meaning that laminated Surlyn™ is more stable to visible and UV light. Compared to the promising results in the literature, it may be that the higher relative humidity used in these experiments contributes to the less successful results on these experiments.

a)



b)

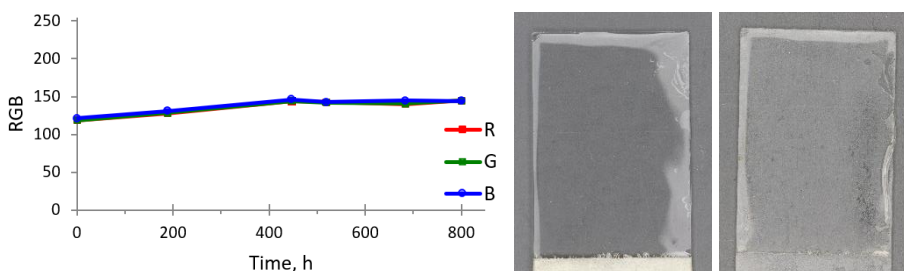


Figure 15a) Sylgard® 184 average RGB values on the light soaking test. On the right side, Sylgard® 184 sample before and after the light soaking test. b) Sylgard® 184 average RGB values on the damp heat test. On the right side, Sylgard® 184 sample before and after the damp heat test.



Figure 15a) shows that Sylgard® 184 remains relatively stable on the light soaking test. The average RGB values increase slightly, from around 120 to 123 (Fig. 15a). The same goes for the damp heat test, where the average RGB values increase from 120 to around 144 (Fig. 15b). The changes that occur in Sylgard® 184 are therefore small, but changes are more noticeable at high temperatures and humidity. Comparing these results with PDMS as an encapsulant for PSCs in the literature, the results are somewhat comparable, with both showing good results.

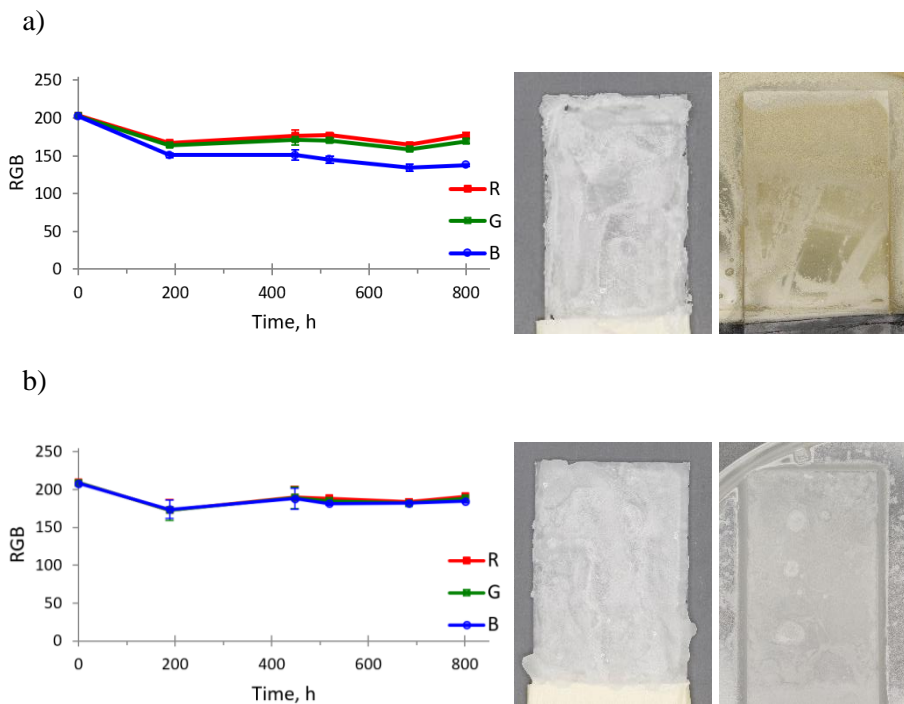
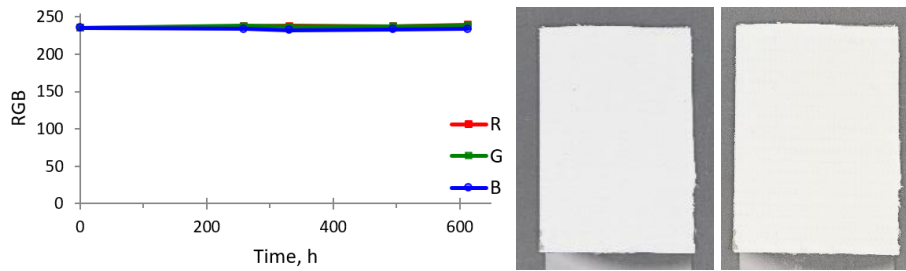


Figure 16a) Paraffin average RGB values on the light soaking test. On the right side, paraffin sample before and after light soaking. b) Paraffin average RGB values on the damp heat test. On the right side paraffin sample before and after the damp heat test.

The average RGB values of paraffin decreases from 200 to as low as 137 on the light soaking test (Fig. 16a). On the damp heat test, the average RGB values decreased from 210 to 185 (Fig. 16b), showing noticeable degradation. In less than 200 hours, the paraffin of the samples started to melt in both the damp heat test and the light soaking test, indicating that paraffin is not suitable for the encapsulation of PSCs. When comparing the results obtained with the results in the literature, the results differ to some extent, which may be because the tests in the literature did not use temperatures as high as those used in these tests.

a)



b)

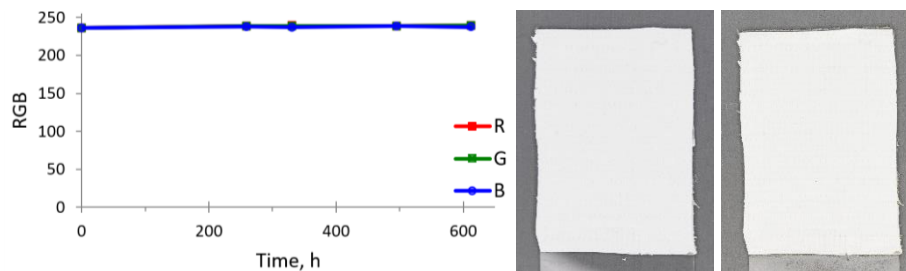


Figure 17a) Gorilla tape® average RGB values on the light soaking test. On the right side, Gorilla tape® sample before light soaking. b) Gorilla tape® average RGB values on the damp heat test. On the right side, Gorilla tape® before and after the damp heat test.

On both light soaking (Fig. 17a) and damp heat test (Fig. 17b) Gorilla tape® remains stable, showing that it is highly resistant to high temperatures and humidity as well as to the effects of light. On the light soaking test, the average RGB values remained nearly the same as the initial values (Fig. 17a). The same goes for the damp heat test, where the average RGB values were slightly increased from 235 to 239 (Fig. 17b) meaning that the degradation was minimal on both of the tests. However, the tests with Gorilla tape® took 200 hours less than with the other samples, but the results seemed promising so far. What still needs to be studied is how well it works with the cell itself, or how it permeates moisture, to know if it is suitable as an encapsulant.



Figure 18. Oppanol® B sample before light soaking.

For Oppanol® B samples, there was not enough data for graphs yet, but the results in the literature for polyisobutylene as an encapsulant seem promising.

## Conclusions

Perovskite solar cells are a promising photovoltaic technology due to their low cost, high efficiency and other promising features. However, the commercialization of PSCs, is still limited by their instability mainly caused by different environmental factors, such as moisture and oxygen. Encapsulants can act as a protective layer against such factors and prevent them for affecting the cell and its efficiency. Therefore, the main focus of this thesis was to find the most promising encapsulants for perovskite solar cells by performing a damp heat and light soaking tests on them.

The literature review discussed previously used encapsulants for perovskite cells and the experiments that have been carried out with these encapsulants. Such encapsulants were EVA, Surlyn™, PDMS, PIB, epoxy, paraffin and TPUs. Based on the literature review, the most promising encapsulants seem to be PDMS, PIB and TPUs. These can be used on flexible devices, are cost effective and have shown good stability. The findings in the literature were mostly applicable to the results of the experimental part of this thesis. However, comparing the results is challenging due to the differences between the experiments of encapsulated cells.

The most promising encapsulants tested were EVA, Silikon, Sylgard® 184 and Gorilla tape®. The average RGB values of these samples showed only minor changes, which means that they were the most resistant to high temperatures, humidity as well as visible and UV light, making these materials the most suitable candidates for perovskite solar cell encapsulation. These encapsulants can be further studied on perovskite solar cells to ensure their compatibility. In addition, a moisture permeability test can be carried out to see how these encapsulants allow moisture to pass through.

Some samples that showed better performance in the light soaking test than in the damp heat test, including laminated EVA, laminated Surlyn™ and Gel glue. This means that these encapsulants were more stable under visible and UV light than under high temperatures and humidity. With the polyurethane sealant, the results were the opposite, with relatively good stability against high temperatures and humidity but not against the effects of light.

Marin & Teknik glue and Surlyn™ had some variation in their average RGB values, so they were not among the most promising encapsulants for PSC encapsulation. Epoxy, Glas glue and paraffin showed the most significant degradation based on the average RGB values in the

damp heat and light soaking tests, indicating that these encapsulants are not suitable as encapsulants for PSCs.

Addressing the stability challenges of perovskite cells with encapsulation could be one of the major factors enabling their future commercialization. This would require an encapsulation method that does not require expensive or complex processes and takes into account the sensitivity of perovskite to different environmental factors. The encapsulant itself should be inexpensive, easy to use, stable and compatible with PSCs. Furthermore, the need for clear protocols for testing perovskite solar cells is important to ensure that the experiments are reproducible and comparable in the future.

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