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## Biological growth on rendered façades

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# Biological growth on rendered façades

Sanne Johansson



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*If we knew what it was we were doing, it would not be called  
research, would it?*

Albert Einstein (☆1879 †1955)

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## Preface

Present project was financed by FORMAS, the Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning. They are greatly acknowledged for their financial support making this Ph.D-project possible to carry out. I would also like to thank all my colleagues at Building Material (BML) for making my daily life at the division a pleasure. Especially I would like to thank the technicians Stefan Backe, Bengt Nilsson and Bosse Johansson for all help at any possible (and impossible) time. Also thank to the administrative staff Marita Persson and Britt Andersson; without you the division would be a mess (not only the lunch room). And last - but definitely not least - a special thank to my supervisors Lars Wadsö and Kenneth Sandin. It cannot be emphasized enough my appreciation to how much I have learned from both of you.

I would also like to thank my three special guys; Casper, Alexander and Shankly and the newest addition to my family my special little girl Gaia -thank you all for being a part in my life.

Present project is a multi-disciplinary study in several areas of science, and therefore some parts of this thesis might seem trivial to some people, other parts by others, but I found it necessary to make a general introduction to certain fields mainly in biology and building physics. It also reflects the areas of science I had to learn (and relearn) about during my years as a PhD student.

*Sanne Johansson*

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## Abstract

Biological organisms have an incredible ability to adapt to almost any environment and the humans activities on earth have created many new habitats for different kinds of organisms. For example can certain organisms grow on rocks and vertical cliffs, and when humans started building houses with mineral based façades, some organisms found that these were new habitats to live on. Some of these expansions of habitats to our houses are not desirable for the us humans and are considered as contaminations". Even if this contamination sometimes only is an aesthetically problem, some contamination is highly unwanted because it can be unhealthy for the inhabitants - for example the growth of moulds - or it can degrade the building materials it grows on -as for example wood-degrading fungi.

For an organism to grow in a certain environment, different requirements on abiotic (physical and chemical) and biotic (biological) factors have to be fulfilled. Suitable conditions for growth of organisms on façades are certain ranges in temperature and a high moisture level (RH), but also the surface structure, nutrient availability, pH, cardinal direction etc. might be influencing. Different organisms have different demands on these factors and it is a complex interaction of these different factors that decides if an organism can grow in a certain environment.

The last decades many houses in Sweden have been built with constructions of thin rendering on thermal insulation, a so called ETICS construction (External Thermal Insulation Construction System). This construction consist most often of a framework of wooden studs with thermal insulation in between, and gypsum boards or cement based boards on both sides. On the outside a thermal insulation layer is applied and the render is then applied directly on the outside of this thermal insulation layer. This is a an efficient and compact construction

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which is easy to produce. However, many of these constructions have experienced discolourations from growth of algae and moulds on the façades already a few years after construction. It has not always been possible to explain this discolouration. Sometimes one part of the façade had discolorations and another part of the same façade did not.

One possible explanation for the fast growth of organisms is the external rendering layer (on thermal insulation that has a low heat capacity and during night the long-wave radiation from the material to the sky can contribute to a lower temperature on the surface than the temperature in the air -on clear nights, when the heat losses through long-wave radiation is high. The lowered surface temperature then causes the RH on the surface to increase, sometimes giving condensation -which increases the risk of biological growth.

In this project we have compared temperatures and RH on surfaces on façade elements in a test house with constructions with low heat capacity in the outermost layer (light walls) and constructions with a high heat capacity in the outermost layer (heavy walls). Simulations of the growth risk showed that thin rendering on thermal insulation has a higher growth risk than traditionally render on bricks especially on the north side. On the south side the most important factor was the surface colour. In our study we compared a red and a white surface, and since dark surface colours absorb more short-wave radiation from the sun they have a higher temperature during daytime and therefore a lower RH on the surface.

Another factor which might influence the growth risk is the surface structure of the render. We fabricated specimens with different renders with different surface structures and with a thin and thick rendering layer (3 mm and 20 mm, respectively) and exposed the specimens outdoors for four years. This study showed that algae preferred a very rough surface structure while moulds (*Cladosporium* sp.) also grew on more smooth surfaces. In addition we found that algae

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most often grew on the north side whereas moulds rather grew on the south side (*Cladosporium* has a dark pigment in the cells which protects against radiation from the sun). Furthermore we found a connection between the amount of growth and the season of the year. The biological growth was more clearly seen during spring and especially autumn and occasionally seemed to disappear during summer and winter. It was found that thin (3-4 mm) and thick (20 mm) render on thermal insulation had the same amount of discolouration.

The activity of photosynthetic organisms -algae, lichens and mosses- on façades can be measured with Imaging-PAM. This is an instrument that measures the chlorophyll fluorescence and gives an indirect measure of photosynthetic activity. A pilot study was performed where we -during three days in the autumn- studied algae and mosses growing on render. Algae dries out easily and is dependent of moisture from the surroundings and showed the highest activity during mornings before the sun dried them out. The mosses were active a greater part of the day; they are able to some extent store water in their leaves and is not as dependent on moisture from the surroundings as algae.

Another method for measuring activity of biological organisms is isothermal calorimetry which measures the produced heat from an organism's metabolism. In this project we tested a new type of calorimeter that measures activity at four different temperatures at the same time. With measurements of a moss (*Tortula ruralis*) we found that it was possible to get an activity measure at four different temperatures at the same time, thus being able to get an understanding of how the temperature influences the activity. This method should therefore be very useful in future studies of activity of different types of biological organisms.

The aim of this project was to investigate constructions of thin rendering on thermal insulation and the biological organisms growing on the façades of these constructions. With a multidisciplinary approach

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we have increased the knowledge of the façade as a habitat, the organisms growing, and their interactions with different biotic and abiotic factors.

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## Sammanfattning

Biologiska organismer har en fantastisk förmåga att anpassa sig till alla möjliga miljöer. Människans aktiviteter på jorden har skapat många nya habitat för olika typer av organismer; t ex kan vissa organismer växa på sten och vertikala klippor och när människor bygger hus så kan dessa organismer flytta över till väggar och tak som blir nya biotoper att leva på. Några av dessa habitatutbredningar till våra hus är dock inte önskvärda för oss människor och betraktas som en "kontaminering" av våra byggnader. Även om denna kontaminering till stor del är ett estetiskt problem, finns det påväxt som är oönskad eftersom den är skadlig för invånarna - mögelsvampar - eller bryter ner materialet de växer på - rötsvampar.

För att organismer ska kunna växa i en viss miljö skall olika krav på abiotiska (fysikaliska och kemiska) och biotiska (biologiska) faktorer vara uppfyllda. Essentiella faktorer för påväxt på husfasader är temperatur och relativ fuktighet (RF), men också ytstruktur, tillgång till näring, pH och väderstreck påverkar. Olika organismer har olika krav till dessa faktorer och det är ett samspel mellan alla dessa faktorer där avgör om en organism kan växa i en given miljö.

De senaste årtiondena har många hus blivit byggda med en konstruktion av så kallad tunnputs på isolering. Konstruktionen består ofta av en träregelstomme med isolering mellan reglarna och gips- eller cementbaserade skivor på båda sidorna. På utsidan finns ett isoleringsskikt och putsen fästas direkt på utsidan av detta skikt. Detta är en effektiv och kompakt konstruktion som är enkel att bygga, men den saknar ett dränerande och ventilerande skikt. Det har visat sig att många av dessa konstruktioner har fått påväxt av alger och mögelsvampar på fasaderna redan några år efter konstruktion. Det har dock inte alltid varit möjligt att fastställa orsakerna till denna snabba påväxt. Dessutom kan en del av en fasad ha påväxt, medan

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en annan del inte har det.

En möjlig förklaring till snabb påväxt på puts på isolering är att dessa putsskikt har minimal värmekapacitet och då bidrar nattutstrålningen från putsen att yttemperaturen blir lägre än luftens temperatur - särskilt i samband med klara nätter, där nattutstrålningen är hög. Den lägre yttemperaturen orsakar då hög RF på ytan och ibland också kondens - vilket ger hög risk för påväxt. I detta projekt har vi jämfört temperatur och RF på ytor av konstruktioner i ett provhus med låg värmekapacitet i ytskiktet (lätta väggar) och konstruktioner med högre värmekapacitet (tunga väggar). Simuleringar av påväxtrisen visade att fasader med låg värmekapacitet hade signifikant högre ytfuktighet jämfört med fasader med högre värmekapacitet och därmed har tunnputsfasader högre risk för påväxt. Detta gäller framförallt på norrsidan. På södersidan var färgen på ytan av stor betydelse. I vårt försök jämförde vi en röd och en vit yta, och eftersom mörka ytor absorberar mera solstrålning har de därför en högre medeltemperatur och därmed lägre RF på ytan.

En av de andra faktorerna som visat sig ha stor betydelse för påväxtrisen är strukturen på putsens yta. Vi tillverkade putsprovkroppar av olika putstyper och putsstruktur och med tunn och tjock puts och exponerade dessa utomhus i 4 år. Studien visade att alger fördrog en mycket grov ytstruktur medan mögelsvampar (främst av släktet *Cladosporium*) helst växte på mer släta ytor. Dessutom växte alger oftast på norrsidan medan mögelsvamparna växte på södersidan (*Cladosporium* har det mörka färgämnet melanin i cellväggarna som skyddar mot solstrålning). Därutöver sågs ett mönster i påväxtgraden efter årstiderna. Påväxten - vare sig det var mögel eller alger - sågs tydligare under vår och höst, och såg ibland ut att försvinna under sommar och vinter. Vi fann ingen skillnad i påväxt mellan tunna (3 mm) och tjocka (20 mm) putser på isolering.

Aktiviteten hos fotosyntesaktiva organismer - alger och lavar på



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fasader - kan mätas med Imaging-PAM. Detta är ett instrument som mäter klorofylfluorescens och ger ett indirekt mått på fotosyntesaktivitet. Ett pilotförsök utfördes med Imaging-PAM där vi under tre dagar under hösten mätte fotosyntesaktivitet hos alger och mossor som växte på puts. Alger torkar lätt ut och är helt beroende av fukt från omgivningen och visade högst aktivitet under förmiddagen innan solen torkade ut dem. Mossorna var aktiva under större delen av dygnet; eftersom de bättre kan hålla vatten i sina blad är de inte så beroende av direkt fukt från omgivningen.

En annan metod att mäta aktiviteten hos biologiska organismer är isotherm kalorimetri som mäter värmen som utvecklas vid organismers metabolism. I denna studie testade vi en ny typ av kalorimeter som kan mäta aktivitet vid fyra olika temperaturer samtidigt. Med mätningar på en mossa (takmossa, *Tortula ruralis*) visade det sig möjligt att få ett aktivitetsmått vid fyra olika temperaturer samtidigt och på så snabbt bilda sig en uppfattning om hur aktiviteten beror på temperaturen. Metoden bör därför vara mycket användbar för framtida aktivitetsmätningar på olika typer biologiska organismer.

Syftet med projektet bakom denna avhandling är att undersöka tunnputskonstruktioner och de biologiska organismer som växer på fasaderna. Med ett multidisciplinärt tillvägagångssätt har vi ökat kunskapen om fasaden som en biotop, de organismer som växer där, och deras samspel med olika biotiska och abiotiska faktorer.

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## Keywords

algae, biological growth, calorimetry, desiccation tolerance, ETICS, heat, heat capacity, humidity, Imaging-PAM, lichens, moisture, mortar, mosses, moulds, photosynthesis, radiation, render, temperature

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## Abbreviations

ATP	Adenosine triphosphate
Chl	Chlorophyll
DSC	Differential scanning calorimetry
ETR	Electron transport rate
$F_0$	Minimal fluorescence signal when $Q_A$ are fully oxidized (dark-adapted)
$F_m$	Maximal fluorescence signal when $Q_A$ are fully reduced
NADPH	Nicotinamide adenine dinucleotide phosphate hydrogen
OEC	Oxygen evolving complex
PAR	Photosynthetic active radiation
PSII, PSI	Photosystem II, Photosystem I
RH	Relative humidity
$Q_A$	Quinone molecule involved in the electron transport chain in the light-dependent reactions of photosynthesis
SEM	Scanning electron microscopy

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## Wordlist

Explanations of words in following list is based on [88] and Wikipedia<sup>1</sup>.

Abiotic factors	Non-living chemical and physical factors in the environment
Actinic light	Light used for photosynthesis
Autotroph	Able to use inorganic sources of carbon as starting material for biosynthesis
Biotic factors	Living factors in the environment
Cyanobacteria	A phylum of photosynthetic bacteria. Are often misleading called blue-green algae
Chlorophyll	A green pigment critical in the photosynthesis
Chloroplasts	Organelles that conduct photosynthesis
Eukaryote	Organisms with membrane-bounded nucleus in the cells and whose cells contain complex structures enclosed within membranes
Heterotroph	Able to only utilize organic carbon as starting material for biosynthesis
Obligatory	Limited to one mode of life or action
Poikilohydric	A condition in organisms that lack a mechanism to prevent desiccation
Polyphyletic	A taxonomic group having origin in several different lines of descent
Prokaryote	Organisms without a nucleus
Protist	Unicellular eukaryotes that either exist as independent cells, or if they occur in colonies, do not show differentiation into tissues
Thallus	An undifferentiated vegetative tissue; usually the entire body of a multicellular non-moving organism in which there is no organization of the tissues into organs
Thylakoid	Membrane vesicle inside the chloroplasts which contain the photosynthetic apparatus

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## Papers included in the thesis

This thesis is based on the following papers, which will be referred to in the text by their Roman numerals. The papers are appended at the end of the thesis.

### **I Biological organisms on building façades**

Johansson, S., Li, Y., Wadsö, L. (2005)

*Proceedings of the 7<sup>th</sup> symposium on Building physics in the Nordic Countries*, The Icelandic Building Research Institute, Reykjavik, Iceland, pp: 719-724.

**(Published)**

### **II Microbial growth on building façades with thin rendering on thermal insulation**

Johansson, S., Wadsö, L., Sandin, K. (2005)

*Proceedings of the 7<sup>th</sup> symposium on Building physics in the Nordic Countries*, The Icelandic Building Research Institute, Reykjavik, Iceland, pp: 1126-1130.

**(Published)**

### **III Estimation of mould growth levels on rendered façades based on surface RH and surface temperature measurements**

Johansson, S., Wadsö, L., Sandin, K. (2010)

*Building and Environment* 45: 1153-1160.

**(Published)**

- 
- IV **A four-year study of biological growth on rendered surfaces on thermal insulation**  
Johansson, S., Sandin, K., Wadsö, L.  
*Construction and Building Materials*  
(Manuscript)
- V **Biological applications of a new isothermal calorimeter that simultaneously measures at four temperatures**  
Wadsö, L., Salamanca, Y., Johansson, S. (2011)  
*Journal of Thermal Analysis Calorimeter* 104(1): 119-126.  
(Published)
- VI **Pilot study of activity of photosynthetic organisms growing on render measured with Imaging-PAM**  
Johansson, S., Wadsö, L., Abu-Elsaoud, A.M.  
*Photosynthetic Research*  
(Unfinished manuscript)

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# Introduction

*The beginning of knowledge is the  
discovery of something we do not  
understand*

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Frank Herbert (☆1920 †1986)

The diversity of biological organisms is astonishing. If we take a look in any ecosystem, we will find a world teeming with different organisms. It is easy to recognize all the different plants and animals, but looking more carefully we will also recognize some fungi and lichens, and with the help of a microscope, bacteria and other microscopic life forms. Not only the ecosystems teems with different life forms, also for example your skin, your mouth and your intestine is home for a diverse community of bacteria etc.

Any organism's environment can be thought of as everything that may affect its development, survival or reproduction. These factors are of both abiotic and biotic origin. Which aspects of the environment that are important to an organism vary from species to species and depends on the organisms evolutionary history.

The genus of humans (*Homo* spp.) have over the last millions of years increased incredibly in numbers and spread over the whole world and this has had a tremendous influence on the ecosystems on earth. Many biotopes have disappeared, but the human expansion has also created new "non-natural" biotopes. As some organisms can live on

stones and vertical cliffs, the building of houses has given new opportunities for some organisms to expand by using buildings as habitats. However, this habitat expansion is not desirable for the humans living in the buildings, and is therefore considered to be "contaminations". Even if most of the contamination on façades is only of aesthetical character some biological growth in buildings is highly unwanted because it can be harmful to the inhabitants and/or degrade the building itself.

This is especially true for the kingdom of Fungi, which among many others include organisms that causes health problems and organisms that causes decay on timber. The history of fungal problems in buildings is long. The oldest reference of mould damages in houses is probably from the old testament in the christian bible (the third book of the hebrew bible), which today is considered to be written from the 13<sup>th</sup> century BCE. Even if this book as a scientific resource is very doubtful it is still interesting in a historical perspective. In the standard english version of the christian bible, it is described how to get rid of "leprous disease"<sup>1</sup> which God has put in some houses (Leviticus 14: 33-42):

<sup>33</sup>The LORD spoke to Moses and Aaron, saying, <sup>34</sup>"When you come into the land of Canaan, which I give you for a possession, and I put a case of leprous disease in a house in the land of your possession, <sup>35</sup>then he who owns the house shall come and tell the priest, 'There seems to me to be some case of disease in my house.' <sup>36</sup>Then the priest shall command that they empty the house before the priest goes to examine the disease, lest all that is in the house be declared unclean. And afterward the priest shall go in to see the house. <sup>37</sup>And he shall examine the disease. **And if the disease is in the walls of the house with greenish or reddish spots, and if it appears to be deeper than the surface,** <sup>38</sup>then the priest shall go out of the house to the door of the house and shut up the house seven days. <sup>39</sup>And the priest shall

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<sup>1</sup>The translation to *leprous disease* can be discussed. In other versions of the bible it is translated to *skin disease* and in the new International version of the Christian Bible it is translated to *defiling mold*.

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come again on the seventh day, and look. If the disease has spread in the walls of the house,<sup>40</sup> **then the priest shall command that they take out the stones in which is the disease and throw them into an unclean place outside the city.**<sup>41</sup> **And he shall have the inside of the house scraped all around, and the plaster that they scrape off they shall pour out in an unclean place outside the city.**<sup>42</sup> **Then they shall take other stones and put them in the place of those stones, and he shall take other plaster and plaster the house.**

Also Vitruvius, a roman architect, engineer and writer (born ca 80–70 BCE and died after 15 BCE) notice in his *De architectura* ("The Ten Books on Architecture") the importance of constructing houses correctly (Vitruvius I: 1.10):

The architect should also have knowledge of the study of medicine, on account of the questions of climates, air, the healthiness and unhealthiness of sites, and the use of different waters. For without these considerations, the healthiness of a dwelling can not be assured.

And as he later so exquisitely writes (Vitruvius I: 6.1):

Cold winds are disagreeable, hot winds enervating, moist winds unhealthy.

Even if moisture itself is inevitable and indeed not dangerous it can cause serious problems in to high amounts or being found in the wrong places. There are several aspects on this:

### **Degradation of materials**

Moisture can cause or contribute to corrosion of metals, frost damage, salt frost scaling, wood decay by fungi and other biological activity from certain insects.

### **Health issue of inhabitants**

Mould growth is the main agent causing health risks such as hypersensitivity, nausea, allergic rhinitis and asthma for inhabitants due to moisture problems, but also other organisms -like

house dust mites (*Dermatophagoides pteronyssinus*)- can cause allergic reactions. In addition, emissions from materials like pressure impregnated wood can emit bad odor when humid and that give decreased indoor air comfort as well as social and economical consequences.

### **Increased energy requirement**

Moisture in materials can lead to increased heat consumption as increased moisture levels generally give increased heat conduction (and it requires energy to evaporate moisture).

### **Growth of organisms on the building façades**

Even though this problem might only be of aesthetic character, a façade is perhaps a building's most important architectural feature. Discoloured façades will therefore give an impression of a poorly maintained building (even if it is not).

The aim of the present project was to study different aspects of the complex phenomenon of biological growth on rendered building façades. The background for the project was the emerging need for knowledge of the increasing problem of biological growth on newly constructed houses in Sweden. My main focus is on the fundamental influences of different abiotic factors (primarily temperature and relative humidity) on biological growth and activity. This is needed to get a deeper understanding of the biological physiology of organisms living in extreme<sup>2</sup> environments such as building façades.

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<sup>2</sup>The formulation *extreme environment* is a commonly used expression for organisms living in biotopes we humans find extreme, but it is rather misleading as these organisms are adapted to such environments and do not find them extreme.

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## ETICS

*Science is facts; just as houses are made of stones, so is science made of facts; but a pile of stones are not a house and a collection of facts is not necessarily science*

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Henri Poincare (☆1854 †1912)

For the last decades many new houses in Sweden have been built with a so called ETICS construction [122]. ETICS is short for External Thermal Insulation Composite System (in North America this construction system is often called EIFS [120]). Commonly, the construction is built up as shown in Figure 2.1. This system was developed from Germany, where many brick houses needed extra thermal insulation. A thermal insulation layer was then placed on the outside of the original façade and covered with a render. During the energy crisis in Sweden in the 1970's, many Swedish houses also got an additional thermal insulation layer in the same way. During the 1980's the Swedish construction industry also started to use this thermal insulation layer directly on structures of a wooden framework in new buildings. Hereby one got a compact and well insulated construction with a rendered façade [123].

A serious disadvantage with this one-step sealed and undrained construction type is that there is a high risk that water penetrates into

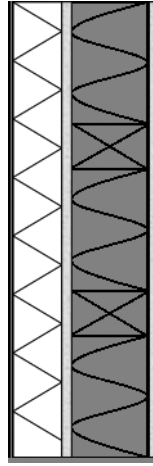


Figure 2.1: A schematic picture of a cross section of ETICS. From the left (outside) to the right (inside) the construction consists of following layers: 3-5 mm layer of render, 50 mm expanded polystyrene, 9 mm gypsum board, 145 mm x 45 mm wood studs c/c 600 and 145 mm mineral wool, 0.2 mm vapour barrier and a 9 mm gypsum board.

the wall. This has caused a considerable manner of moisture damaged buildings in Sweden. In 2001 significant moisture related damage was seen in a building area with newly built ETICS constructions in Stockholm [124]. During spring and summer 2001 there was focus in the Swedish daily press and television on the problems with this construction type. In 2009 the SP Technical Research Institute of Sweden did an inventory of ETICS constructions in Sweden to investigate the extent of moisture damage [122]. It was found that 55% of the investigated ETICS buildings in Sweden did to some extent have moisture damage<sup>1</sup>. Buildings in the western part of Sweden had most moisture damage (60%) while in the northern part no moisture damages were found.

Even though this investigation only studied moisture and mould damages inside the construction it is our experience that the risk for

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<sup>1</sup>The definition of moisture damage was if it was determined that at least one façade needed to be replaced.

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biological growth on the surface of the outermost thin rendering layer is also high for ETICS. During my PhD-studies I have traveled around Scania (Skåne), the southernmost province in Sweden to investigate ETICS constructions with biological growth on the façades. Every autumn we got phone calls from worried house owners which experienced that their white house façades turned green or greyish (see Figure 2.2).



(a) Building with algae growth



(b) Building with mould growth

Figure 2.2: Buildings with different kind of biological growth on the façade surfaces.

Often the contaminated façades were in weather exposed locations, but sometimes it was not easy to find the reasons which could explain the growth. In one location in the southernmost part of Sweden two neighboring houses were constructed two month after each other, had the same façade colour, but one of the houses had abundant algae growth on the façades whereas the neighboring house did not have any growth at all (see Figure 2.3). An investigation of the constituents of the renders used showed a content of zinc oxide in the house without discolourations (about 0.5%). The influence of zinc

## 2. ETICS

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oxide and other additives in renders and paints on the risk of discolorations is discussed in Paper IV.



Figure 2.3: Two neighboring houses in southernmost part of Sweden. The house to the left has no discolorations whereas the house to the right have pronounced discolorations due to algae growth.

A part of my PhD study was to investigate the reasons for the pronounced biological growth we saw on the façades of ETICS constructions. Several abiotic factors has to be considered to be able to solve this problem:

- Temperature
- Moisture
- pH
- Surface structure
- Heat capacity of the surface layer
- Biocides
- Short waved radiation
- Organic components in the render



Therefore a knowledge of the abiotic and biotic factors influencing growth on and in building and their interaction with heat and moisture transfer in the building construction is necessary to get a deeper understanding of the problem. In the next sections the basic principles of moisture and heat transfer will be explained to give a better understanding of the micro climate on ETICS façades. The section of building physics are based on [22, 53, 98, 125].

## 2.1 The building physics of rendered façades

The question of whether one will get biological growth on a façade - or how much growth one will get - can in principle be answered if we know the climatic conditions on the façade surface and how the relevant biological organisms react to these conditions. I therefore give a principal discussion of the main factors that determine the microclimate on façade surfaces.

### 2.1.1 Thermal conditions

Figure 2.4 shows the thermal balance at a façade. At stationary conditions a one-dimensional heat flux (heat transfer per unit area and unit time) balance at the outer surface is given by (note the directions of the arrows in Figure 2.4):

$$q_{\text{conduction}} + q_{\text{convection}} + q_{\text{short-wave}} + q_{\text{long-wave}} + q_{\text{phase change}} = 0 \quad (2.1)$$

Heat is conducted inside the wall according to Fourier's law of thermal conduction:

$$q_{\text{conduction}} = -\lambda \frac{dT}{dx} \quad (2.2)$$

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Here,  $\lambda$  is the thermal conductivity, a material property and  $\frac{dT}{dx}$  is the spatial gradient in temperature. The thermal conductivity of mortars and bricks is 0.5 to 1.0 W/(mK), while that of thermal insulation is about 0.04 W/(mK). As the thermal insulation is comparatively thick (typically 200 to 300 mm in Sweden) and has a much lower thermal conductivity than the render-brick-layer, the temperature of the render-brick-layer will to a large extent be de-coupled from the interior thermal conditions. Although there will of course be thermal losses through a well-insulated wall by conduction (at least during the cold season) this will only raise the temperature on the outside by a minute amount.

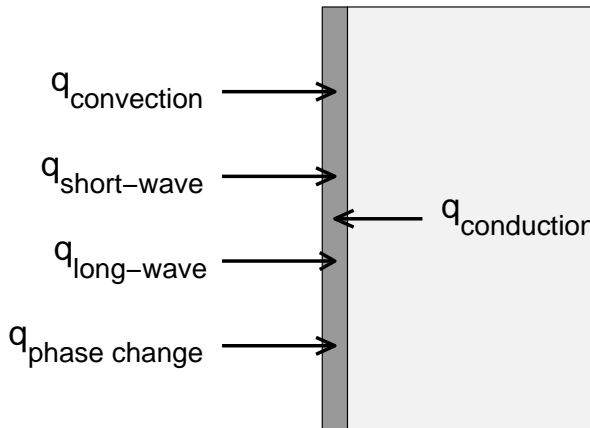


Figure 2.4: Heat balance of a construction at stationary conditions. The exterior - with the render - is to the left. All fluxes are defined as positive when they increase the temperature of the render.

Heat transfer by convection is when heat is transported by a moving fluid. In the present case the fluid is air and the heat transfer takes place when air moves over the wall surface. The relevant equation for heat transfer between a wall and the air is:

$$q_{\text{convection}} = h(T_{\text{wall}} - T_{\text{air}}) \quad (2.3)$$

Here,  $h$  is the heat transfer coefficient. This is a function of the wind speed: in calm weather it is around  $5 \text{ W m}^{-2} \text{ K}^{-1}$ , but at, e.g., 5 meter/second it is about  $30 \text{ W}/(\text{m}^2 \text{ K})$ . Because if this, a façade will be cooled (or heated, depending on the conditions) much quicker when there is a wind, then when the weather is calm.

Short-wave (solar) radiation is an important factor for façades as it heats surfaces in day-time. In the case of short-wave radiation - that is emitted from a body that is much warmer than a façade (the sun) - radiation heat transfer can be modeled as being one-way; from the sun to the wall:

$$q_{\text{short-wave}} = f_1 \alpha I \quad (2.4)$$

Here,  $I$  is the radiation from the sun on a surface facing the sun on a clear day;  $f_1$  is a factor taking into account all the factors that decrease the solar radiation before it reaches the wall; and  $\alpha$  is the absorption factor of the surface, i.e., the fraction of the radiation that hits the surface that is absorbed by the surface (converted to heat). The factor  $f_1$  is in general a complex parameter that includes the time dependent factors, cloud coverage and angle of incidence. The solar radiation on a wall surface is quite different for walls facing in different cardinal directions. For example will (in temperate regions of the northern hemisphere):

- East- and south-facing façades be heated by solar radiation long before the sun reaches a west-facing wall.

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- South-facing façades get the highest heat contribution from solar radiation in the spring and the autumn, but in the summer façades facing east and west actually gain most as the sun is high in the sky at midday.

Solar radiation is usually a positive factor as it heats and consequently dries walls that have become wet by rain or night condensation (see below); for example can the sun dry east facing façades early in the day, while west facing façades will be wet longer. A case of negative influence is the so called "summer condensation" when intense solar radiation drives moisture in a wall into the inner parts of the wall where it can condense.

The absorption factor  $\alpha$  is also an important factor as it is quite dependent on the colour of the surface for short-wave radiation. White façades can have as low absorption factor as 0.3, while dark surfaces have values close to 1.0. The effect of this is clearly seen on south-facing façades, as in paper I in which the temperature and relative humidity of rendered façades with different colours were measured.

Long-wave radiation is different from short-wave radiation in that it is the exchange of energy between surfaces of different temperatures by radiation. As all surfaces (including the sky) has a temperature, all surfaces radiate energy towards all other surfaces within its line of sight. However, as many surfaces have rather similar temperatures, their radiation towards each other will be equal and cancel out. At least for our discussion here we need only look at surfaces that have clearly different temperatures than the façades we are interested in, and most important for our discussion is that nocturnal clear skies are cold and surfaces will be thus cooled by radiation to clear skies. At fully overcast conditions the sky temperature will equal the air temperature, but when it is a clear night sky, its temperature can be significantly lower than the air temperature (and the façade temperature). A simple model for the nocturnal clear-sky temperature that is com-

monly used in building physics is (here  $T$  is in celsius):

$$T_{\text{sky}} = 1.2T_{\text{air}} - 14 \quad (2.5)$$

A horizontal surface may see only the sky and will thus be significantly cooled by a cold sky. For a wall the situation is not as drastic as walls typically are not exposed to the sky to more than 25-50%; the remaining fraction is the ground, other buildings, trees etc.

As long-wave radiation takes place between surfaces with temperatures of a similar order of magnitude, we have to look at the difference in radiation between the two surfaces (with  $T$  in kelvin):

$$q_{\text{long-wave}} = f_2(T_{\text{sky}}^4 - T_{\text{wall}}^4) \quad (2.6)$$

Here, the factor  $f_2$  includes the Stefan-Boltzmann constant, how much sky that the wall sees, and the absorption factor. Contrary to the short-wave radiation, the absorption factor is not dependent on colour for the long-wave radiation.

The last factor in Equation 2.1 takes into account the heat production/consumption when moisture is absorbed/desorbed or condenses/evaporates on/from a surface. For example will heat be produced when water condenses. This process will counteract the condensation/evaporation process; if for example water condenses on a cold surface, heat will be released and raise the temperature of the surface.

Figure 2.4 and Equation 2.1 are for the steady-state situation with constant fluxes and constant temperatures. At unsteady-state conditions (when the fluxes and temperatures change) by simple book keeping the following balance equation of heat conservation can be written:

$$\frac{dT}{dt} = \frac{1}{\rho c} \frac{dq}{dx} \quad (2.7)$$

Here,  $\rho$  is the density and  $c$  is the specific heat capacity of the material. The heat capacity is a measure of how much the temperature will change when the heat content is changed. For mineral materials (dry mortar, bricks, glass wool)  $c$  is about  $0.8 \text{ J}/(\text{g K})$ ; for polymers it is slightly higher (typically  $1.2 \text{ J}/(\text{g K})$ ); while it is very high for water ( $4.2 \text{ J}/(\text{g K})$ ). The heat capacity will therefore be significantly different for wet and dry building materials. In connection with unsteady-state thermal calculations  $\lambda$  and  $c$  can be combined into a thermal diffusivity  $a = \lambda/c$  that determines the rates of thermal processes in materials.

If we combine the flux-law (Equation 2.2) with the balance equation (Equation 2.7) we get the equation sometimes known as Fourier's second law:

$$\frac{dT}{dt} = -\frac{\lambda}{\rho c} \frac{d^2T}{dx^2} \quad (2.8)$$

This is the unsteady-state equation for heat transfer by diffusion. The three constants are usually combined into one constant called the thermal diffusivity  $a$ :

$$a = \frac{\lambda}{\rho c} \quad (2.9)$$

The thermal diffusivity is a measure of how quickly a temperature change at the surface of a material will influence the inner parts of the material. Interestingly, the thermal diffusivities of render, bricks,

mineral wool and expanded polystyrene are all about  $7 \times 10^{-7} \text{ m}^2/\text{s}$  so temperature profiles after a change in external temperature will look similar in walls made with different combinations of these materials. However, the heat fluxes will be lower for the insulating materials and higher for the more massive materials that require higher heat transfers to change their temperature.

Wall constructions should have a certain thermal resistance. This is usually quantified in terms of a  $U$ -value - an overall heat transfer coefficient. It is most efficient if a wall has the same thermal resistance in all parts, but this is difficult to achieve in practice. For example will steel nails and other fasteners act as cold-bridges (also called heat-bridges) through the construction. Most floor constructions - made of for example concrete - also need to extend out into the wall construction from the inside and there will be increased thermal losses along the floors where there is less space for insulation.

With the above equations and climatic data it is possible to make basic calculations of the thermal balance of for example wall constructions. One example of such a calculation is given in paper II in which it is shown that the effect of night-cooling is similar for thin (4 mm) render and thick (20 mm) render on thermal insulation. One has to use constructions with higher thermal inertia to prevent condensation due to lowered surface render temperatures. As one does not make render on insulation much thicker than 20 mm, this implies that one has to use render traditional construction with render on brickwork etc. to prevent biological discolouring due to night condensation (paper III).

### 2.1.2 Moisture conditions

Although the moisture is the single most important factor for biological growth in façades, it is here treated after heat as the moisture state to a large extent is determined by the thermal events. Similarly to

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Equation 2.1, a steady-state equation for the mass (moisture) balance at a façade surface is:

$$g_{\text{diffusion}} + g_{\text{suction}} + g_{\text{convection}} + g_{\text{rain}} + g_{\text{condensation}} + g_{\text{run-off}} = 0 \quad (2.10)$$

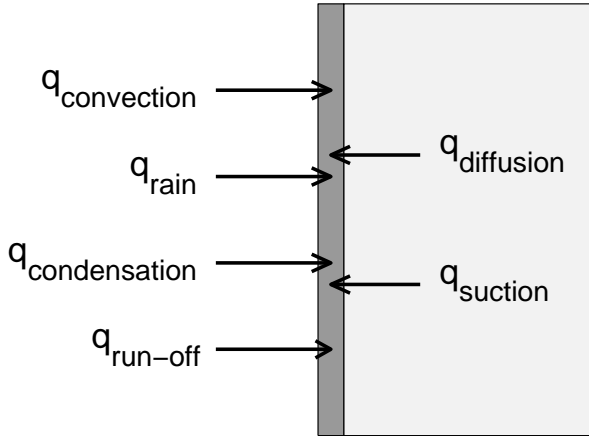


Figure 2.5: Moisture balance of a rendered construction at stationary conditions. The external render is on the left. All fluxes are defined as positive when they increase the moisture content of the render.

Diffusion and suction are the modes of transport of moisture inside the construction. In mineral materials, diffusion is mainly transport in the gas phase in empty pore spaces in the material driven by differences in vapor pressure (or relative humidity at isothermal conditions). Suction is liquid transport driven by pressure differences that have their origin in the different under-pressures (suction pressures) in capillary condensed water. These two processes act together and moisture transfer inside a porous material is in general a complex process and one often simplifies the situation by writing only one transport equation that includes both transport phenomena (and there is



a theoretical basis for doing this at isothermal conditions as relative humidity and suction pressure are related). This can for example be done (at isothermal conditions) by using the relative humidity  $\varphi$  as moisture potential:

$$g_{diffusion} = -\delta \frac{d\varphi}{dx} \quad (2.11)$$

This is a form of Fick's first law and  $\delta$  is a diffusion coefficient that is usually very dependent on the moisture state (relative humidity in this case). When this equation is used for, e.g., façade calculations where it is of interest to work also at high moisture states ( $\varphi \rightarrow 1$ ), it is necessary one different high  $\varphi$ -values, e.g. between 0.99 and 0.999, because these correspond to different moisture contents ( $w$ , kg water per m<sup>3</sup>). The diffusion coefficient will then also have different values for, e.g., relative humidities of 0.99 and 0.999. There are other ways to handle this, but this is a straight forward and robust method.

Moisture convection involves all cases where moisture is carried by air. This could be inside a construction or from/to the external air and the façade surface. The most important is the latter, which is the process by which water is removed from a wall construction, preventing it from continuously increasing in moisture content. Similarly to heat convection at a surface, moisture removal by convection is significantly increased by wind.

Rain is possibly the overall most important source of water for wall constructions. However, it is only the horizontal component (the driving rain) that can hit a vertical wall, so the impact of rain is coupled to the prevailing wind direction when it rains. Included in the rain-component is also liquid water droplets from fog that can wet a wall.

Condensation on walls takes place when the temperature of the wall surface is so much lower than the air temperature that the air

reaches the dew point, releasing the excess vapour as liquid water (fog, dew). This process is only significant when a façade is cooled by nocturnal clear-sky radiation that can lower the temperature of a façades significantly.

The last term in the moisture balance is the run-off of excess liquid water on a façade surface. However, such run-off is not common and probably only takes place during driving rain; we have never seen this on rendered façades after night-condensation, but run-off is commonly seen for example on car roofs that can get a lot of night condensation as they are very exposed to the sky, and that do not absorb any moisture.

Similarly to the heat case, one can write a balance (conservation) equation for the moisture:

$$\frac{d\varphi}{dt} = -\frac{1}{\xi} \frac{dg}{dx} \quad (2.12)$$

Here,  $\xi$  is the moisture capacity of a material, i.e., how much its moisture content changes when the relative humidity is changed. In contrast to heat capacities (and densities) that usually can be taken to be constants in building physics, the moisture capacity is very much dependent on the moisture state. This is usually visualized in the form of a sorption isotherm - a relation between relative humidity and moisture content - as is seen in Figure 2.6. The moisture capacity  $\xi$  is the slope of the curve seen in Figure 2.6. Unfortunately, few data-sets for rendering materials exist today that go up into the suction region.

Equations 2.11 and 2.12 can be combined into Fick's second law:

$$\frac{d\varphi}{dt} = -\frac{\delta}{\xi} \frac{d^2\varphi}{dx^2} \quad (2.13)$$

This is the equation for unsteady-state moisture flow.

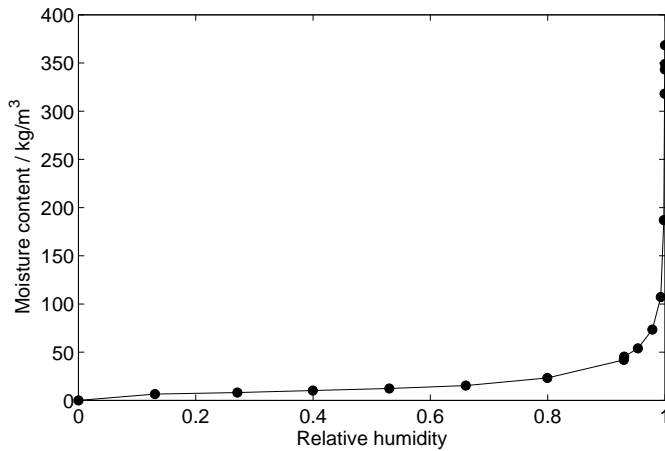


Figure 2.6: Sorption isotherm of a lime-cement mortar [74]. The results are measured in desorption with two methods: equilibration over saturated salt solutions for values below 93% relative humidity (RH) and with the pressure plate method above 93% RH. The highest moisture content is when the porous system is completely full (vacuum saturation).

There are many connections between the heat and the moisture conditions. For example is the thermal conductivity and the heat capacity functions of the moisture content, and the diffusion coefficient is temperature dependent. Many of the parameters are also quite difficult or time-consuming to measure, especially the moisture parameters (diffusion coefficients and sorption isotherms) at high moisture contents. This makes realistic calculations (simulations) - for example to compare different design strategies and different rendering materials - difficult.

### 2.1.3 Examples

I will here shortly describe two types of situations that I have seen during my work that can be explained by the building physics described above.

### Spotted buildings

We have seen several large buildings in the southernmost part of Sweden with regular patterns of white spots. In all cases was this on buildings whose façades had been renovated with external insulation and render. Two examples of such buildings with spots are seen in Figures 2.7 and 2.8. When these buildings were investigated, it was found that below each white spot was a metal fastener that had been used to fasten the insulation to the old façade. Figure 2.9a shows a fastener after the render had been removed at a white spot, and Figure 2.9b shows how it looks without a fastener (under the gray area). This type of pattern has also been reported from Germany [86, 87, 15]. Typically, these fasteners were made with one or many heavy steel nails or screws (commercial fasteners used today do not form such large cold-bridges as they are made of plastics).

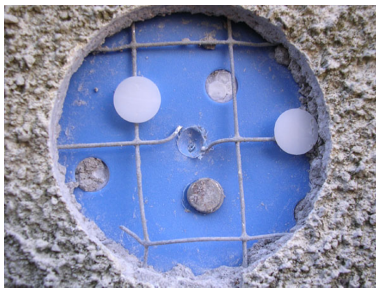


Figure 2.7: A façade that shows white spots.

It was found that the façades were generally discolored by biological growth, but that the white spots were free from this. The reason



Figure 2.8: Another façade with white spots.



(a) Fastener below the white spot on the façade



(b) Below the gray part of the façade without the fastener

Figure 2.9: Drilling holes in two places on a façade, so the interior parts are shown. (a) A fastener found below a white spot on the façade seen in Figure 2.7. Note the heavy steel nail and (b) below a gray part of the façade without the fastener.

was apparently that the heavy fasteners were good heat conductors and thus served as cold-bridges through which heat was conducted from the interior to the exterior. This increased the temperature of the façade outside the fasteners and made the render drier there. And this

prevented biological growth in these places. Generally, the external surface temperature on well insulated walls is not much influenced by the interior temperatures, but in this case the insulating capacity was impaired at the fasteners. This could also be clearly seen by thermography (IR-camera), as is seen in Figure 2.10 that the fasteners will increase the temperature 1 to 2 K during a cold night. This is a small temperature difference, but it is clearly enough to, e.g., prevent night-condensation.

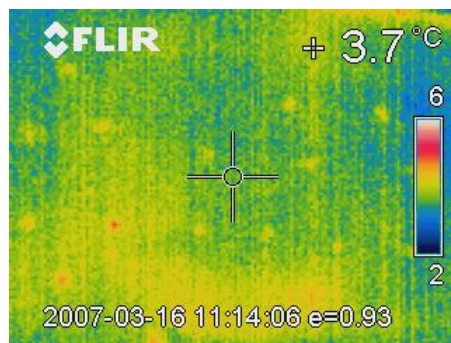


Figure 2.10: Thermography of the building seen in Figure 2.8. The measurement was made early in the morning in March 2007.

### Night condensation

Night condensation is a common phenomena on thin or insulated objects that are exposed to the night-sky: bicycle saddles, car roofs, and steel sheet roofs. It will never be as strong on walls as these are not as exposed to the sky, but it may be more common on well insulated façades than we think, as it is often not clearly visible. You have to touch the surface to see that it is covered with water (Figure 2.11). For night condensation to appear on a wall, several factors are needed:

- The wall should be well insulated.

- The thermally heavy layer outside the thermal insulation should be thin.
- The wall should not have been heated during the day.
- The air temperature should be lowered during the night so that the relative humidity of the air is increased.
- The sky has to be clear and cold.



Figure 2.11: Night condensation of a north-facing wall on the test house (Paper III) around 8 in the morning in October 2007. No condensation was found on the south-facing façades or on the walls with render on bricks.

Another aspect of night condensation is that if the render has a capacity to absorb water the condensed water this water will not be seen as it will be sucked into the surface. This will typically happen on traditional cement-lime mortars that are unpainted or painted with

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mineral paints. If organic materials are used, these are often not at all as absorbing and they may even be hydrophobic so that the water will form droplets on the surfaces.



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## The façade as a habitat

*Nothing in biology make sense except  
in the light of evolution*

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Theodosius Dobzhansky  
(☆1900 †1975)

As many organisms can live on stones and vertical cliffs, the building of houses has then given new opportunities to expand by using buildings as habitats. These are often small organisms with low grow rates, but well adapted to these habitat [5]. As for all other biological habitats the organisms growing on façades are dependent on different biotic and abiotic factors for maintenance and growth. The façade is characterized by extreme fluctuations of temperature, repeated desiccation and high UV-radiation (at least in some cardinal orientations), so any organism living here must be able to tolerate these fluctuations and still maintain a metabolic activity. Research has shown that the species found on buildings are especially adapted to survive repeated drying and rehydration cycles that are found on external building façades (note that we use the term hydration for uptake of water either from the vapour or the liquid state) [104, 24]. The strategy of desiccation tolerance of certain organisms will be further described in Section 3.1.

The façade can consist of different materials (render, wood, concrete, sheet metal etc.), which all can be contaminated with biological

organisms [25, 99, 109, 144]. In present project I concentrate on the render material as façade coating. A render does not only serve as a aesthetical feature, but also has a function of wind- and water protection for the building underneath and in Sweden render as façade coating has been used for hundreds of years. Originally mortars were made with slaked lime, but during the 20<sup>th</sup> century, the rendering systems changed towards more cement based systems. During the last decades we have also seen an increase in organic (polymeric) mortars without lime or cement. The structure of the surface has been shown to have an important influence on biological contamination [151, 141]. This surface structures influence on biological growth on renders used in ETICS was a part of the investigation in Paper IV.

## 3.1 Desiccation tolerance

There are in principle two ways in which organisms can survive drought. One is to store water and keep the biological processes running at a normal rate (homoiohydric organisms). The other way, which is used by most organisms growing on façades, is to tolerate desiccation (poikilohydric organisms) [113]. During desiccation the biological processes are stopped, but they can be rapidly restarted when water is available again and therefore react directly to changes in water availability in the surrounding environment [97]. Homoiohydric organisms, like vascular plants, have systems to control over water loss. The ability to tolerate desiccation is not common, but is widespread within all kingdoms [5]. Desiccation tolerance in organisms are found among the plants, especially Bryophytes (ferns), lichens and terrestrial algae, but they are not ecologically widespread. They seems only to live where the cover of desiccation-sensitive species are low [3, 113] and are often very small ( $\leq 5$  mm long) [5, 126]. It should be noted that desiccation tolerance is not the same as drought tolerance. Drought is low water availability in the environment of an organism, whereas desiccation is low water content in its cells [4]. The mechanism behind survival of desiccation is accumulation of disaccharides (mainly sucrose and trehalose), which enables the cells to stabilize the internal cell structure and maintain the cell integrity during the dehydration [2, 29]. A desiccated stage is often defined as a water content below 10% of the fresh weight as this limit would be fatal for most organisms [82].

Desiccation tolerant organisms seems also better adapted to tolerate other environmental stresses, for example stress of heat and UV-radiation [63, 95, 138]. One mechanism is to change shape to minimize specific surface area and reduce light absorbance [126] another mechanism is to synthesize light-absorbing pigments (for example Zeax-

anthin) [40, 60, 62, 61, 68]. Desiccation tolerant species can survive without water for over ten years [3], but research also indicate that the desiccation rate has a profound effect on the recovery after rehydration, which is greater than the effect of desiccation duration [?]. It is found that poikilohydric organisms are only metabolic active for a very short time period during the day, where water is available and irradiance is not too high (during mornings) [91]. The photosynthetic activity of organisms growing on building façades have been investigated in Paper VI.

## 3.2 Organisms on façades

The community of organisms we find on a façade is often an accumulation of microorganisms at an interface forming a biofilm. A biofilm is a complex microbial ecosystem that consists of different microorganisms together with a matrix of organic and inorganic nutrient and extra cellular polysaccharide substances secreted by the cells [77, 105]. Formation of a biofilm often begins with the attachment of autotrophic organisms to a surface. These first colonist adhere to the surface initially through weak, reversible van der Waals forces, but if they are not directly separated from the surface again they can anchor themselves more permanently using cell adhesion molecules. The first colonists facilitate the arrival of other organisms by building a matrix that holds the biofilm together. It is the biofilm matrix rather than the organisms that is in immediate contact with the surface of the building material. The biofilm can change greatly in volume due to changes weather condition such as freezing and thawing or during wet or dry intervals [105, 42].

Most researchers seems to be agree that microorganisms can degrade stone and other similar substrates and that several organisms contain biomineralization products there may contribute to chemical weathering processes [13, 107, 133], but other researchers have doubted to what extent the organisms actually damage the façades on buildings [51, 111, 137]. Some studies even shows that grow of lichens actually can protect the façade [6, 14, 134] or compensate for environmental stresses [35, 36].

There have been made a large amount of research on the taxonomy and diversity of organisms found on our natural heritage such as monuments, castles, churches and other stone substrates all over the world (see for example [21, 28, 33, 45, 46, 48, 93, 140, 154]), But also growth on modern building façades have been quantified and/or

taxonomically investigated [8, 10, 37, 52, 58, 66, 75, 119, 129].

A short description of the different organisms you can find growing on building façades is given in the following sections and in Paper I.

#### 3.2.1 Algae

Algae are a polyphyletic group of eukaryotic organisms. They belong to several orders in the kingdoms of Plants and Protists. Most of them are aquatic, well known in freshwater and marine environments where they are completely dependent on liquid water. However, some algae, sometimes called terrestrial algae, can live in terrestrial environments as, for instance, on tree trunks or on building façades [67]. As they are autotrophic organisms (see Table 4.1) they only need sunlight as energy source, and to be able to live in "extreme" habitats with frequent variations in abiotic factors, terrestrial algae have developed special morphological and physiological adaptations to cope with these stresses. For example have algae exposed to strong light developed pigmented materials to protect them against excessive sunlight. In addition, many terrestrial algae are also able to survive desiccation. The algae are then only metabolically active when appropriate combinations of abiotic factors are present. Some algae have developed symbiotic relationships with fungi (then together called lichens) and can therefore inhabit environments where unprotected algae would die. The algae we find on building façades are mostly green-algae, belonging to the division Chlorophyta [1, 66, 76] (see Figure 3.1). These algae form green to grey discolorations on façades, but a very characteristic red green-algae *Haematococcus pluvialis*, which is a unicellular green-alga that gets its red color from the pigment astaxanthin, can also be found on façades. The coating of these algae gives the façade a reddish appearance (see Figure 3.2).



Figure 3.1: Algae growth on a building façade (left), a close up picture (middle) and as seen in microscope (x400) (right).



Figure 3.2: Red coloured green-algae (*Haematococcus pluvialis*) on a building façade (left) (photo: L. Wadsö) and as seen in microscope (x400) (right).

### 3.2.2 Moulds

Moulds are an artificial group of microscopic, filamentous fungi. Fungi are not plants, and cannot do photosynthesis, but are heterotrophic organisms (like animals) (see Table 4.1 and have their own kingdom. The most important factor for growth of mould is water availability, but they are also dependent on nutrients from the substrate. Different moulds have different requirements of water; some can live on a substrate with a water activity as low as 0.7, and survive long periods of desiccation [7]. It is well known that many moulds can grow well on soiled substances if the right moisture conditions are available [101, 100]. The most common mould found on external mineral

building façades are the black-colored mould *Cladosporium* spp. (Figure 3.3), which is a common saprotroph organism, therefore also often found in air samples. Another common air-borne mould that can be found on building façades is *Alternaria* spp. Both these moulds are black because of the pigment melanin that protects them against strong UV-radiation [24].



Figure 3.3: The mould *Cladosporium herbarum* (as seen in microscope).

Mould growing in the indoor environment is a well known problem because of the negative health effects on the inhabitants [30, 31, 78, 79, 80, 110, 114] and studies on the effect of moisture on the growth of mould on building materials has been investigated for many years [7, 25, 49, 99, 109, 136, 143]. Since growth conditions varies a lot with the substrate and growth conditions the focus have primarily been on methods to determine limitation curves of mould growth (see for example [23, 71, 131]). One limitation of these curves is that they are based on stationary conditions of temperature and RH. However recently, growth models under fluctuation climate conditions have been presented [73, 142].

#### 3.2.3 Lichens

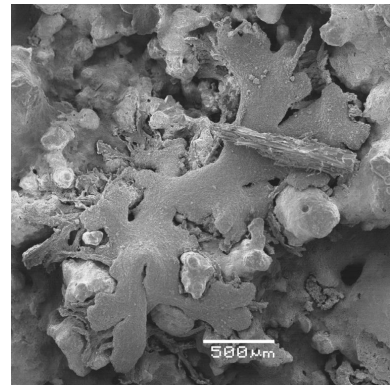
Lichens are composite organisms, a symbiotic association of fungi (the mycobiont) and algae or cyanobacteria (the photobiont) that are lich-



enized in a unique morphology. Lichens are by now described by the mycobiont and are therefore a part of the fungal kingdom [50], but were in long time thought of as plants, just as fungi were. The lichen can grow where the fungi and algae alone can not survive on their own, and they are found on almost every terrestrial substrate in the world and can tolerate repeated desiccation (see Section 3.1, [69, 83, 96, 108, 135]. The unique morphology of lichens consists of several layers. The mycobiont forms a tissue within which the photobiont occupy a relative small volume in particular positions within the thallus. Figure 3.5 shows a cross section of a lichen thallus. At the top there is an upper cortex, a layer of fungal hyphae in a hydrophilic matrix (this structure can sometimes also be found in the bottom of the lichen, as seen on Figure 3.5). Within this, the central part (medulla) provides a gas-filled zone of filamentous hyphae covered in a hydrophobic protein. The medullary hyphae grow into the gelatinous sheath that surrounds the photobiont and the associated photobiont and hyphal cells become sealed together within the hydrophobic material.



(a)



(b)

Figure 3.4: Lichen found on one of the render specimen used in Paper IV. (a) The lichen on the render. Fastener with a width of 4 cm. (b) The lichen taken with SEM.

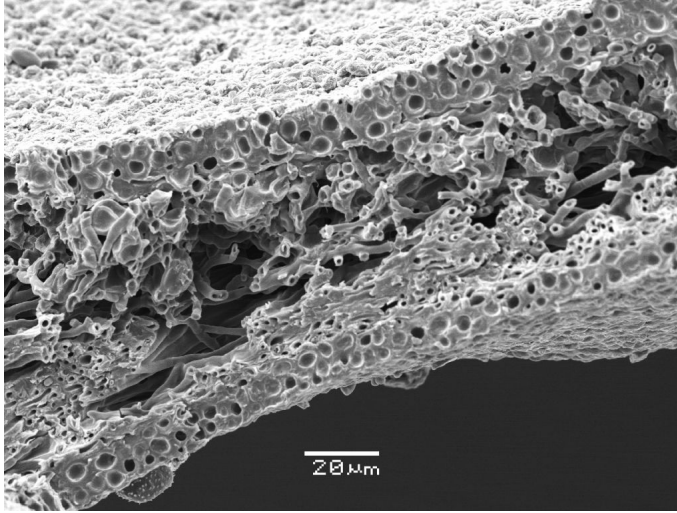


Figure 3.5: A cross section of a lichen thallus (Photo: L. Wadsö).

In the unique symbiosis of lichens, the fungi surrounds and protects the algae against drought and excess light intensity, and the fungi gets nutrients from the photosynthetically active algae [97]. The lichen symbiosis is considered obligatory for the mycobiont as regards growth and reproduction, but the significance for the photobiont is less clear. For some algae, the symbiosis may be obligatory for survival in a certain habitat, but in other cases, the symbiosis might not be an advantage for the algae. Therefore, it is not certain whether the lichen symbiosis should be referred as a mutualistic or a parasitic relationship.

Lichens are poikilohydric organisms, which means they react directly to changes in water availability in the surrounding environment [97]. Lichens do not, like leaves of higher plants, have an internal water supply through special transport tissue, but needs to remain exposed to their environment in order to allow natural moistening and drying. Lichens are desiccation tolerant and can therefore survive long periods of desiccation and return to an active, photosynthetic state within few hours with certain amount of water. Note though, that lichens with green-algae as photobionts can extract moisture from

non-saturated air and does not need the availability of free water [89]. It is found that the respiration rate of lichens is highly influenced by thallus hydration, especially at the lower relative humidity, and does not occur in desiccated lichens [90]. The growth of lichens is often very slow, only a few mm per year [97]. Because whole lichens cannot be readily grown in culture, it is difficult to know the precise amount of different nutrients necessary for growth. Lichens living on mineral surfaces are in contact with inorganic nutrients but are also affected by dust from the air. Airborne dust can be incorporated in the lichen thallus and act as a nutrition source. Because many nutrients are affected by the pH of the substrate, the availability of nutrients is different from limestone to acidic substrates. As a consequence, we find very different lichen communities on different substrates. Mineral building façades are in general alkaline, and the lichens we find on building façades are therefore adapted to these conditions and are also found in nature on limestones etc.

### 3.2.4 Mosses

Mosses belong to the kingdom of plants. They constitute a diverse group of rather simple, small plants that have many characteristics in common with green algae. In the classification system today, mosses are placed in a division of spore-bearing plants (Bryophyta). Mosses are photoautotrophic organisms (see Table 4.1); using light as energy source by photosynthesis. Mosses are found world wide, but often in rather moist and shadowed habitats. The moss lack the protective tissue (cuticula) to protect against sunlight which many other plants possess, but desiccation tolerance is common within mosses [102, 112, 152] and can survive extremely rapid desiccation and are generally a rapid recovery time (within few hours). Mosses do not have specialized conductive tissue like plants, but water absorption occurs directly and throughout the thin leaves and are like lichens

poikilohydric organisms. That means the moss can absorb water and mineral nutrition from the whole surface of the organism. In addition mosses do not have any roots, but uses small threads (rhizoids) to attach to a surface.



Figure 3.6: A moss growing in a crack between the render and a plastic shell from a specimen used in the investigation of Paper IV.

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# Metabolic strategies

*Nothing in this world is to be feared,  
only understood*

---

Marie Curie (☆1837 †1894)

Every organism on the earth needs a primary carbon source and an energy source for their biosynthesis, but different organisms use different strategies to obtain carbon and energy. In this chapter I will briefly describe different metabolic strategies and go into detail with some of the most important processes for my studies. An overview of the different metabolic strategies with respect to carbon and energy sources is shown in Table 4.1. Some organisms depends solely on one metabolic strategy and are then obligate in that strategy, others can switch between different strategy forms (often dependent on the abiotic conditions) and are then referred to as facultative. The following sections are based on [94, 121].

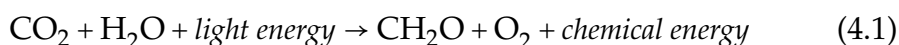
Table 4.1: Scheme of primary nutrition groups, based on information in [94].

Energy source	Reducing equivalent source <sup>a</sup>	Carbon source	Name	Example
Light ( <i>Photo</i> -)	Organic (- <i>organo</i> -)	Organic (- <i>heterotroph</i> )	Photoorganoheterotroph	Green- and purple non sulfur bacteria
		CO <sub>2</sub> (- <i>autotroph</i> )	Photoorganoautotroph	Some bacteria and archaea
	Inorganic (- <i>litho</i> -)	Organic (- <i>heterotroph</i> )	Photolithoheterotroph	Purple and green sulfur bacteria
Chemical compounds ( <i>Chemo</i> -)	Organic (- <i>organo</i> -)	CO <sub>2</sub> (- <i>autotroph</i> )	Photolithoautotroph	<b>Plants, green algae</b>
		Organic (- <i>heterotroph</i> )	Chemoorganoheterotroph	<b>Animals, most fungi</b>
	Inorganic (- <i>litho</i> -)	CO <sub>2</sub> (- <i>autotroph</i> )	Chemoorganoautotroph	Some bacteria and archaea
		Organic (- <i>heterotroph</i> )	Chemolithoheterotroph	Some sulfur-oxidizing bacteria
		CO <sub>2</sub> (- <i>autotroph</i> )	Chemolithoautotroph	Methanogens, nitrifying bacteria

<sup>a</sup> source used as electron donor

## 4.1 Photosynthesis

Photosynthesis is the biochemical process in which phototrophic organisms convert light energy to chemical energy. Photosynthesis is actually the route by which nearly all energy enters our biosphere, the only exception being some chemosynthetic bacteria [117]. The photosynthesis actually occurs in two stages, where only one stage needs light. In the light dependent reaction the conversion of light energy to chemical energy takes place, in the light independent reaction two processes occur; carbon fixation and the so called Calvin cycle where the fixated  $\text{CO}_2$  is converted to organic carbon compounds [121]. All processes will be described in further details below. The overall reaction in photosynthesis is:



The  $\text{CH}_2\text{O}$  symbolizes a carbon unit of produced carbohydrate that contains the chemical energy. Light is the promoter of this process, and different photosynthetic organisms contain different specialized photosynthetic pigments (chlorophylls, carotenoids, phycobilins) in the chloroplasts thereby being capable to absorb and use photons of light at different wavelengths of the incoming light in the photosynthesis. In this thesis I focus on the primary photosynthetic pigment for eucaryotic organisms (and cyanobacteria); chlorophyll *a* (Chl *a*). Chl *a* is found in the chloroplasts (in eukaryotic organisms) in the cells and are arranged in special light absorbing complexes called photosystems in the thylakoid membranes (see Figure 4.1). Chl *a* absorb light principally in the violet, blue and red wavelengths reflecting green light and this is why photosynthetic organisms often are green. When

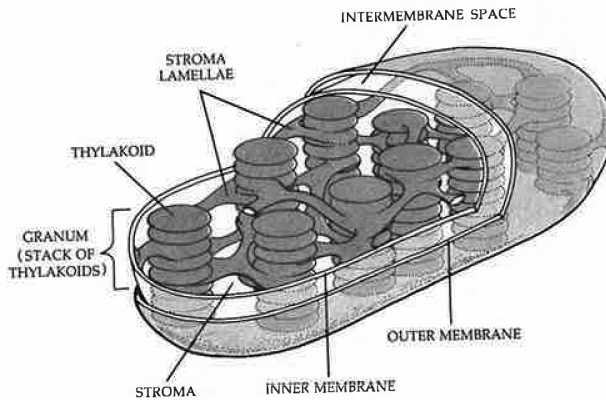


Figure 4.1: A sketch of the chloroplast of eukaryotic cells. The chlorophyll pigments are found in the thylakoids, where photosynthesis takes place on the thylakoid membrane [117].

photons of light are absorbed by chlorophylls in the photosystems electrons in the chlorophylls are brought to an excited stage. As photons of different wavelengths have different energy the wavelength of a given photon decides which excited stage the electron will go to. Figure 4.2 shows a simplified model of the chlorophylls molecules energy levels. Photons of blue light have a higher energy and therefore the electrons in the chlorophyll excited with a blue photon will go to a high energy level, but decay (quench) extremely rapidly to a lower excited energy level by release of heat. Photons of red light excite chlorophyll electrons to this lower excited energy level, and red photons are therefore more efficient at an energy perspective in photosynthesis. From the lower excited energy level the rest of the energy is either lost by heat dissipation, by fluorescence of the electrons (see also Section 5.1) or by energy transfer by inductive resonance in the photosynthesis.



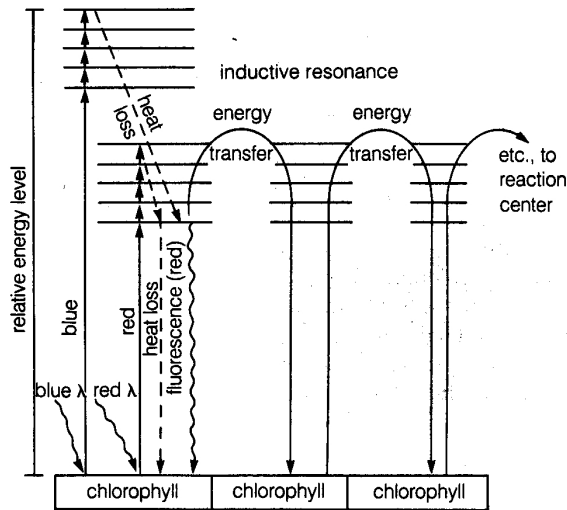


Figure 4.2: Simplified model of how light energy behave when striking a Chl molecule [121].

#### 4.1.1 Light dependent reaction

In the light dependent reaction photons are absorbed in chlorophyll molecules in photosystems as described above. The photosystems are complexes of different pigment molecules and two separate photo-system complexes exists in the photosynthesis; photosystem I (PSI) and photosystem II (PSII). PSII absorbs only wavelengths shorter than 690 nm whereas PSI also absorbs long red wavelengths. In Figure 4.3 the light dependent reaction in photosynthesis is sketched. In PSI photons of light drives the excited electrons through a series of molecules and together with  $\text{h}^+$  ions form chemical energy in the form of  $\text{NADPH}^1$  molecules. The electrons used for forming the NADPH molecules in PSI are replaced of electrons from PSII which on their way to PSI goes through a electron transport chain of different molecules, transferring

<sup>1</sup>NADPH stands for Nicotinamide Adenine Dinucleotide Phosphate Hydrogen, but is always named by its abbreviation.

$\text{h}^+$  ions from the stroma to the lumen of the thylakoids. The electrons in PSII are replaced by the oxidation of  $\text{H}_2\text{O}$  to  $\text{O}_2$  in a so called oxygen evolving complex (OEC) connected to PSII molecule complex in the the thylakoid lumen leaving  $\text{O}_2$  as a waste product. This oxidation of  $\text{H}_2\text{O}$  also contribute to additional  $\text{h}^+$  ions in the thylakoid lumen. The high  $\text{h}^+$  concentration in the lumen makes a proton gradient which drives another molecule complex (ATP synthase complex) to make chemical energy in form of  $\text{ATP}^2$ .

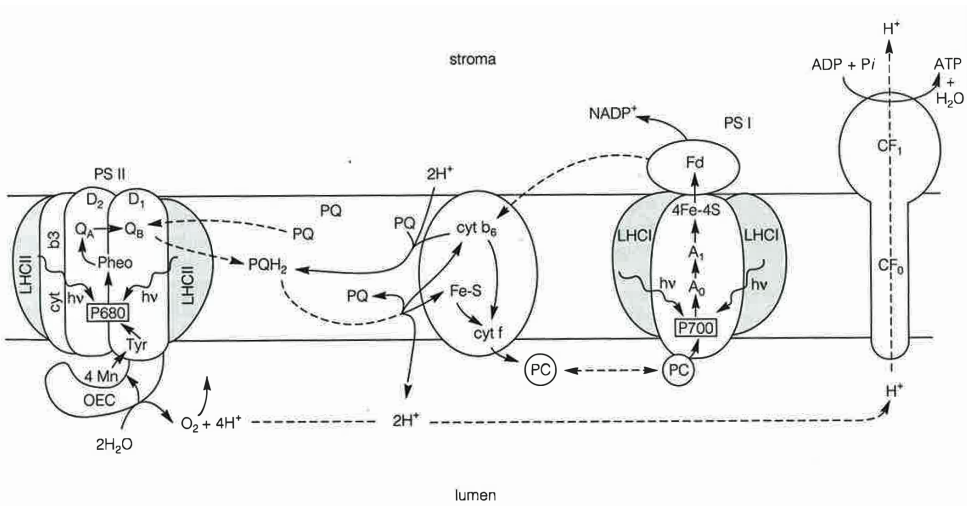


Figure 4.3: A schematic description of the light dependent reaction in photosynthesis. [121].

### 4.1.2 Light independent reaction

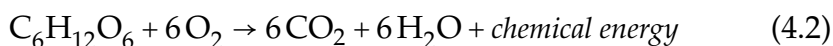
In the light-independent reaction the chemical energy harvested by the light dependent reaction is used to reduce  $\text{CO}_2$  to larger carbohydrates (the organic compounds). There are three different ways to do this among autotrophic organisms, but it all ends in the Calvin cycle,

<sup>2</sup>ATP stands for Adenosine Tri-Phosphate, but is always mentioned by its abbreviation

where the carbohydrate glucose is produced. Glucose can then be further converted to sucrose (for transport), cellulose (to build cell walls) or starch (for storage).

## 4.2 Respiration

Respiration is a energy releasing process by which the chemical energy stored in carbohydrates is extracted to energy-carrier molecules (ATP) for immediate energy requirements of the cell. Respiration takes place in the cytosol and in the mitochondria in the cells of heterotrophic organisms and is normally considered to be an aerobic process with  $O_2$  as a oxidizing agent (electron acceptor). Chemical energy can also be extracted from carbohydrates without  $O_2$  as electron acceptor by an anaerobic process called fermentation. Generally, energy rich carbohydrates are stored in the cells as starch or sucrose, but the normal respiration process is normally considered to begin with glucose (preliminary step to the actual respiration is therefore hydrolysis of the storage saccharide). The overall process is as follows:



Respiration actually involves three stages:

- **Glycolysis**, in the cytosol, where the six-carbon glucose molecule is broken down to two three-carbon molecules gaining ATP and releasing electrons to energy carrying molecules.
- **The Krebs cycle**, in the mitochondria matrix, where the three-carbon molecules are broken down to  $CO_2$  molecules and releasing electrons to energy carrying molecules.

#### 4. METABOLIC STRATEGIES

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- **Oxidative phosphorylation**, via the electron transport chain in the mitochondria membrane, where the electrons bound in the energy carrying molecules from the above stages are used to form ATP and in the end reducing  $\text{H}_2\text{O}$  from  $\text{O}_2$ .

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# Methods of measurement

*Theory guides, experiment decides*

---

An old saying in science

## 5.1 Chlorophyll fluorescence measurements

In the beginning of the 1930's Kautsky and his coworkers discovered the red fluorescence light from plants when transferred from dark to light and that this light reflects different photosynthetic events. Since then there have been a significantly amount of chlorophyll (Chl) research (see reviews [16, 18, 64, 85]) as these types of chlorophyll fluorescence measurements can be made in all physiologically relevant stages in a non-destructive way. The principle of Chl fluorescence measurements is that absorbed light photons in the photosynthetic pigment molecules results in electrons in an excited stage (as explained in Section 4.1) which is quenched as either fluorescence, chemical energy or heat. The Chl fluorescence measuring technique is based on the first law of thermodynamics; the sum of energy from photosynthetic energy conservation (photochemistry, fluorescence and heat dissipation) must be equal to one. Both fluorescence and heat dissipation is measured by the measuring technique and thereby information of chemical energy can be obtained.

In the Chl fluorescence measuring technique it is important to notice the difference between fluorescence intensity and fluorescence yield. Fluorescence intensity may vary in several orders of magnitude depending on the light conditions, whereas fluorescence yield in normal applications only vary by a factor of 5-6 [127] and it is the fluorescence yield that provides information about the photosynthetic status of an organism [127]. To be able to measure the fluorescence yield without changing the status of the sample it is important that the measuring system can distinguish between the different light sources (see section 5.1.1) and the resulting fluorescence signals. Conventional Chl fluorometers do not distinguish between measuring light and actinic light and are therefore not suitable for in-situ measurements. To measure fluorescence excitation yield the signal has to be modulated so it can be distinguished from the ambient light. Such a measuring system (Pulse-Amplitude-Modulated Chl fluorescence measuring system (PAM)) was developed by Schreiber and coworkers some decades ago [128] and will be described in further details in the following sections (for more detailed explanations and analysis of the theory of Chl fluorescence and its connection to the photosynthetic apparatus see [17, 47, 70, 84, 115]).

### 5.1.1 Principle of PAM measurements

The principle of the selective detection of light-induced changes of Chl fluorescence yield can be demonstrated by the experiment shown in Figure 5.1. Here the response to actinic light is shown for a bean leaf (A) and a Chl solution (B). After measuring with measuring light the minimal fluorescence signal ( $F_0$ ) can be monitored. When the samples are exposed to the stronger actinic light and the even more stronger saturation light pulses the fluorescence yield of the Chl solution is not affected, but the fluorescence yield of the leave show a typically induction pattern. This experiment shows that even if the

strong non-modulated saturation light pulses actually induces much higher fluorescence intensity than the modulated measuring light, the non-modulated fluorescence signal caused by the saturation pulse is rejected by the system (the same applies any other non-modulated light source as for example ambient daylight).

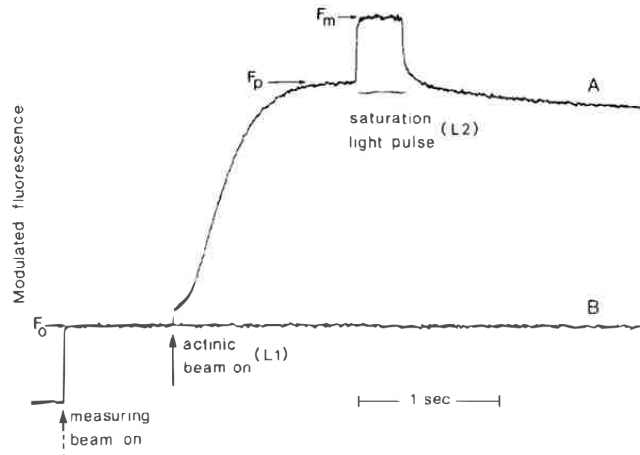


Figure 5.1: Selective determination of light induced changes of Chl fluorescence yield. Comparison of leaf (A) and Chl extract (B) [127].

With the development of Pulse Amplitude Modulation (PAM) Chl fluorescence measuring system it was possible to make continuous measurements of chlorophyll fluorescence induction and be able to evaluate different types of quenching parameters that gives reliable interpretations of the redox- and energy state of chlorophyll in intact leaves [128]. It is also a non-invasive method and therefore allow us to measure photosynthetic activity in situ. Some studies have also correlated the Chl fluorescence measurements and biomass on biofilms [37, 132] The theoretical basis for the PAM technique is developed for higher plants and green algae and since it assumes that 90% of the fluorescence originates from Chl *a* of PSII (at room temperature), which it true for plants and green algae it might not be true for organisms containing other photosynthetic pigments [18, 127].

The PAM system consists of four radiation sources:

- measuring light ( $0.05 \mu\text{mol}/(\text{m}^2 \text{ s})$  PAR)
- actinic light ( $80 \mu\text{mol}/(\text{m}^2 \text{ s})$  PAR)
- saturation light pulses ( $8000 \mu\text{mol}/(\text{m}^2 \text{ s})$  PAR)
- near infrared radiation (780 nm LED)

The measuring light intensity is sufficiently weak for assessment of the fluorescence yield of a dark-adapted sample without disturbing the photosynthetic status of the organism.

Before each PAM measurement the organisms should be dark adapted for several minutes (or preilluminated with far-red light) to be sure the  $Q_a$ 's (see section 4.1) are fully oxidized (the reaction centers of PSII remains open) and absence of a thylakoid proton gradient [84, 127]. This means that in the dark adapted state the photochemical quenching is at its maximum and the non-photochemical quenching is minimal (the heat dissipation rate is assumed to be constant at this so called rapid fluorescence induction kinetics). Hereby you can measure the minimal fluorescence yield ( $F_0$ ) with the application of low frequencies of pulse modulated measuring light. The maximal fluorescence yield ( $F_m$ ) is then measured by the application of saturation irradiance pulses (all the reaction centers closes (are reduced)). The difference between the minimal and the maximum fluorescence yields in the dark adapted state is called variable fluorescence yield ( $F_v$ ) see Figure 5.2. By these measurements the optimal fluorescence yield can be obtained by the equation:

$$(\phi_{II})_{max} = \frac{F_m - F_0}{F_m} = \frac{F_v}{F_m} \quad (5.1)$$



The values of  $F_0$  and  $F_m$  obtained in the dark adapted state is essential for all other measurements of photochemical and non-photochemical quenching by the saturation pulse method by the PAM-instrument.

### 5.1.2 Saturation pulse method

Saturation pulses can be applied repetitively without affecting the state of the sample [127]. The principle of the saturation pulse method is that at any given illumination a saturation pulse can be given so that the photochemical quenching is completely suppressed while the other yields assume maximal values. A saturation pulse gives a value of the maximum fluorescence yield ( $F_{m'}$ ) which generally is lower than  $F_m$  (see Figure 5.2) and assuming that the non-photochemical quenching is constant during short saturation pulses the lowering between  $F_{m'}$  and  $F_m$  will give a selective measurement of non-photochemical quenching. During illumination the PSII quantum yield will be lowered due to closure of reaction centers (decreased photochemical quenching) and by stimulated heat dissipation (increased non-photochemical quenching) and thereby we can calculate the effective fluorescence yield of PSII by the equation [47, 150]:

$$\phi_{II} = \frac{F_{m'} - F}{F_{m'}} = \frac{\Delta F}{F_{m'}} = Y(II) \quad (5.2)$$

In principle a quantum yield varies between 0 and 1. This means that (as mentioned in Section 5.1) that all quantum yield from photosynthetic energy conservation (photochemistry, fluorescence and heat dissipation) must be equal to one:

$$Y(II) + Y(NPQ) + Y(NO) = 1 \quad (5.3)$$

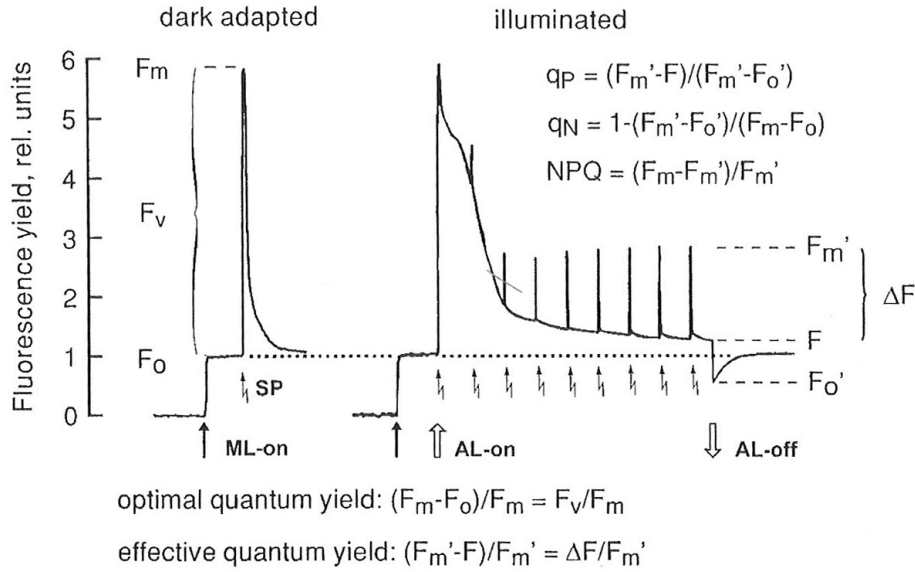


Figure 5.2: A theoretical scheme of the fluorescence quenching analysis by the saturation pulse method [127].

$Y(NPQ)$  is the quantum yield of regulated energy dissipation in PSII and  $Y(NO)$  is the quantum yield of nonregulated energy dissipation in PSII [81] (the theoretical background and calculations of these parameters can be seen in [81]). A high  $Y(NPQ)$  value indicates both that the photon flux density is excessive and shows that the sample has retained the physiological means to protect itself by regulation (i.g. dissipation of excessive energy into heat) [149]. A high  $Y(NO)$  value indicates that both photochemical energy conversion and protective regulatory mechanisms are inefficient. Therefore it indicates that the investigated organism have serious problems to cope with the incident radiation (which is either damaged or will be photodamaged upon further irradiation).

### 5.1.3 Imaging PAM

Chl fluorescence imaging was pioneered by Omasa *et al.* (1987) and Daley *et al.* (1989), and in 2001 the Imaging-PAM (Walz, Effeltrich, Germany) was presented that incorporated highly sensitive CCD-camera technology and data exchange between camera and the Imaging-PAM Chl fluorometer [106, 127]. Image capture is then synchronized with the pulse modulated measuring light and with extremely strong light emitting diodes (LED)'s as all light sources the system is portable and battery powered and are therefore very useful for *in-situ* measurements. The LED-array measures images of fluorescence ( $F_0$ ,  $F$ ,  $F_m$ ) and of absorbed PAR the latter being important for quantifying photosynthetic activity as the actual photosynthetic activity depends on Chl content and the absorbed PAR (saturation pulse method as such gives only information on PSII quantum yield).

With the development of Imaging-PAM fluorometers has become possible to obtain images of photosynthetic activity and heterogeneities together with information of all relevant chlorophyll fluorescence parameters using the Saturation pulse method [127]. The Imaging-PAM has been used successfully on *in-situ* investigations of algae and lichen growth [12, 37, 41], to differentiate between plant leave strategies due to different stress factors [65, 72, 116] or to reveal heterogeneous patterns of photosynthetic performance within leaves [9, 92, 116]. The use of Imaging-PAM on the investigation of activity of a green algae (probably *Stichococcus bacillaris*) and the moss *Hedwigia ciliata* when growing on rendered substrate is described in Paper VI.

## 5.2 Isothermal Calorimetry

Calorimetry is the direct determination of heat, thermal power and heat capacity (*calor* means heat in Latin). There are many different types of calorimeters. The most common is probably the differential

scanning calorimeter (DCS) in which thermal events like melting are recorded while the temperature is changes. A quite different -and not as common - type of calorimeter is the isothermal (heat conduction) calorimeters with which the aim is the measure the heat output from samples at constant temperature conditions [19, 146, 145, 148]. As nearly all processes (physical, chemical and biological) produce heat, isothermal calorimetry is an interesting method for studying kinetics of processes, especially slow processes (hours, days, months) [57].

Isothermal heat conduction calorimeters consists of an ampoule with the sample placed in contact with a heat flow sensor, which is in contact with a heat sink. When heat is produced in the sample, it will be (slightly) heated, the heat will flow through the sensor to the heat sink and be recorded. All such instruments are twin-systems in which one measures the difference between the signals from the sample and a reference that does not produce any heat. This arrangement reduces the noise.

The measured thermal power (or heat production rate) is denoted  $P$  and is typically measured in units of microwatt. The strength of isothermal calorimetry comes from that the measured thermal power is proportional to the rate of the process being studied (at least for simple processes  $A \rightarrow B$ ):

$$P = \Delta H \frac{dn}{dt} \quad (5.4)$$

Here,  $\Delta H$  (J/mol) is the reaction enthalpy and  $\frac{dn}{dt}$  (mol/s) is the rate of the process.

The history of isothermal calorimetric measurements on biological organisms started with Crawford and Lavoisier and Laplace a the end of the 18<sup>th</sup> century. Lavoisier and Laplace used an ice-calorimeter for their study on different animals - most famous is the illustration of a guinea-pig inside their ice-calorimeter). However, it was not until

the first part of the 20<sup>th</sup> century that the modern type of heat conduction calorimeter made it possible to perform good measurements on biological systems. In the 1960's Calvet and Prat (see for example [20]) investigated many different biological systems and can be said to be the fathers of modern biological calorimetry. Since then an large amount of calorimetric research has been carried out on different biological systems [27, 54, 59, 118]. Calorimetry has also been shown to be a useful tool for the study of, e.g., metabolic kinetics as a function of temperature [26, 139, 147, 153].

Calorimetry is an especially good technique to study (aerobic) respiration as all combustion processes have an enthalpy of 455 kJ/mol( $\text{O}_2$ ) [56]. A measurement of thermal power thus gives the respiration rate, but an advantage compared to respirometers is that isothermal calorimetry directly measures the rate (the heat production rate) while respirometers typically measure the oxygen concentration. With isothermal calorimetry it is possible to follow biological processes minute by minute. This makes it possible to see when certain events - for example depletion of oxygen - takes place. It should be noted that despite that the photosynthesis is necessary for plants existence, studies of photosynthesis and its efficiency is not the best way to measure growth parameters [55], because it is not the photosynthesis, but the rate and efficiency of building biomass from the products of photosynthesis, that determines the actual growth rate of an organism. Calorimetric heat rate measurements under dark conditions can thus give information on the temperature dependence of the growth rate of an organism.

### 5.2.1 A novel calorimeter

Calorimetric measurements at different temperatures are interesting for many different types of systems as thermal powers measured at many temperatures makes it possible to assess the influence of tem-

perature on respiration; for example by calculating activation energies. However, a practical limitation is that isothermal calorimeters are rather slow in changing their temperature (as they are designed to keep the temperature constant). A study of a process that takes a week will take a month or more, if one wants to get data at 3-4 temperatures (if one does not have many calorimeters). Therefore Wadsö has developed a new isothermal calorimeter that simultaneously measures at four different temperatures. It is based on placing the four calorimeters in a temperature gradient so that each calorimeter has its unique temperature. For a detailed description of the calorimeter, see Paper V. In my project I used this calorimeter to study the influence of temperature on the respiration of the moss *Tortula ruralis*.

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## Conclusions

*One is always a long way from  
solving a problem until one actually  
has the answer*

---

Stephen Hawking (☆1942–)

**Paper I** Moulds, algae, lichens, mosses and bacteria can be found growing on façades. These very different organisms thus seem to have similar environmental demands as they are found growing side by side on the same façades. Most important for survival on a façade is the adaption to periodic desiccation, but other environmental parameters like excessive irradiance and heat also play a role.

**Paper II** The problem of microbial growth on façades is a complex phenomenon influenced by a number of interacting factors related to both abiotic and biotic conditions of the façade system. For example temperature, thermal conductivity and heat capacity in the outer wall, nutrition availability, uses of fungicides, surface roughness, climate conditions, and UV-radiation are all factors that may have to be considered to avoid growth on façade constructions.

**Paper III** The ETICS façades are more prone to biological discolorations than traditional constructions of render on masonry. This is mainly

because of the reduced heat capacity of ETICS constructions. The surface colour is the most important factor for the surface humidity levels on a south-facing façade (in the northern hemisphere), while on a north-facing façade the thermal inertia is most important.

**Paper IV** There seems to be only a minor difference between ETICS constructions with thin and thick render; it is the heat capacity of the masonry that provides enough thermal inertia to avoid the lowering of surface temperature during nights. Rough surfaces increase the biological growth especially the growth algae, but also lichens were growing after four years of exposure.

**Paper V** Isothermal calorimetry directly measures the respiration rate on biological samples. Using a novel instrument the respiration of a moss was quantified at four different temperatures at the same time.

**Paper VI** With the Imaging-PAM instrumentation it is possible to get a wide range of information of photosynthetic status and activity of different organisms when growing on rendered façades. At the same time you get a visualization of heterogeneities in the organism. Photosynthetic activity of a moss and a algae growing on the north and south side of render specimens showed differences in their activity levels, where the algae was only active during mornings, whereas the moss showed more some activity not only in the mornings and mid mornings but also during the evenings.



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## Future investigations

*Results! Why, man, I have gotten a lot of results. I know several thousand things that won't work*

---

Thomas Edison (☆1847 †1931)

This work has answered some questions concerning biological growth on ETICS. However, there are still unanswered questions. I have following suggestions for future projects:

- Measure moisture properties of different mortars and paints (especially at high humidities) and model the building physics of rendered systems in more details.
- Study the photosynthetic activity of mosses, algae and lichens growing on façades in more details with the Imaging-PAM instrument.
- Use the novel calorimeter to map biological activity as a function of temperature and RH for organisms found on building façades.
- Study the effect of different "exposures" for example to different levels of dry conditions and moisture of different organisms with the calorimeter.



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## **My contribution to the papers**

- I I wrote the paper and gave a presentation on the conference.
- II I wrote the paper and gave a presentation of present work on the conference.
- III I planned the study in collaboration with my supervisors. I did the evaluation of the results together with Lars Wadsö. We also wrote the paper together.
- IV I planned the study in collaboration with my supervisors and Rolf Blank on Weber, Sweden. I did all the experimental work and evaluated the results. I also wrote the paper together with Lars Wadsö.
- V I did the experimental work of the moss study. I wrote the associated parts of the paper.
- VI I planned the study and performed the experimental work. I evaluated the results with some help from Abdughafar Abu-Elsaoud. I wrote the paper.



## **Additional publications by the author during time of Ph.D studies**

### **Licentiate thesis**

#### **Biological growth on mineral façades**

Johansson, S. (2006)

*Licentiate thesis* Report TVBM-3135, Division of Building Materials, Lund University, Lund, Sweden.

### **Peer reviewed conference papers**

#### **Why do we often get biological growth on thin rendering on thermal insulation constructions?**

Johansson, S., Wadsö, L., Sandin, K. (2008)

*Proceedings of the 8th Symposium on Building Physics in the Nordic Countries* (C. Rode, editor), Report R-189, Dept. of Civil Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark. pp: 919-926.

### **Others**

#### **Chapter 12: Building biology**

Wadsö, L., Johansson, S. (2010)

*Kompendium i Byggheterovetenskap*. Division of Building materials, Lund University, Lund, Sweden, pp: 1-18.

#### **Alger och mögel trivs på ytor av tunnputs**

Johansson, S. (2008)

*Husbyggaren*, 2: 88-89. (in Swedish)

#### **Biologisk påväxt på putsade fasader**

Johansson, S., Sandin, K., Wadsö, L. (2007)

*Bygg och Teknik* 8: 42-43.(in Swedish)

### **Biological growth on mineral building façades**

Johansson, S., Wadsö, L., Sandin, K. (2007)

*Conference Abstract to II International Conference on Environmental, Industrial and Applied Microbiology*, Seville, Spain, p: 126, November 2007.

### **Biological organisms on rendered building façades**

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*Conference Abstract to Algae in Terrestrial Ecosystems*, Kiev, Ukraine, August 2005.

### **Biologisk påväxt på mineraliska fasader**

Johansson, S., Sandin, K.

*Bygg och Teknik*, 8: 12-14. (in Swedish)