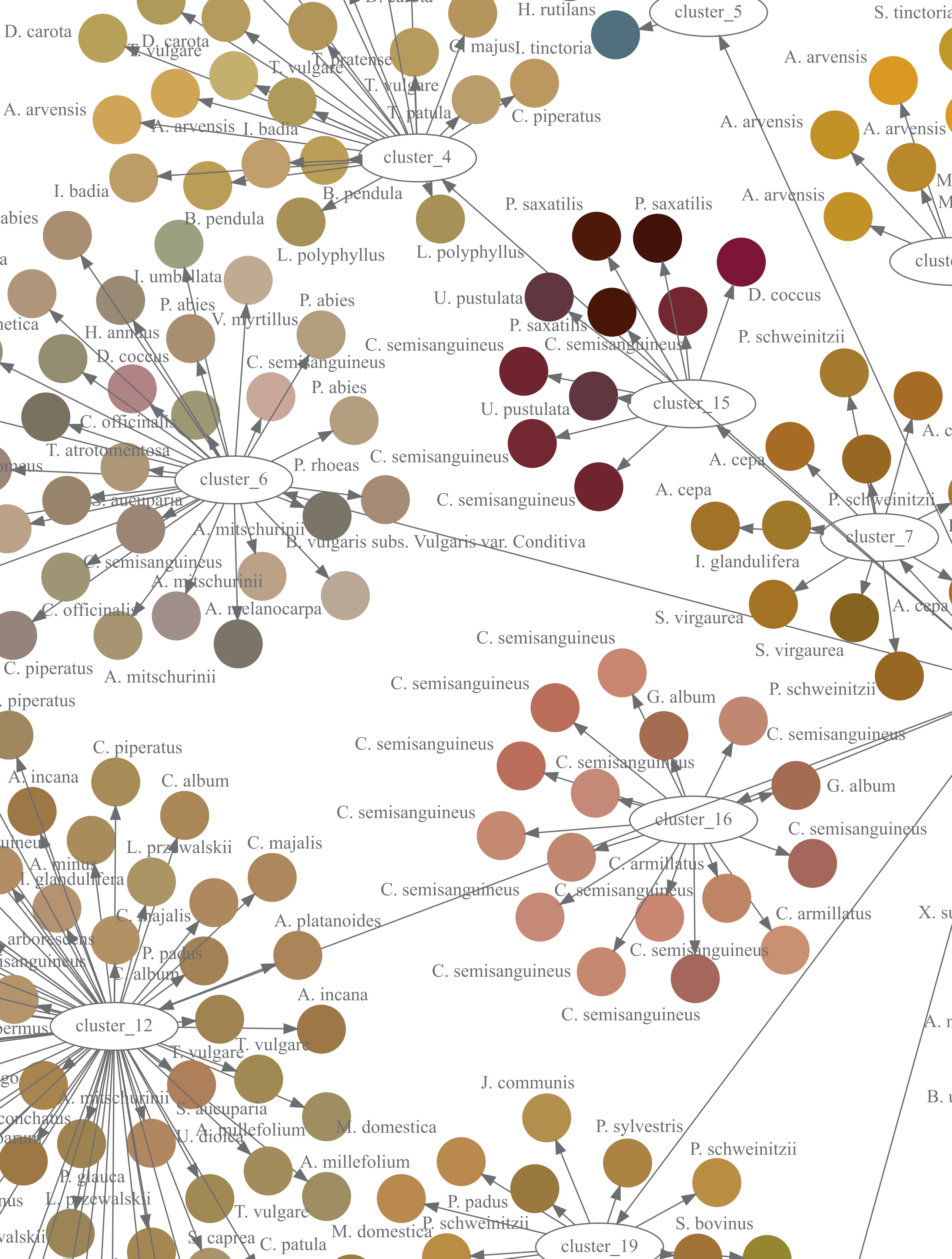
BIO colours

SUSTAINABLE STORIES FROM NATURE, LAB AND INDUSTRY

Aalto University

Kirsi Niinimäki & Julia Lohmann (Eds.)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cluster_4
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P. schweinitzii
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P. abies
cluster_15
U. pustulata
C. officinalis
A. c
T. atrotomentosa
A. cepa
neus
P. rhoeas
C. semisanguineus
cluster_6
A. cepa
P. schweinitzii
S. aucuparia
C. semisanguineus
cluster_7
A. mitschurinii
B. vulgaris subs. Vulgaris var. Conditiva
I. glandulifera
C. semisanguineus
A. mitschurinii
S. virgaurea
A. cepa
C. officinalis
A. melanocarpa
C. semisanguineus
S. virgaurea
C. piperatus
A. mitschurinii
C. semisanguineus
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C. semisanguineus
uineu
C. majalis
cluster_16
C. semisanguineus
A. minus
L. przewalskii
C. armillatus
I. glandulifera
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X. su
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cluster_12
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T. vulgare
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S. aucuparia
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M. domestica
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barum
U. dioica
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A. millefolium
P. glauca
P. padus
L. przewalskii
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C. patula
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BIO colours

SUSTAINABLE STORIES FROM NATURE, LAB AND INDUSTRY

Kirsi Niinimäki & Julia Lohmann (Eds.)

Aalto University
School of Arts, Design and Architecture

Fabric samples dyed with floral and food waste for experimental costume designs by Ingvill Fossheim, (pp. 2–15).
Photos Ingvill Fossheim and Julia Lohmann

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Introduction

Humans have been using natural dyes for thousands of years, and the colours obtained from soil, plants, fungi, lichen, bacteria and animals in this multi-species collaboration has entwined and enriched our histories. Since the middle of the 19th century, natural dye sources have been replaced by synthetic colours, which are cheaper, more predictable, and more suited to large-scale industrial production cycles. However, synthetic dye processes can be detrimental to the natural environment and to human health, and are adding further harmful substances to the already problematic industrial production of textiles. As we try to come to terms with the extent of the destruction we are causing, we seek natural alternatives to our dyes and, through them, a less destructive relationship with our environment. It is time to re-kindle a spirit of learning, regenerative co-operation and co-creation between humans and the organisms that generate the colours we use.

In this book, BioColour consortium* researchers as well as other contributing researchers tell us stories from nature, the lab and industry. They share insights that connect biocolour with agriculture, biotechnology, chemistry and design research. They describe what biocolours are and where they come from, as well as how we can research and apply them to different materials and surfaces. The texts also explore the sustainability of biocolours and what benefits or obstacles their use might entail. The contributions touch on the aesthetics, performance and durability of biocolours, and provide examples of how designers are challenging the aesthetics of synthetic dyes and industrial mass-manufacturing. They highlight the importance of collaboration and of combining different stakeholders, knowledges and skills while developing a new understanding of biocolours.

The book has three sections: foundations, narratives, and lastly, sustainability and applications. It also portrays the organisms that lie at the heart of the scientific and practice-based artistic research into biocolours.

* The BioColour project is a multidisciplinary research project run by University of Helsinki and Professor Riikka Räisänen. The project has two phases, the first of which was 2019–2022 and the second, 2022–2025. https://biocolour.fi/

Professor Riikka Räisänen from University of Helsinki lays the foundations for this book by presenting the BioColour project and different kinds of bio-based colour sources. Marjo Keskitalo, Johanna Leppälä and Pirjo Yli-Hemminki from Luke explain how developing sustainable cultivation methods for dye plants may facilitate the creation of entirely new, desirable value chains and business models for rural areas. Mervi Toivari, Merja Penttilä and their colleagues from VTT showcase how synthetic biology can enhance the production of microbial colourants. These kinds of colours can enable contained, year-round production of dyes.

The second section focuses on narratives and the relationships that craft artists and designers construct with natural materials and nature while working with bio-based colourants and natural dyes. Leonardo Hidalgo Uribe from Aalto University proposes a way of understanding dyeing as a practice in which colour emerges from the correspondences between dyers and the environment. This opens a discussion on current colour practices in the field of crafts and design and offers a theoretical perspective of dyeing that involves the influence of environments on colour. Siren Elise Wilhemsen from the University of Bergen, Norway initiates a design-driven study of colours and approaches to using invasive plant species and their potential for natural dyeing, in a Norwegian context. Through a personal story, she offers insights into how we should see and take into account the complexity of ecosystems and the human impacts. Professor Carole Collet from Central Saint Martins, UK, projects into the futures of biodesign and its connection to colours. Noora Yau, together with Konrad Klockars and Kirsi Niinimäki from Aalto University expand the book's scope into the world of structural colour and how designers can understand and work with these fascinating nano-scale colour phenomena.

The third section of the book focuses on the sustainability aspects of biocolourants and explains how we in the BioColour consortium, and our contributing partners, have been researching the use of bio-based colours with different materials and involving different stakeholders. Kirsi Niinimäki and Leonardo Hidalgo Uribe from Aalto University provide a basis for defining sustainable aesthetics in the context of bio-based colours. Harold Freeman and Tova Williams from North California State University, USA, with Gisela Umbuzeiro, the University of Campinas, Brazil and Riikka Räisänen unfold the many layers of sustainability in relation to colourants. Päivi Laaksonen and Juha Jordan from HAMK, as well as Monica Österberg from Aalto University present examples of colour research that is part of the BioColour project. They have been studying colour attributes such as stability, camouflaging and antioxidative properties, as well as how to use biocolours with biomordants. Kirsi Niinimäki, Noora Tommila and Riikka Räisänen introduce collaborations between academia and industry within the BioColour project and how these collaborations can be understood as a value-adding element in the textile sector. The book will enable readers to learn about the organisms such as plants, fungi, bacteria and animals that inspire scientists, artists and designers and support their collaboration in generating and developing natural colours, while ensuring that they are sustainable and safe for both humans and the Earth's ecosystems.

We wish to thank all the researchers, writers, reviewers and interviewed companies who have contributed to this book and its content. We hope that this book will inspire readers interested in and engaging in the field of colour to seek out more sustainable alternatives to synthetic colourants. We also hope that the texts provide food for thought on how we could build more meaningful relationships with our products, garments, materials, especially colours, as part of having a more positive impact on the environment.

Kirsi Niinimäki & Julia Lohmann

Abbreviations

AL Alum, a hydrated double sulphate of aluminum and potassium
AM Arbuscular mycorrhiza
ATR-FTIR Attenuated total reflection Fourier-transform infrared spectroscopy
AWCB Agricultural waste, co-, and by-products
CAGR Compound annual growth rate
Ch Chitosan
CNC SC Structural colour based on cellulose nanocrystals
CI Citric acid
Cr Chromium
Co Cobalt
CO_2 Carbon dioxide
Cu Copper
DBTL Design-build-test-learn cycle
DNA Deoxyribonucleic acid (is the molecule that carries genetic information)
DW Dry weight
Fe Iron
FTIR Fourier-transform infrared spectroscopy
GHG Greenhouse gas emissions
GM Genetically modified
GOTS Global organic textile standard
GRAS Generally recognized as safe
Hg Mercury
H_2O Water
HTD Cytotoxicity test
IAPS Invasive alien plant species
LCA Life cycle analysis
LC-MS Liquid chromatography-mass spectrometry
MAP Microwave-assisted pyrolysis
MPA Mutagenicity test
MRSL Manufactured restricted substance lists
MSDS Material safety data sheet
NaCl Sodium chloride, salt
NaOH Sodium hydroxide, also called caustic soda or lye
NH_3^+ Ammonium
-NH2 Amino group
N_2O Nitrous oxide
OA Oxalic acid
OEKO-TEX Label based on different standards to measure the harmful substances in textiles
OH Hydroxide
OTR Oxygen transmission rate
OX Oxalic acid
pH Acidity scale
PLA Polylactic acid, bioplastic
PO Participant observation
QCM-D Quartz crystal microbalance with dissipation monitoring
R&D Research and development
ROD Red onion dye
RtD Research through design
TA Tannic acid
UV Ultraviolet radiation
ZDHC Zero Discharge Hazardous Chemicals
Zn Zinc

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Contents

FOUNDATIONS

NARRATIVES

SUSTAINABILITY AND APPLICATIONS

FOUNDATIONS

Photos Riikka Alanko

Cortinarius semisanguineus mushrooms

Cortinarius semisanguineus fungi grow abundantly in our Northern boreal forests. Once you become aware of them you see them everywhere.

There is a long history and extensive craft knowledge on using the reddish-orange caps and yellowish stems of Cortinarius fungi as dyestuffs. However, we can only collect the fungi seasonally.

Today, scientists are analysing colourant samples donated by dyers and are compiling them into a digital biocolourant database. This enables them to link old and new knowledge, with the potential of creating large quantities of biocolourants in laboratories all year round.

Cortinarius
semisanguineus

"I dyed these theatre performance costumes with subarctic mountain birch, pine bark and cones for mordanting and subtle colouring, sourced from the yard of my childhood home in Tromsø/Sápmi.

Cortinarius mushrooms gathered near my current residence in Finland offered a range of vibrant and soft colour expressions – from almost skin-like beiges to pink and burnt orange. The biocolourants in their many shades and colours reflect my personal connection to land and homeland.

The costume colours will slowly evolve during the lifecycle of the performance, through dyeing and re-dyeing. I design, research and learn alongside these biobased materials, using them as a tool to re-think performance-making practices." – Ingvill Fossheim

Costumes for the performance *Muohtadivggažat / The sound of snow* (2021), produced by Ferske Scener and the Sámi National Theatre Beaivváš. Costume design by Ingvill Fossheim

Photo Ingun Mæhlum

Knitted samples by Päivi Kovanen
Photos Julia Lohmann (left), Riikka Alanko (right)

Photo Riikka Räisänen

Riikka Räisänen

Introduction to the BioColour project – research on bio-based colourants

ABSTRACT

This introductory chapter highlights the background of the BioColour project and discusses what kind of natural colourant research has been carried out in Finland. It also describes the aims and implementation of the biocolour research in the BioColour project. The text starts with a short historical overview for the developments of dyes. Natural dyes have a continuum from history until today, and current interests towards natural and bio-based colourants are strongly expanding among researchers, and also among industries. Natural colourants are not only history and small-scale craft practice – they are already part of the more sustainable colour futures.

Keywords
colourant, dye, environment, sustainable, aromatic, synthetic

Photo Laila Siitonen and Julia Lohmann

Introduction

When natural dyes are inspected from the historical perspective, it can be seen that there is a continuum from history until the present day, however the focus have changed during the years. Firstly, natural dyes were the only colourants used till the 1850's when the first synthetic dyes were produced. Industrial revolution, which started already in the middle of the 18th century, made change into large scale production and increased the demand for colourants. The scale in which natural dyes were used was massive and applying methods were in industrial scale. Soon after the synthetic routes to the first colourants were created, the man-made production very quickly replaced the natural dyes, which required much more resources in extraction and application to textiles and other materials. However, craft and artist-based activities have continued during the centuries and the knowledge of producing and applying natural colourants have been passed on to new generations.

It was the second millennia technology and material innovations, when sustainability and environmental issues became crucial in all production, and this have had an effect on the research of natural dyes, as the hazardous effects of synthetic dye production and their ill effects to environment and human health raised the need of finding alternatives to hazardous compounds. The research of natural and bio-based colourants has expanded enormously from the year 2010 onward, revealed by the Google Scholar search for keyword "natural dye" which brings about 992 articles in 30 years between 1970–1999, 2380 articles in the years 2000–2009 showing 240% expand, and 13600 articles between 2010 and 2019, an exponential growth. The topic is absolutely important in the current bio product and sustainable material research.

Natural dye research started in Finland at the end of the 1990's and two doctoral theses of the topic have been finished at the University of Helsinki (Keskitalo, 1999; Räisänen, 2002). Also, in the beginning of the second millennium several research projects were launched as co-operation projects within research institutes in Finland

and Europe, for example EVTEK Natural Dyes Development Project 2000–2003 and SPINDIGO 2000–2003, in which Kirsi Niinimäki and Marjo Keskitalo were involved. Further, individual researchers have carried out research, and bachelors' and masters' theses have been made, but it was not until 2019 that the importance of colour as a part of a recyclable and sustainable artefact has been recognized also by research funders, and the funding from the Strategic Research Council at the Research Council of Finland opened up the opportunity to carry out research of bio-based colourants in an international multidisciplinary research consortium, the BioColour - Bio-based Dyes and Pigments for Colour Palette - project (https://biocolour.fi).

Why research on bio-based colourants?

Bio-based materials have gained growing interest in different applications, such as food, cosmetics, medical applications, textiles and packaging, as companies actively want to enhance their products sustainability and remove environmental and hazardous pollutants during the manufacturing process. Biodegradable and recyclable textile and package innovations are increasing. However, currently synthetic colourants are used in most of such products and they are designed to be stable, which runs counter to bio-degradability.

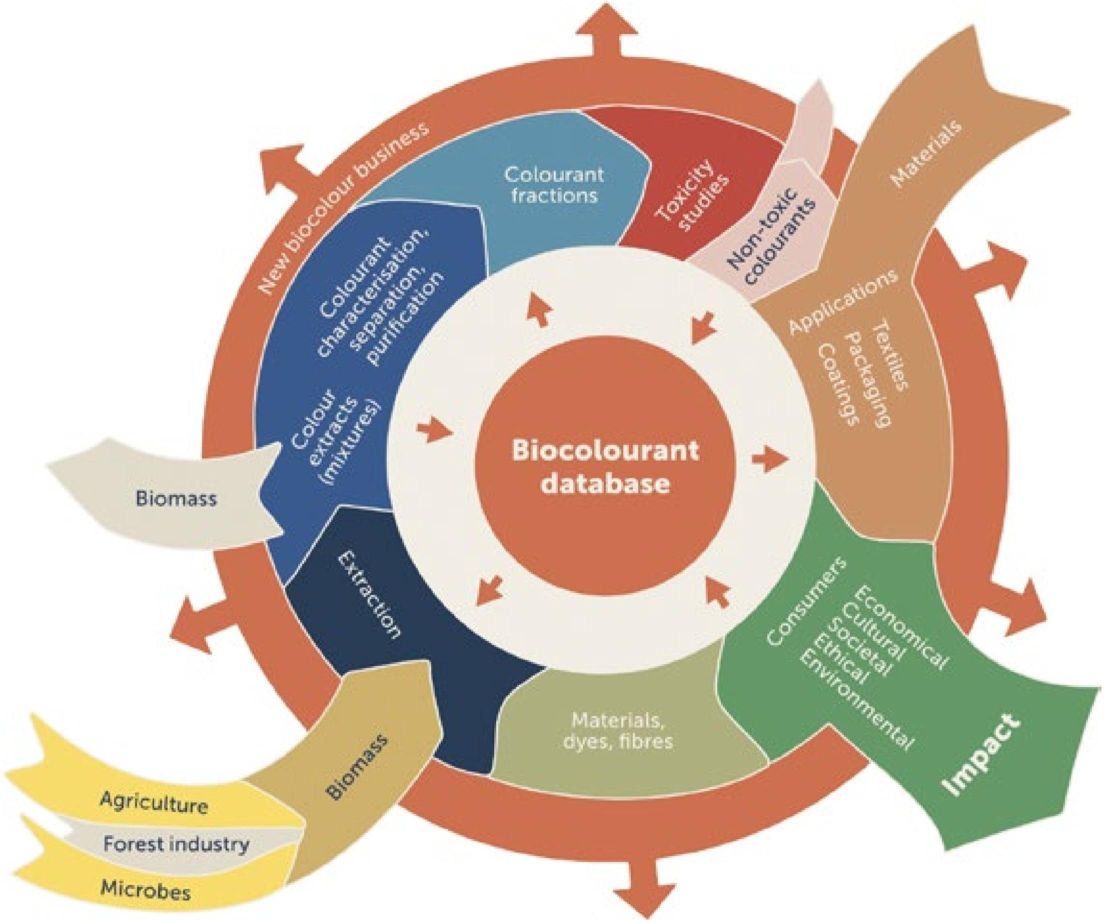
The United Nation's Agenda 2030 for Sustainable Development Goals (United Nations, 2015) motivates researchers to move even deeper in green solutions and develop new industrial products to be based on environmentally sound colourants. Natural compounds as such have a variety of properties, for example in addition to colour they may also have UV-protective, antimicrobial, water resistance and electric conductive properties, which would give additional value when applying them to products. Multifunctionality means efficiency in manufacturing, shorter industrial processes and reduced energy requirements. This comes from the fact that in textile production every functionality is added in a separate process using additional chemicals (Räisänen et al., 2017).

BioColour is a research project funded by the Strategic Research Council at the Research Council of Finland for the years 2019–2025. Its aim is to develop new methods for the large-scale production of biocolourants, along with their characterisation and application. Important is, the gained fundamental understanding of biocolourants, their characteristics and properties, among which also the toxicological aspects are the ones under investigation. Natural dyes are often argued to be nontoxic and safe, but natural origin *per se* does not mean that a compound could not cause hazard.

The studies at the BioColour project are focused on three major sources of colourants: 1) agriculture and 2) forest industry waste streams and 3) microbes, and three application areas textiles, packaging and coatings. Cultivated plants and by-products of agriculture and forest industry are studied as dye raw materials, which promote sustainable farming and forest economics. Utilization of by-products increases material efficiency. As a longer term, microbial dye production with a small footprint will be enhanced and developed by metabolic engineering. The aim being to conduct economic feasibility studies of the production of biocolourants from different sources.

In addition, this research is focused on the societal acceptance needed for successful implementation of biocolourants and products. As it is known that behavior is different from intention and it is difficult to change learned ways of habits (Carrington et al., 2010). Education has influence and attainment of promoting and fostering sustainable lifestyles (Lee et al., 2015), raising awareness of new innovations, new aesthetics and characteristics of biocolourants. Therefore, a multidisciplinary team of experts undertakes studies pertaining to biocolourant production methods, structure-property relationships, toxicology and dye-substrate interactions with scale-up, co-creation and investigation of cultural, along with societal and ethical aspects associated with producing and applying biocolourants. Figure 1 shows the content of the BioColour project and the continuum of the research targets. All these topics will be discussed in this article.

BioColour consortium is clearly multidisciplinary, combining researchers from eight universities and research institutes: University of Helsinki, University of Eastern Finland, Aalto University, Häme University of Applied Sciences, Luke Natural Resources Institute Finland, VTT Technical Research Centre of Finland, North Carolina State University, USA, and University of Campinas, Brazil. It captures the versatility of disciplines from natural sciences, toxicology and applied technology to cultural, design and consumer studies. Through its multidisciplinary approach, a more comprehensive understanding of complex phenomena can be obtained. The research in the BioColour



consortium applies mixed methodologies (Creswell & Plano Clark, 2008) using both quantitative and qualitative data. The work involving dye extractions, characterisation, toxicological and application studies uses analytical and quantitative methods to understand the chemical and physical nature of the biocolourants and their interactions with various substrates and biological environments. In this programme, cultural and social studies are focused on questions related to social sciences as well as consumer and design research employing mostly qualitative methods but also quantitative data obtained from surveys. Surveys are carried out to map consumers opinions about natural and bio-based colourants in textiles and packaging, for example.

1 BioColour project and the continuum of the research flow.

Figure Riikka Räisänen and KasKas Media Oy

Colour and colourants

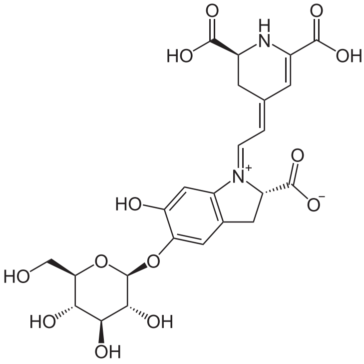
Colour, as visual element, is everywhere in our built and designed environment and there is a growing demand for colourants (i.e. dyes and pigments) due to growing population and increasing standards of living. Dyes (which are soluble in water and related solvents) and pigments (which are non-soluble in water and related solvents) are sold yearly by worth of 33 billion euros and their value is estimated to grow by 5% by the year 2027 (Grand View Research, 2021). Need is especially in textiles, paints and coatings, construction and plastics. Synthetic dyes are based on derivatives from oil refinery, and the price of raw material, such as benzene, determines the production costs.

Production of colourants

Colourants are synthesized in factories where their starting materials are simple aromatic compounds, for example benzene. In these synthetic chemical reactions heavy metals such as zinc (Zn) and chrome (Cr) are used to aid the synthesis to proceed smoothly and to the highest possible degree. In addition, synthetic reactions need solvents and for them water, acids and alkali are needed. Synthesis result never 100% output. The yield may be as low as 30% and contains starting materials and by-products, and therefore purification is needed (Hunger, 2002). The level of purification is increasing due to international agreements such as Manufactured Restricted Substance Lists (MRSL) and Zero Discharge of Hazardous Chemicals (ZDHC) (ECHA, 2023).

Properties of colourants

Demanded properties for colourants are stability, affinity to the substrate, exhaustion and colour fastness properties in the material (Hunger, 2002). Safety profile of a dye is important and the Material Safety Data Sheet (MSDS) highlights the safety data which includes reference to skin and eye contact, inhalation and ingestion, but there is no necessarily specific data available for human and environmental toxicity. Colourants are usually stable, but dyes and/or their by-products or degradation products may cause hazard to humans and environment (Korinth et al., 2013). EU chemical legislation recommend liquid form dyes, to decrease the hazards caused by the dusting of dye powders (ECHA, 2023). However, for biocolourants the liquid form is challenging as natural compounds start degrading easily in aquatic environment and as being organic and extracted from natural biomass the extract contains microbes which start fermentation process and spoil the extract.



2 Red betanin is the colourant in beetroot. It is very water-soluble as can be indicated from many COOH- and OH- groups.

Colour and natural dyes

There are two terms: natural dye and biocolourant. Is there any difference between these two? Natural dye is produced by nature and can be extracted from biomass. Biocolourant is a broader term covering not only natural dyes but also colourants produced through bio-synthesis, even utilizing synthetic biology technologies.

Colourants in living organisms are secondary metabolites, meaning that they are not vital for the plant, but they have other important roles such as chemical defence, defence from attacks of micro-organisms and animals, as well as role in reproduction. They can be end or by-products of other biosynthesis but they seldom are inert end-products, instead they continue changing into new compounds. (Czygan, 1980.)

Secondary metabolites, in this case colourants, are synthesized in cytoplasm in a cell and they can be stored in the same cell or the cell next to, or can be stored to a totally different part of the plant for example into roots, as betanin (food colourant E162) in beetroot (Figure 2).

Natural compounds have plenty of hydroxyl groups (OH-), which are important as they increase water solubility. Colourants are also very often linked to sugars and they can be mono-, di- or tri- glucosides for example, that increase water solubility. Oil soluble colourants are stored in cell walls. They are not suitable for dyeing but may be used as food colourants for example.

Colourants in living organisms

Chlorophyl is probably the best-known natural colourant which exist in green plants. It decomposes easily and cannot be used in dyeing. Instead, anthraquinones are one of the most stable natural dye structures, and have been known long in traditional dyeing. They give colour ranging from yellow to red. Anthraquinones are found in madder (*Rubia* species), fungi and lichen for example. Yellow producing carotenoids are linear structured and can be divided into water soluble xantophyls, and lipid soluble carotenes. Flavonoids compiles of a large group of different structures which are water soluble and produce colour varieties from yellow to blue. Flavonoids can be divided into several subgroups from which anthocyanids produce colours from red to violet and blue for example in berries and flowers. Anthocyanids are interesting because of the rareness of blue in nature.

In recent years colourants in fungi and microbes have gained more interest because they can be grown on different substrates easily and they can even be manipulated with synthetic biology means to produce desired compound, even one single dye structure.

Biocolourants in large scale utilization

If we think of biocolourants in industrial scale utilization, criteria need to be set for biomass sources and colourants. The amount of colourants in biomass is typically ca. 4% of the dry weight.

Colourants need to be soluble in water. They need to have adequate stability in different conditions, for example in heat (important for garments in ironing), UV radiation and visible light so that the colour does not fade, also pH stability is important in washing of textile. Colourant needs to have affinity to the substrate, to be attached to the fibers so well that it does not wash off. Colour strength and intensity are important as they determine the cost efficiency.

Biocolourant sources

Biocolourants can be obtained from agriculture and its side streams, as well as cultured dye plants such as woad (*Isatis tinctoria*), madder (*Rubia tinctoria*) etc. Stems and leaves of food crops like broad bean and lupin produce much yet unused biomass. Weeds, like mayweed, have potential as dye source.

Also, gardening and environmental care produce streams that are already collected: *Salix* spp., alder, rowan, lupin and common reed. Some of these are also named as invasive species and actions are taken to prevent their spread.

Forest industry produce bark and twigs of trees and food industry skins of vegetables and fruits. In Finland foraging networks are used to collect eatable mushrooms, and these could be utilized for collecting fungal material for colourant purposes as well. Digital platform economy enables a variety of ways for value creation, especially for individual small producers to join forces and deliver raw materials for the next-step refiners. One example of this kind of activity is the Keraaja.fi (2023) portal, which connects actors who are interested in trading non-wood forest products (NWFP) raw material and related products in Finland.

A new page is turned in biocolour production when colourants are let to grow in fermentation tanks and synthetized by fungi and other microbes. Microbial cultivations provide unlimited possibilities in colourant production, as the microbes can be grown in large bioreactors in regulated conditions all year around. Also, processes can be modified in many ways. Metabolic engineering gives various possibilities for example to eliminate toxins and produce more targeted end products, meaning dye production suitable for specific textile fiber, and modification of the core structure in a way which enables enhanced performance on the intended base material.

Safety of natural dyes

What do we know about safety vs. toxic effects of biocolourants? Flavonoids are the most common group of colourants in plants (Czygan, 1980). Besides colouring properties flavonoids have many pharmacological properties – for example anti-inflammatory activity, anti-viral activity, vitamin C-sparing activity, antimutagenic activity, anti-X-ray tissue damaging activity, anti-asthmatic activity and anti-neoplastic activity - and they have been studied intensively for their antioxidant activity. They have highly recommended positive effects on human health. They have also protein binding properties. (Sharma et al., 2018.)

When natural colourants are obtained from food processing side streams, they are marked as GRAS, i.e. Generally Recognized As Safe. Such would be for example dyes from onion skins. Anthocyanins, like the red colourants in red onion skins and berries, can be bound to sugar moieties to produce mono-, di-, or tri-glycosides, a total of 19 anthocyanidins have been reported in plants, among which the six major ones are cyanidin, peonidin, delphinidin, pelargonidin, malvidin, and petunidin. Anthocyanins' colour is pH depended which stems from the compounds' chemical structures. The average anthocyanins intake in France to be ~57 mg/day (Perez-Jimenez et al., 2010), and in Finland an average of 47 mg/day of anthocyanins has been estimated. Anthocyanins are generally considered safe in humans because they have been consumed as part of regular diet for generations without any adverse health effects. No adverse effect was noted in oral dosing. The general consensus suggests that anthocyanins are safe for human ingestion as usually consumed in the diet.

But not all plant-based colourants are safe. Large numbers of flavonoids have been examined for mutagenic activity. And plants may contain other compounds such as phytotoxic alkaloids, for example in lupin (*Lupinus* spp.). Lupin is very common and growing as weed in road sides, but species is also cultivated as protein rich crop. It is suggested that natural toxins may contribute to poor chemical quality of natural waters, and that natural toxins from upcoming crops or invasive weeds should be considered in aquatic risk assessments (Griffiths et al., 2021).

Are natural dyed textiles safe?

Our earlier study provides one example of investigating the safety aspects of natural dyes. We studied dyed woollen fabrics from the consumer point of view (Räisänen et al., 2020). Natural colourants in our studies were from fungal and plant sources and represented different dye structures: fungi *Cortinarius semisanguineus* (blood red webcap) contained anthraquinones and *Tapinella atrotomentosa* (welwet rol rim) terphenylquinones, plants *Tanacetum vulgare* (tansy) flavonoids and *Salix phylicifolia* (willow) tannins.

Cortinarius semisanguineus contains a mixture of 14 anthraquinones which are in fresh fungus bound to glucosides in ca. 90%. Most abundant colourants are emodin glycoside and dermocybin glycoside as well as dermorubin and endocrocin, which are carboxylic acids. Even belonging to *Cortinarius* spp., the fungus has not been found to contain fungal toxins, such as nephrotoxic orellanine. In the fungus the anthraquinone content is fairly high, ca. 6% of dry weight, compared to plants in which typically 4% of dry weight is the amount colourants.

In the test *Cortinarius* extracts and dyed woolen fabrics did not show any cytotoxic effects when hepa-1 cells (rat liver) were used (Räisänen et al., 2020). Later we carried out a miniaturized micro-suspension assay from Ames test applying 5 different strains with and without S9 (liver enzyme showing possible metabolism of the studied compound). As a result from these tests emodin proved to be mutagenic as according to the literature. However, emodin-O-glucoside, in which form emodin is in 90% in the fresh fungus, was not mutagenic, nor dermocybin or dermorubin (Umbuzeiro et al., 2020a).

Fungal blue dyes

Tapinella atrotomentosa welvet roll rim, contains terphenylquinones of which atromentin is the main colourant and it exists as colourless precusos leucomentin 2 and 3 in the fungal flesh. Also, violet colour providing spiromentins are present. Colourant content may be from 2–5% of the fungal mass dry weight. The flesh of fruiting body is pale or colourless due to colourless precursors of the dyes, but when extracted in water intensive violet colour liquor appears.

Tapinella showed the most change in the morphology and viability of the exposed cells (hepa-1, hepatoma cells), compared to the other tested dyes (Räisänen et al. 2020). The average of the HTD value was 2 meaning that maximum of 50% of the mouse hepatoma cells had lost their viability. Terphenylquinones have been reported to induce a broad-spectrum of antimicrobial activity, for example against Gram positive and Gram negative pathogens, and a significant inhibitory activity against resistant bacterial strains, for example MRSA (Methicillin-resistant *Staphylococcus aureus*). This will make them interesting compounds from also from the colourant and textile applications point of view as multi-functionality would shorten textile finishing operations.

Tancy

Tanacetum vulgare, tancy, contains flavonoids, such as luteolin and quercetin as main compounds and carotenoids, such as violaxanthin and β-carotene, in the intensively yellow flowers. For dyeing purposes, the whole plant can be used, resulting in a greenish-yellow colour, while flower heads produce bright yellow. *Tanacetum* extracts, together with *Tapinella*, were the most toxic samples of the hepa-1 tested biomass and fabric samples. *Tanacetum* contains also potentially harmful alkaloids and terpenes such as sesquiterpene lactones, in variable amounts depending on the chemotype. Also, the essential oils of tansy have shown cytotoxicity. Literature reports that water extract of tansy leaves possessed a strong diuretic action but no renal toxicity or other detrimental effects in tests on rats. (Räisänen et al. 2020).

Willow

Willow twigs and bark contains condensed tannins in an amount of approximately 2–3% of dry weight. The composition varies highly among *Salix* species, between genotypes and hybrids. The condensed tannins are procyanidins, which consist of chains with varying numbers of flavan-3-ol monomers linked to each other. *Salix* extracts and dyed woolen fabrics did not show cytotoxic effects (hepa-1) (Räisänen et al. 2020).

We also carried out Ames test for the water extract of *Salix* bark which showed that willow bark water extract was non-mutagenic in the *Salmonella enterica serovar typhimurium* strains TA98 with and without S9 at 5% at the mutagenicity test (MPA) (Umbuzeiro et al., 2020b). Traditionally, willows (*Salix* spp.) have been considered safe, as they have been used as a medicine to reduce fever, inflammation and pain.

The concentrations of dyes used in the assays (Räisänen et al., 2020) were very low, imitating the dose of the user. The extraction method also revealed that only small amounts of the dye comes out from the fabric after dyeing – which is good from the user point of view. The *Salix* and *Cortinarius* samples did not show any cytotoxic effects, whereas the *Tanacetum* and *Tapinella* samples had slightly higher test values but were not interpreted as being significantly toxic. This was both for the biosamples and dyed fabrics.

Iron induced the least change in exposed cells, although the differences compared to other mordants were statistically insignificant. This lower value might be due to irons ability to form complexes and stabilize the molecules, and thus also prevent molecules from toxic reactions.

It was found that the cytotoxicity of the fabrics dyed with the biocolourants did not differ significantly from the undyed wool fabric, and this emphasized the importance of testing the undyed fabrics as well – and that many different chemicals are used during textile producing processes including dyes but also other finishing chemicals – and it is important to test those also.

Biocolourants on an industrial scale and their potential toxicity

When exploiting biocompounds as dyes in large industrial scale – how to avoid potential toxicity, and compounds harmful effects to humans and environment? Correct identification and characterisation of the biocolourant's source is crucial as toxic compounds are concentrated in certain taxa, this bring up the necessity to use safe biomass sources. For example, favouring food production side streams because they are generally regarded as safe.

The safety risks can be minimized by understanding reaction mechanisms of colourants formation and degradation, and how the reactions can be controlled.

The historical background does not necessarily give any guarantee of safeness as even widely-used dye sources can contain toxic secondary metabolites: madder root extracts (*Rubia tinctorum*) having alizarin as the main anthraquinone aglycone, but also contain toxic lucidin, rubiadin and xanthopurpurin.

When developing the larger, industrial scale utilisation of biocolourants, profound bioassays and chemical analyses are necessary from single purified compounds to tackle the possible hazardous pathways of dyes in the human metabolism and environment. It is also important to develop right kind of extraction and purification methods.

As it is known that natural origin *per se* does not mean safe or non-toxic, the toxicity of biocolourants to human health and the environment need to be assessed. Biocolourants are often mixtures of compounds extracted from numerous sources. The chemical composition of dye structures and their metabolites need to be determined to evaluate their ability to cause harmful effects. Metabolic profiles of biocolourants in aqueous medium are essential to be characterized by non-targeted metabolomics. Also, the mutagenicity and toxicity on human cell lines need evaluation. Our research has shown that the greatest potential for hazardous effects occur for those working in the industries, and for aquatic animals in the water bodies. The concentration of colourants is very small in textiles, and using natural dyed textile is safe for a consumer.

When targeting greater sustainability and improved colouration of materials, focus can be laid on colourants, substrates and methods. In the applications area, waterless dyeing techniques such as the super critical carbon dioxide and atmospheric plasma aided dyeing, mass colouration and reduced colourant concentrations in dyeing and printing are to be examined. With the studies of interactions between biocolourants and substrates, understanding for improved and sustainable colouration methods can be gained. Furthermore, studies other than colouration, such as electric conductive properties and usage of biocolourants in solar cells, are important.

Agenda 2030 goals for the biocolour economy

When it comes to the United Nations (2015) goals for sustainability in the form of Agenda 2030, many of them are in the core of the biocolour economy. The value chain for biocolourants aims for zero-waste and upcycling at every step of the process.

Consumer awareness of environmental degradation and climate change is increasing, and educational attainment is a strong predictor of climate change awareness, which will also lead to changed consumption patterns. Promoting environmental literacy through education, and promoting sustainable-driven businesses are approaches in meeting the challenges of the future (Martínez et al., 2021). These support the United Nation’s Agenda 2030 goals for high quality education. Biocolour economy enhances sustainable production and consumption patterns and protect, restore and promote sustainable use of ecosystems and halt biodiversity loss.

Natural dyes have low tinctorial strength, therefore they do not pose as high hazard to the aquatic environment as do the synthetic dyes in terms of colour in effluent. Alum and iron sulphate, which are the most commonly used metal salt mordants, are used in purifying drinking water – they are not particularly toxic substances. Therefore, they can be used in stabilization of the colour compound, when as low amounts as possible are obtained to create adequate colour quality. Metal mordants increase colour intensity in addition to stability. Natural choice are biomordants, but because of their similar nature with biocolour compounds they do not particularly increase colour intensity.

The degradability of biocolourants is a positive feature in circular material production, whereas in the textile dyeing process, the requirements of colourants are set in high affinity to fibres and stability under end-use conditions. Thus, the utilisation of bio-based colourants requires careful consideration of dye technical and toxicological properties as well as economic feasibility, in which the multi-functionality through antimicrobial and UV-protective properties can create interesting and value adding prospects.

BioColour project outcomes – Conclusions

BioColour consortium is expecting to develop

1. novel methods and innovations for biocolourant production from crops, agricultural waste, forest industry side streams and fungal/microbial sources,
2. a group of nontoxic biocolourants, mixtures or purified compounds, producing a colour palette of yellows, reds, browns, greens, blues and blacks,
3. procedures for laboratory and industrial scale colouration of textiles, packaging and coatings,
4. a prototype collection of created biocoloured textile items,
5. an open biocolourant database serving researchers, industry and policy makers and
6. interventions such as educational packages helping stakeholders, policy makers and educators to disseminate the knowledge of sustainability, biocolourants and their applications.

To launch biocolourants successfully, we aim to understand impacts of biocolour production at society and stakeholder levels, and how consumers value and negotiate the new qualities of products (e.g. biocolour package, the variety of aesthetics in textile products) into their choices.

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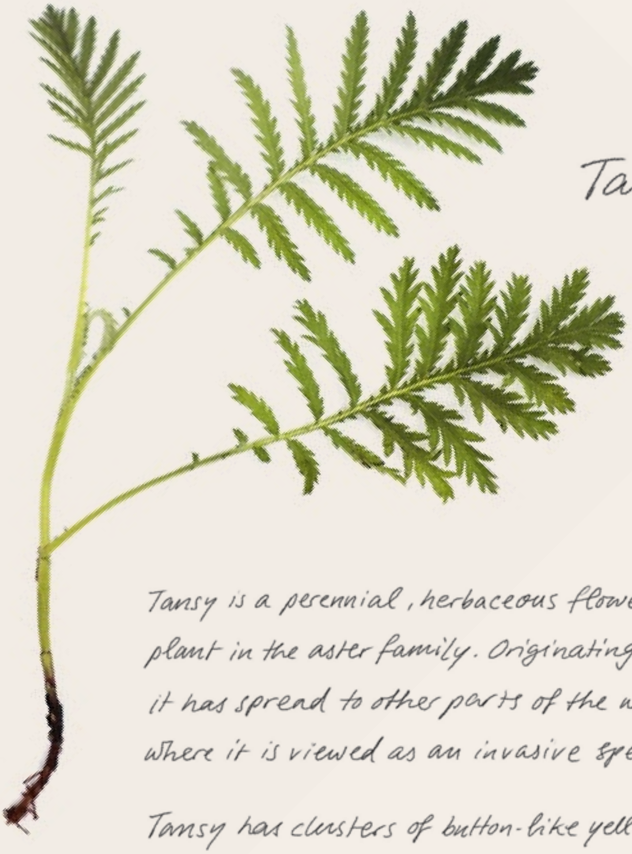
Photos Leonardo Hidalgo Uribe (left), Julia Lohmann (right)



Tansy (tanacetum vulgare)

Tansy is a perennial, herbaceous flowering plant in the aster family. Originating in Eurasia, it has spread to other parts of the world, where it is viewed as an invasive species.

Tansy has clusters of button-like yellow flowers and finely serrated compound leaves. It can grow from fifty to one hundred and fifty centimeters tall.

Tansy contains volatile essential oils that are toxic in larger quantities. In measured dosages, it has been used for medicinal purposes, to expel parasitic worms and repel insects, in garden pest control, for meat preservation and in embalming. Tansy has also been used as a food flavouring.

As a dyestuff, tansy produces yellow colours.

tansy flower cluster

a single tansy flower, side and top view

Photos Leonardo Hidalgo Uribe

Photo Leonardo Hidalgo Uribe

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Increasing biodiversity along with the development of sustainable dye plant production

ABSTRACT

A comprehensive colour palette can be obtained from plants and their harvest residues. Dye extraction may add to the value chain and bring a new business model for rural areas. Colour plants cannot take land area from food production, but their cultivation on unprofitable field blocks and marginal areas adds much needed variety to the agricultural landscape. Regarding sustainability, it is important to develop natural dye production so that it needs fewer chemical inputs and supports carbon sequestration. Optimal management practices ensure dye production, i.e. plant yield. Additionally, soil nutrient status and ability to compete with weeds can be improved by intercropping dye plants with nitrogen-fixing plants. Woad, tansy, nettle, and lady's bedstraw among others, adapted to harsh conditions, have interesting chemical and underground traits that can affect both aboveground and soil biodiversity. Wild plants are genetically variable, and a high colour yield is a desirable trait for their crop improvement.

Keywords
dye plants, crop production, carbon sequestration, biodiversity, on-farm upgrading, biodiversity business model

Photo Julia Lohmann

Introduction

The fashion textile industry uses significant amounts of synthetic dyes and chemicals, and their effects on the environment and human health is now a major concern. One of the suggested solutions is to replace synthetic dyes with natural degradable dyes to minimise the negative impact on the ecosystem. The science has also taken environmental aspects into account. However, there are quite wide variations how the word 'sustainability' has been considered along the value chain.

Overall, using stems, roots, flowers, leaves, fruit, and peels from natural plants (Che & Yang, 2022; da Silva et al., 2018; Lachguer et al., 2021; Romdhani et al., 2022) or utilising agricultural by-products is considered to be sustainable and environmentally friendly (Gecchele et al., 2021). Simply, plant-derived compounds are interesting because they are considered biodegradable, non-polluting, and have many applications and uses (Özomay, 2023). Sometimes 'natural' has another meaning when microbes are also included. For example, the enhanced production of indigoidine blue pigments with metabolically engineered *Corynebacterium glutamicum* was considered to be sustainable, along with improved competition with synthetic dye production (Ghiffary et al., 2021).

There have been attempts to make the extraction of natural dye compounds greener using no or at least fewer hazardous solvents, such as the research with anthocyanins (Gecchele et al., 2021) and polyphenols (Rehman et al., 2022). In some cases, extracted natural dyes are mentioned as being safer (Dulo et al., 2021) or up to 60% more environmentally friendly (Dulo et al., 2022) compared to synthetic counterparts, as was also the case with quinones (Dulo et al., 2021).

Enhancing natural colour strength, fastness, and stability properties with the pre-treatment of fabrics (da Silva et al., 2018), with (Pinheiro et al., 2019) or without bio-mordants (Hossain et al., 2022; Rahman et al., 2023) made the process more sustainable and environmentally benign. Concern about the availability of pure water as well, as the wastewater impact on the aquatic eutrophication system, has also affected the dye industry (Handayani et al., 2018).

Life cycle assessment (LCA) provides more systematic information about the environmental impact of the cultivation of the dye crop on colour fastness and quality. The challenge is to obtain enough data from different steps in the production chain, and only a few studies are therefore available. An experiment with the dye obtained from pomegranate peels showed that LCA is only meaningful when dyed textile has good colour fastness properties (Anandhan and Prabaharan, 2018). LCA revealed that the solvent and energy used during the extraction and the liquor-fabric ratio in the dyeing were the most challenging hotspots to using madder for dyeing. In addition, the adoption of new technology reduced the impacts of both hotspots and made the process less harmful for the environment (Agnhage et al., 2017). With the aid of LCA, it can be stated that food waste and agricultural losses are environmentally competent sources for various dye compounds (anthocyanins, carotenoids, and quinone) compared to synthetic dyes (Phan et al., 2021).

Despite the large number of dye-producing plant species, relatively few if any publications are available concerning how the cultivation of dye species can contribute to biodiversity and carbon sequestering, for example. Phenotypically, many dye crops differ from the cultivated crop alternatives and have a much richer root system, or the seed setting requires insect pollination. Integrating dye crops into cropping systems could therefore improve the sustainability and biodiversity of the field environment in many ways.

It is well known that crop cultivation is one of the most resource-demanding phases in the production chain, and we can therefore affect sustainability by selecting the species with the best traits. We therefore propose that when crops are selected for natural dye production, methods for avoiding fossil-derived nitrogen supply should be among the requirements. However, there may also be highlights to consider. Dye crops can also be valuable sources of biodiversity and may have carbon sequestering potential, and their traits to provide ecosystem services should therefore be examined as part of a sustainable environmental assessment. Thus far, sustainability has only been linked to the steps after dye crop production, e.g. the extraction of the dye and the dyeing process itself. This chapter presents relevant issues for the development of sustainable business models for dye crop production and the value chain starting from cultivation. Various ecosystem services provided by dye crops adapted for harsh conditions are also described.

Commercialisation of plant-derived dye production

Potential of plants to produce dyes

Plants have been utilised for dyeing for thousands of years. Plant dyes are therefore part of humankind's cultural heritage. Overall, crops and plants form a huge source of all types of raw materials for various biomaterials and biochemicals. The total number of plant species was 374,000 by 2016, and annually about 1,500–2,000 new vascular plants are described (Christenhusz & Byng, 2016). In each plant, the chemical composition of roots, stems, leaves, flowers, and seeds may differ during the growing season. Considering the effect of sunlight, moisture condition, nutrient availability, soil condition, and other aspects affecting growth and plant metabolites, the number of raw materials which may have a different chemical composition and potentially yield different dyes and shades, will increase many-fold. Unsurprisingly, numerous recipes, books, and research papers related to the use of plants as colourants mainly on a smaller scale have been published in the last century.

The number of plant species varies between countries; the richest sources are usually found from the warmer areas of the world. But, even in Finland, located between latitudes 60° and 70° N, 3307 vascular plant species have been observed (LAJI.FI, 2023). And, more than 150 of those species were cultivated on the arable land in Finland in 2021 (EUMUDA, 2023).

Drivers for the re-commercialisation of natural dye value chains

Global warming and the increase of CO_2 in the atmosphere is now also affecting the synthetic dye industry in a way which may significantly alter current practices. As part of textile manufacturing, the dye industry plays a significant role in GHG emissions on a world scale. In recent decades, most of the textile industry was outsourced from Europe to other countries. It was estimated that the EU imported about 9,000 kilotonnes of CO_2 from China alone in 2008 (Valodka et al., 2020). The synthetic era of textile dyes began more than one century ago, but the industry is again gradually moving to more natural practices.

Indeed, the compound annual growth rate (CAGR), which describes the mean annual growth rate of an investment between 2019 and 2024, is expecting to be 11%, reaching a monetary value of USD 5 billion. The driving force for the augmentation of CAGR is environmentally conscious consumers, who increasingly value natural and organic materials and sustainability. The natural dye markets are dominated by plant-based segments, with a share of two thirds, while the rest are animal- and mineral-based products. Cosmetics, food and beverages, pharmaceuticals, textiles, and leather were mentioned as the most important market segments of natural dyes by end users (Aritzon, 2019).

Before the industrialisation of the mid-18th and early 19th centuries, most dyes were of natural origin, and especially indigo, one of the most valuable dyes, was used for trading. The question of the re-commercialisation of natural dye production has emerged simultaneously with the goals of transferring textile industry manufacture from fossil sources to renewables and to improving the circular economy.

Sustainability starts with plant production

We are facing the fact that the entire value chain related to botanical resources and dye production must be developed. Today, there is a great momentum to make dye production genuinely sustainable, without the previous burdens. There are plenty of publications and examples in the current food and feed production system about what we should not do. One of the biggest inequities is the unequal sharing of revenue for those producing the raw materials, meaning new sustainable expertise or technology cannot be applied. Biodiversity, carbon sequestering, and adaptation to climate change are also fundamental issues to be considered at the outset of value chain development. Specifically, the use of synthetic inputs and the choice of crops and soil types for production are among the first issues to be surveyed.

Arable crop production will be the major goal when developing sustainable and larger-scale dye production from herbaceous species. Wild areas may be rich sources for various species, but caution is needed in gathering and commercial larger-scale utilisation, as the trading of wild species may endanger their natural existence. This has been observed in medicinal plants (Schindler et al., 2022). When crops are cultivated on arable land, the newest expertise developed for primary production are available to optimise management practices, homogenise raw material production, guarantee the raw material supply, and make the production technically feasible overall.

Dyes from plant production resources

Dyes are plant secondary metabolites

Dyes and pigments are among the vast group of metabolites occurring in plant species that is referred to as secondary compounds, distinguishing them from primary ones. Traditionally, secondary compounds have been considered less important than primary ones that play a basic role in plant growth and development. New research has increased the understanding that the difference may not always be so clear, as the functions of secondary compounds in the plant are often interactive. There are plenty of plant species yielding various shades and colours, but less information available concerning how to affect or optimise dye production through management practices in the field. Crops growing in the field are exposed to various weather and moisture conditions and nutrient availability. Attacks by insects and diseases can damage plant cells and cause stress to the entire plant, which may alter metabolic pathways.

Tansy (*Tanacetum vulgare*) has traditionally been used as a medicinal plant. For example, tansy flavonoids are involved in protection against both biotic and abiotic stresses and may act as antioxidants (reviewed by Mierziak et al., 2014). Toxic effects have been shown in rodents with increasing doses of aqueous tansy extract, although chronic administration did not cause any significant effects (Lahlou et al., 2008). The toxic effects are potentially due to alkaloids and terpenes like thujone and sesquiterpene lactones (Lahlou et al., 2008; Rosselli et al., 2012), although other compounds may also be involved (Räisänen et al., 2020). The same molecules protecting the plants against various pest attacks may be used for dyes when extracted from plant tissues. The occurrence of secondary compounds has inspired scientists for decades, and more understanding about the mechanisms essential for optimising production with agrotechnological practices is needed.

Underutilised harvest residues

After harvesting seeds or tubers for food and feed, significant amounts of plant residues in soil are underutilised. Estimations have been made of the potential of biomasses for energy production (Hakala et al., 2009; Scarlat et al., 2019), and the same biomasses may also be utilised for dye production, at least to some extent (Phan et al., 2021), (Jameel et al., 2023) when regulatory aspects have been taken into account (Benucci et al., 2022). However, only part of the residues may be harvested from the field, and the terms 'theoretical', 'technical', and 'sustainable' residues have therefore been employed to explain this. Technically, the lower part of the stem, the stub, is left in the field, and about 70–75% of the theoretical maximum residue is therefore actually obtained (Hakala et al., 2009). In sustainable terms, soil fertility and organic matter content is also considered in this way, as the technical harvested residue is less than the maximum theoretical residue (Scarlat et al., 2019). Besides the residues left in the soil, significant amounts of raw materials are lost or spoiled during food processing and consumption (Bedoic et al., 2019). With better logistic planning, the amount of these biomasses could be reduced or used more efficiently (Table 1).

It was estimated that the potential to produce different natural dye classes from agricultural and food processing waste from fruit or vegetables was 56 kg t^{-1} DW for anthocyanins, 18 kg t^{-1} DW for quinones, and 593 kg t^{-1} DW for carotenoids (Phan et al., 2021). Plant residues are also left when dye crops are cultivated for dyes, as the dye content of the dry material is only a few per cents or less of the dry weight (Gaspar et al., 2009, Sales et al., 2006, Zamani et al., 2014). This means that more than 90% of the dry mass of the dye crops are left as residues, the amounts being 2,000–4,000 kg DW ha^{-1} for weld (Hartl & Vogl, 2003) and about 2,500–11,000 kg DW ha^{-1} for woad (Sales et al., 2006). Attempts are needed to develop dye extraction from various plant resources. For example, technologies in which dual-purpose plant material may be harvested and sorted already in the field may be one solution. Examples of biorefinery concepts are already available (Jin et al., 2018). For example, decentralised microwave-assisted pyrolysis (MAP) to produce biochar, bio-oil, and bio-gas could help small-scale plants among farms produce these value-added products (Fodah et al., 2022). Similar innovations are also welcome in dye production to improve the implementation of circularity and give opportunities to farmers to earn value-added from crops and harvest residues.

Table 1. Examples of underutilised crop residue dry weights (total Mt DW y^{-1}), which are left in the field after seeds or tubers have been harvested for food or feed, or which are formed during processing and consumption and could be used as raw materials for various purposes. Comparisons are made to demonstrate the waste amount per inhabitant (kg/inhabitant y^{-1}) in the EU, Europe, and globally, the population being 447.7 million (European Union 2023), 748.9 million, and 8.026 billion respectively (Worldometer, 2023).

Residues or waste

Area	Total Mt (DW) y^{-1}	Per inhabitant, kg y^{-1}	Description	Crops included	References
Europe	212	283	Residues, which can be technically harvested from the field.	Wheat, rye, barley, oats, maize, rice, rapeseed, sunflower	Scarlat et al., 2019
Europe	149	199	Residues sustainable for harvesting from the field	Wheat, rye, barley, oats, maize, rice, rapeseed, sunflower	Scarlat et al., 2019
EU28	566	1,264	AWCB*	Cereals: barley, maize, triticale, oats, rice, rye, and wheat	Bedoić et al., 2019
EU28	1,131	2,526	AWCB*	Vegetables: tomatoes, cabbages, cauliflowers, broccoli, onions, carrots, potatoes, sunflower seeds, rapeseed, sugar beet, and olives	Bedoić et al., 2019
EU28	51	115	AWCB*	Fruit: apples, grapes, oranges, peaches, and tangerines	Bedoić et al., 2019
World	4,840–5,135	603–640	Residues that can be technically harvested from the field	Cereals, oil crops, pulses, sugar crops, root crops	Hakala et al., 2009

*AWCB, Agricultural waste, co-, and by-products formed during harvesting, processing, or consumption

Plant species and crops cultivated for dye production

Dye crops for harsh conditions

In agriculture, a significant transition to non-chemical input cropping system is occurring, with a reduction of the use of synthetic pesticides by 50% by 2030 (European Commission, 2022). When new crops are introduced to cultivation, one of the prerequisites should be good competition against various stresses and suitability for integrated cropping systems.

Semi-natural plant species were tested in field conditions at Natural Resources Institute Finland, Jokioinen (60°48’15”N, 023°29’10”E) as part of the BioColour project. The aim is to find wild plants which could be transferred to field cultivation with minimal input. The prerequisites are that the crop is abundantly growing and have good competition against weeds, and the yield can be mechanically harvested.

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The experience from currently ongoing experiments is that the growth and development of perennial crops takes significantly longer than in annual or biennial crops, and the field is susceptible to both annual and perennial weeds. The intercropping of a perennial dye crop with annual legumes was therefore chosen to avoid weed infestation during the plants’ slow growth periods. Preliminary results have been obtained from tansy (*Tanacetum vulgare*), which produces abundant vegetation during the second year of its establishment, and the fresh biomass can be mechanically harvested. Tansy flowers and leaves can typically be used to produce yellow to greenish-yellow colours. The flowers and stems contain flavonoids like luteolin and quercetin (Ak et al., 2021) and carotenoids like violaxanthine (Horváth et al., 2007), which are involved in the dyeing process.

Stinging nettle (*Urtica dioica*) is a common perennial herbaceous plant which grows wild in nutritious soil, and it was one of the tested crops. The

1 Tansy (*Tanacetum vulgare*) grows abundantly and competes well with weeds.

Photo Ville Toivonen, Natural Resources Institute Finland

2 Stinging nettle (*Urtica dioica*) is a multipurpose crop that also yields greenish shades.

Photo Johanna Leppälä, Natural Resources Institute Finland

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entire nettle plant can be used to produce greyish-green colours. As pigments, the nettle leaves contain flavonoids like quercetin, isorhamnetin, and kaempferol, as well as carotenoids like lutein, β-carotene, lycopene, neoxanthin, and violaxanthin (Grauso et al., 2020; Guil-Guerrero et al., 2003). Nettle is also used for fibre, medicine, and food because of its healthy nutritional value. Its phytochemical composition has been well studied. A high phenolic content, alkaloids, terpenoids, and flavonoids may explain the antibacterial and antioxidant properties of nettle (Ghaima et al., 2013; Grauso et al., 2020).

Nitrogen requirements of dye crops

Synthetic nitrogen fertilisers are manufactured using the Haber–Bosch process, which uses a lot of energy to produce extremely high pressure to force nitrogen from the air to combine with hydrogen from natural gas to produce ammonia (Brentrup & Pallière, 2008). The production and end use of ammonium as fertilisers are among the major sources of N_2O emissions contributing to the overall GHG accumulation (Meyer-Aurich et al., 2020). The energy used in agriculture also increases the emission load (Streimikis et al., 2021) and

may thus prevent the goals of the commercialisation of sustainable botanicals for dye production.

Relatively little information is available about the fertilisation and optimal requirements of various dye crops. Madder (*Rubia tinctorum*), which belongs to the Rubiacea family, characterised by weak stems and abundant root systems, is the source of reddish dyes, anthraquinones. Both nitrogen and phosphorous fertilisation were important at the level of 50–150 kg/ha to the root growth of madder in salinity stressed conditions, but interaction between different nutrients was also observed (Zamani et al., 2014).

Reseda luteola L. (weld), which belongs to Resedaceae, is a biennial plant that especially yields yellow dyestuff in its flowers, consisting mainly of flavonoids, luteolin, and apigenin, along with their glycosides. The effect of high- and low-fertility soil as a growing habitat for seven different seed accessions was compared. Soil fertility and genetic differences caused variation in the growth of weld and dye stuff formation. In

3 Woad (*Isatis tinctoria*) was intercropped with faba bean (*Vicia faba*) to avoid weed infestation and to improve the soil nitrogen status in the experimental field of Natural Resources Institute Finland.
Photo Niina Niinimäki

highly fertile soils, the dye content including luteolin and apigenin content was about four times higher than in plants grown in less fertile soil (Gaspar et al., 2009).

The species *Indigofera, Polygonum*, and *Isatis* belong to the Fabaceae, Polygonaceae, and Brassicaceae families, respectively. They are the most studied crops for the production of natural blue indigo dye. Various production inputs were researched, and their effect on the indigo formation of *Isatis tinctoria* (woad) and *I. indigotica* was compared. The increase of nitrogen fertilisation from 0 to 200 kg/ha doubled the indigo yield of *I. tinctoria* from 11.4 kg ha^{-1} and 22.5 kg ha^{-1} up to 19.4 kg ha^{-1} and 40.4 kg^{-1}, depending on the year (2003 and 2002 respectively). The yield of *I. indigotica* was about half that obtained from *I. tinctoria* and was therefore a less effective source of the dye (Sales et al., 2006). Dyer's woad and other cruciferous plant tissues also contain other secondary metabolites, or glucosinolates, which are often related to plant defence. When plant tissues are damaged e.g. by aphid feeding, glucosinolates degrade into sulphur-containing volatile molecules that repel pests. They give brassica crops their recognisable taste and odour.

The transfer from synthetic-based dyes to plant-origin dyes also requires critical consideration. Although there are enthusiastic and devoted people working with natural dyes, methods and technologies need to be re-evaluated. As has been mentioned, the dye crops providing blue, red, and yellow shades usually produce higher amounts of dry biomasses, and the dye yield is higher when nutrients such as nitrogen are available in the soil or supplied as fertilisers. Nevertheless, the current intensive use of synthetic fertilisation in dye crop production should be replaced by other options. We must be aware that using botanicals is not always 'better'. For example, if the crop species or material choices are not carefully considered, or cultivation and postharvest technologies are not optimised, the desired effects on the environment may not be achieved (Meyer-Aurich et al., 2020; Phan et al., 2021). Legumes are one of the most important solutions because they grow symbiotically with nitrogen-fixing bacteria, resulting in a lower need of applied nitrogen fertilisation. Using legumes as a source for dyes (Gerometta et al., 2020) or integrating legumes into crop rotations or intercropping systems are the most important practical possibilities for reducing nutrient runoff and GHG emissions (Lötjönen & Ollikainen, 2017).

Aboveground biodiversity and cultivation of dye crops

Genetic diversity among dye crops

Modern agriculture extensively utilises developed plant varieties that yield plants of uniform quality. Cultivated plant varieties are often self-pollinating (e.g. wheat, barley, oats) which makes it easy to create plant varieties representing a single genotype. In cross-pollinated species like grasses, uniform varieties are gained by breeding e.g. an open-pollinated random-mating population and selecting seeds from the phenotypically best individuals over several years. This will yield a similar result to self-pollinating plant varieties: there is great genetic variation between varieties, but very little to no genetic difference within a variety. For example, uniformity is useful for seed traits: similarly sized and at the same time ripening seeds are easier to harvest and produce a high-quality crop. Dye plants increase genetic diversity, as they typically have not been bred into varieties, or selection has been done for only a very short time (Hartl & Vogl, 2003). Dye plants are therefore typically genetically much more diverse than modern agricultural plant varieties (Keskitalo et al., 1998).

Variability in the morphology and phytochemical characteristics of dye plants is not always desirable, as dyers prefer plants with high yield and dyestuff content. There is therefore increasing demand to improve crops or breed more uniform dye plants. Also, increasing dye plant cultivation among fields that are currently used for conventional farming will already increase diversity among cultivated plants, which can feed positively into the overall diversity of the agricultural landscape.

Landscape diversity and dye crops

Increasing dye plant cultivation can increase diversity, not only by having genetically more diverse plant species in the fields, but also by increasing interspecies diversity, or heterogeneity, in an area, which in turn may increase overall biodiversity. An extensive meta-analysis (more than 150 peer-reviewed articles) has shown that increasing landscape complexity significantly and positively affects non-domestic terrestrial biodiversity (Estrada-Carmona et al., 2022). Increasing the number of cultivated plant species and their genetic diversity not only increases overall biodiversity but may also increase ecosystem resilience and stability (Feit et al., 2021; Gámez-Virués et al., 2015), which in turn may help maintain agricultural production in varying environmental conditions like droughts. As agricultural land is the Earth's largest human-managed ecosystem, increasing diversity in agricultural land should be an urgent goal of management in slowing biodiversity loss.

Maintenance or increase in landscape-scale heterogeneity can be supported through farming practices. Introducing dye plants to crop rotation, intercropping them with another crop plant, establishing them as border plantings around fields, or establishing mosaics of crop types across multiple fields contributes positively to landscape heterogeneity. Compared to conventional farming, besides resilience, the diversification of agricultural landscape may enhance weed and disease control, pollination services, soil quality, and carbon sequestration (Kremen & Miles, 2012; Rosa-Schleich et al., 2019).


Nettle leaf

Dye crops attract pollinators

As several dye plants (e.g. *Tanacetum, Galium, Helianthus*) are insect-pollinated, they can bring diversity to the agricultural landscape. There is evidence of flavonoids acting both as attractants and deterrents for insects and playing a role in the formation of mycorrhiza and symbiotic relations with bacteria (Mierziak et al., 2014). Besides causing yellow-orange to red colours in flowers and fruit, carotenoids are important in the photosynthetic tissues of plants in enhancing light harvesting and the photoprotection of chloroplasts, as well as in stress signalling (Havaux, 2014; Sierra et al., 2022).

Dye plants and other insect-pollinated plants can provide pollen and nectar, but also a refuge for beneficial insects that can act either as pollinators or in pest control. Some dye plants like nettle can be important hosts for dozens of insect species (Davis, 1973), or dye plants can be used as companion plants to repel pests (e.g. tansy) due to their chemical composition (Bostanian et al., 2004; Landolt et al., 1999). It has been shown that introducing areas of flowering herbaceous plants (e.g. 'flower strips') around agricultural field edges enhances natural pest control services (Albrecht et al., 2020). Pest control services were unrelated to the species richness of the flower strips (Albrecht et al., 2020), which indicates that even a single species flower strip from a dye plant could improve the natural pest control

of nearby crop species. Promoting crop diversity in combination with the preservation of semi-natural habitats has been shown to positively affect the potential natural enemies of pests (carabids) and pollinators (Aguilera et al., 2020).

Belowground biodiversity and dye crops

Most species of microscopic organisms remain unknown, but their numbers are astronomical, and their functions are undeniable in the soil. Bacteria and fungi also mineralise organic matter for plant nutrition, and they produce and transform various compounds that are harmful or beneficial to plants. Plants form intimate relationships with many growth-promoting microbes, the most studied of which are symbiotic mycorrhiza fungi and nitrogen-fixing bacteria.

4 Golden rod (*Solidago virgaurea*) flowerheads attract bumblebees (*Bombus* sp.) and other insects.
Photo Ville Toivonen, Natural Resources Institute Finland

Indigo-yielding woad interacts by root exudates

Dyer's woad establishes a two-layered rooting pattern, with lateral roots in the upper soil and a deep taproot. Cruciferous plants do not generally form symbiotic mycorrhizas. However, the mycorrhiza has been observed to form normally in compatible host crops despite the presence of cruciferous plant roots nearby (Glenn et al., 1988; Vestberg et al., 2012). With this in mind, woad has been successfully grown as a nitrate-scavenging catch crop in rows between leek (*Allium porrum*) (Xie & Kristensen, 2017). The observations indicate that rather than repelling them, cruciferous plants lack the signal molecules necessary for communicating with mycorrhiza-forming fungi (Cosme et al., 2018). Fungi can survive without their hosts as spores or propagules in soil. Even if two years of cropping woad can result in lower levels of fungal propagule numbers in soil than in the cultivation of mycorrhizal plants (Vestberg et al., 2012), introducing woad in rotation is still unlikely to be too harmful to fungi, which are beneficial for many other crops.

The soil adhering to and between roots is in the rootzone. Root exudates of woad influenced soil bacteria populations in test conditions (Fritz & Schneider, 2015). Biosynthesis of glucosinolates in cruciferous plants roots is often constant, and their degradation products are released from the root tips as they grow through the soil matrix (van Dam et al., 2009). Some of these compounds may be inhibitors of ammonium oxidation and may reduce the number of bacteria involved (Bending & Lincoln, 2000). This is an important management application in agricultural soils, which are often sources of dinitrogen oxide (N_2O). It is a potent greenhouse gas that evolves from the microbial processing of nitrogen fertilisers. Woad can release up to 4 µg of indole glucosinolates per g^{-1} (fresh weight) root over six weeks (Elliott & Stowe, 1971). The ecological importance of this may be that crucifer species may be selected based on their glucosinolate profiles, and they could be used as tools for managing the mineralisation of nitrogen from crop residues, and thus improve synchrony with the needs of subsequent crops (Bending & Lincoln, 2000).

Bacteria are naturally associated with the harvested leaves of woad. Thus, bacteria within the dye vat enter with the plant material, and many, e.g. *Clostridium isatidis*, may ultimately originate from the soil (Hartl et al., 2015; Milanović et al., 2017). The functionality of

the traditional vat relies on the enrichment of indigo-reducing bacteria in carefully controlled hot, anoxic, alkalic conditions (Aino et al., 2018). Its maintenance requires craftsmanship.

Stinging nettle has multifunctional roots

Nettle (*Urtica dioica*) establishes rhizomatous growth and forms dense stands. Nettle cultivation efficiently removes nutrients from the soil, and it can grow on soil contaminated by heavy metals (Hakala et al., 2009; Khan & Joergensen, 2006). Leaves are rich in minerals, and when falling return a significant amount of nutrients to the soil (Di Virgilio et al., 2015). Nettles also contain a considerable number of biologically active compounds in the roots (Kregiel et al., 2018), which may be a source of future agrochemicals (Maričić et al., 2022., Vierheilig et al., 1996). Nettle rhizospheres, stems, and leaves host bacteria, some of which produce antifungal compounds (Mojicevic et al., 2019; Toubal et al., 2018).

5 Dried roots of wood (*Isatis tinctoria*). Their strong root system improves the soil structure.

Photo Aino Lahti,
Natural Resources Institute Finland

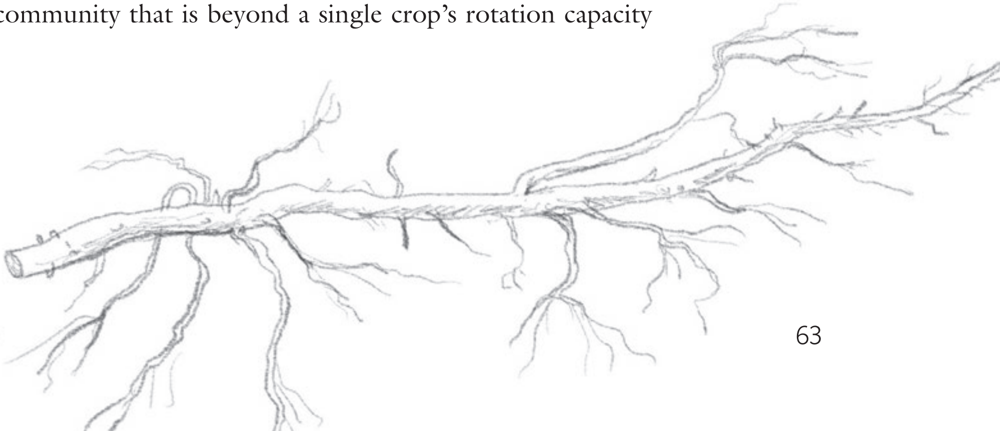
Tansy and lady's bedstraw rhizospheres are colonised by fungi

Tansy (*Tanacetum vulgare*) roots are colonised by beneficial arbuscular mycorrhiza (AM) fungi and by dark-septate-endophytic fungi, whose role in plant performance still remains something of a mystery (Řezáčová et al., 2021; Schittko & Wurst, 2014). Tansy can accumulate large amounts of metal elements through its root system. The response to various environmental stress conditions (drought, a high temperature, intense radiation, contamination) is shown in the qualitative and quantitative content of tansy essential oils (Nikolić & Stević, 2015). Nevertheless, an air pollutant, ozone, had no marked effect on the structural diversity of the bacterial community in the tansy rhizosphere, even if foliar injuries were detected after elevated ozone episodes (Dohrmann & Tebbe, 2005).

Yellow bedstraw or lady's bedstraw (*Galium verum*) is a perennial herb with rhizomatous growth. It has a stout, deep-reaching, and branched root that yields a red colour. Yellow bedstraw prompts scientific interest because of its many phytochemicals and their potential pharmacological applications. Yellow bedstraw grows well on sandy dry meadows, presumably because it may form both AM and ectomycorrhizal interactions (Bernhardt-Römermann et al., 2009).

Dye plants may affect soil microbes in cropping systems

Agricultural soil is among the environments most controlled by people. Modern agricultural systems often have very simple plant communities, one or two crops in rotation, without interspecies interaction. Root morphology, mucilage, and exudates shape communities of microbes, which are more abundant around roots than in bare soil (Berg & Smalla, 2009). Intercropping may promote a microbial community that is beyond a single crop's rotation capacity



Nettle root

(Garland et al., 2021). In crop rotation, seedlings inherit soil traits and microbial communities from previous crops, but seedlings soon start to influence their own rhizosphere (Benitez et al., 2021; Lapsansky et al., 2016; Yang et al., 2020). Yet increasing plant species in crop rotations may increase the quantity and chemical diversity of residues that can sustain the functional redundancy of microbial communities in soil (Tiemann et al., 2015). Functional redundancy means that the community can perform a certain function even if its composition changes. Conventional farming can benefit from multispecies crop rotations with potentially beneficial microbes, especially within low-input cropping systems which use organic fertilisers (Kahiluoto et al., 2009).

Plant species differ in the quantity and chemical composition of their root exudates and harvest residues. Plant material accumulations vary between annual and perennial crop fields. The annual plant input to root-associated microorganisms is greatest at the flowering stage (Houlden et al., 2008), but perennials provide continuous deposits of litter, and their root system develops over a longer period than annual plants. As roots age, they leave physical bio-pores in the soil (Young & Bengough, 2018). Answering questions about how microbial community diversity is related to important soil functions, and how can we control them to the benefit of plant production, requires an understanding of the rhizosphere as a dynamic habitat (Young & Bengough, 2018).

Conclusions

Royal Botanic Gardens, Kew assesses that there are more than 350,000 plant species on Earth. We utilise only a fraction of plant characteristics' potential in agricultural systems. Wild plants should not be collected from nature for industry that needs a lot of material.

The transition to more sustainable natural dye production starts with plant production, although a natural origin does not always guarantee that the product is environmentally friendly. Many wild and semi-wild species can also be transferred to field cultivation, which, however, requires new management practices for, for example, weed control. Collecting wild colour plant seeds from different areas and propagating the plants in nurseries can be one option to start cultivating colour plants. Especially during harvesting and processing, a large amount of agricultural waste, co-, and by-products are formed, which could be used as dyes.

Dye plants may contribute various ecosystem services. Chemical fertilisation reduction by natural nitrogen-fixation for cultivation, carbon sequestration of perennial plants, and utilisation and recycling of residues are possible in dye plant production. Increasing dye plant species cultivation can increase rural landscape heterogeneity, which in turn sustains pollinators and other insects and the entire food web, which depends on them. Although we know that plant species diversity supports belowground biodiversity, the present studies cannot yet explicitly present any specific crop combinations that enhance soil microbial diversity (Venter et al., 2016). The colour plants presented here grow large root systems that communicate with soil fungal and bacterial communities, which in turn have yet to be fully explored. Wild colour plants are adapted to many kinds of environments and conditions. Some, like tansy and yellow bedstraw, can be low-maintenance crops on marginal lands. Tansy and nettle survive even on polluted soils. Others, like nettle and woad, can remove nutrients from eutrophic soils.

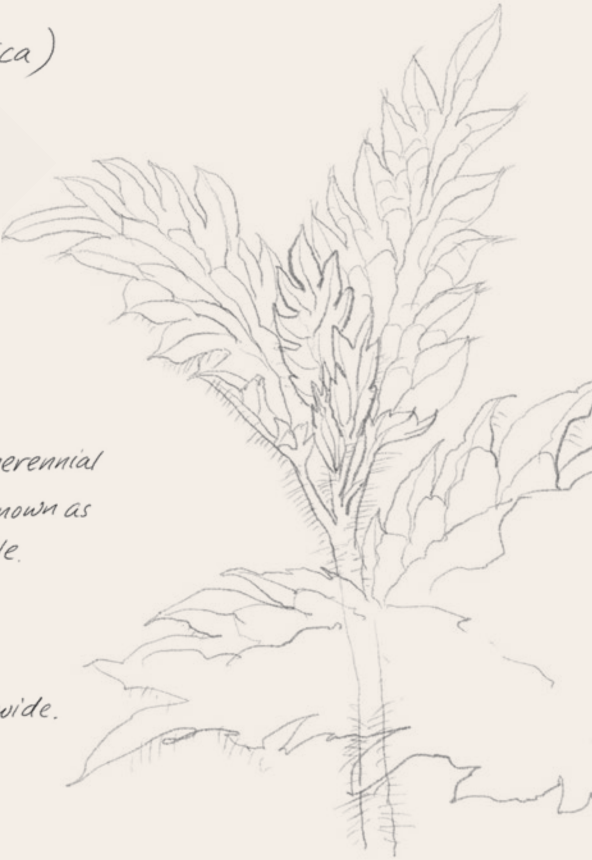
Important step on the plant-derived dye production is to develop on-farm extraction methods, which improve circularity and farmers' integration to the value chain and increase farmers' share of revenues. It is time now to make dye production genuinely sustainable and not to repeat the failures concerning environment aspects made in food or feed production systems.

Wild, semi-cultivated dye crops may have a big role when attempting to increase biodiversity of farming areas. Slopes and marginal areas have been proposed for e.g. nettle cultivation in Europe, and forest-field margins may be suitable for the cultivation of many 'marginal' dye yielding wild crops in Finland. To improve biodiversity may need alterations for management practices, selection of crops, and, also left aside fields. To include suitable perennial and semi-cultivated species into extensive cultivation may be one option. Combining the biodiversity cultivation and on-farm processing for novel dye stuff production could provide farmers biodiversity-friendly business model.

Photos Julia Lohmann

Stinging nettle

(Urtica dioica)



The stinging nettle is an herbaceous perennial plant of the Urticaceae family, also known as common nettle, burn or stinging nettle.

Spreading from its native European, temperate Asian and North African habitats, it can now be found worldwide.

The plants can grow from just under one meter to two meters tall. Nettle stems and leaves have hollow stinging hairs called trichomes that inject histamines resulting in a stinging sensation.

Traditionally, nettles have been used as medicinal plants. They can be used to prepare teas, soups, pesto and other foods. Nettles are a source of fibre in textile production.

Their roots produce a yellow dyestuff and their leaves yellowish green colours.

Nettle root

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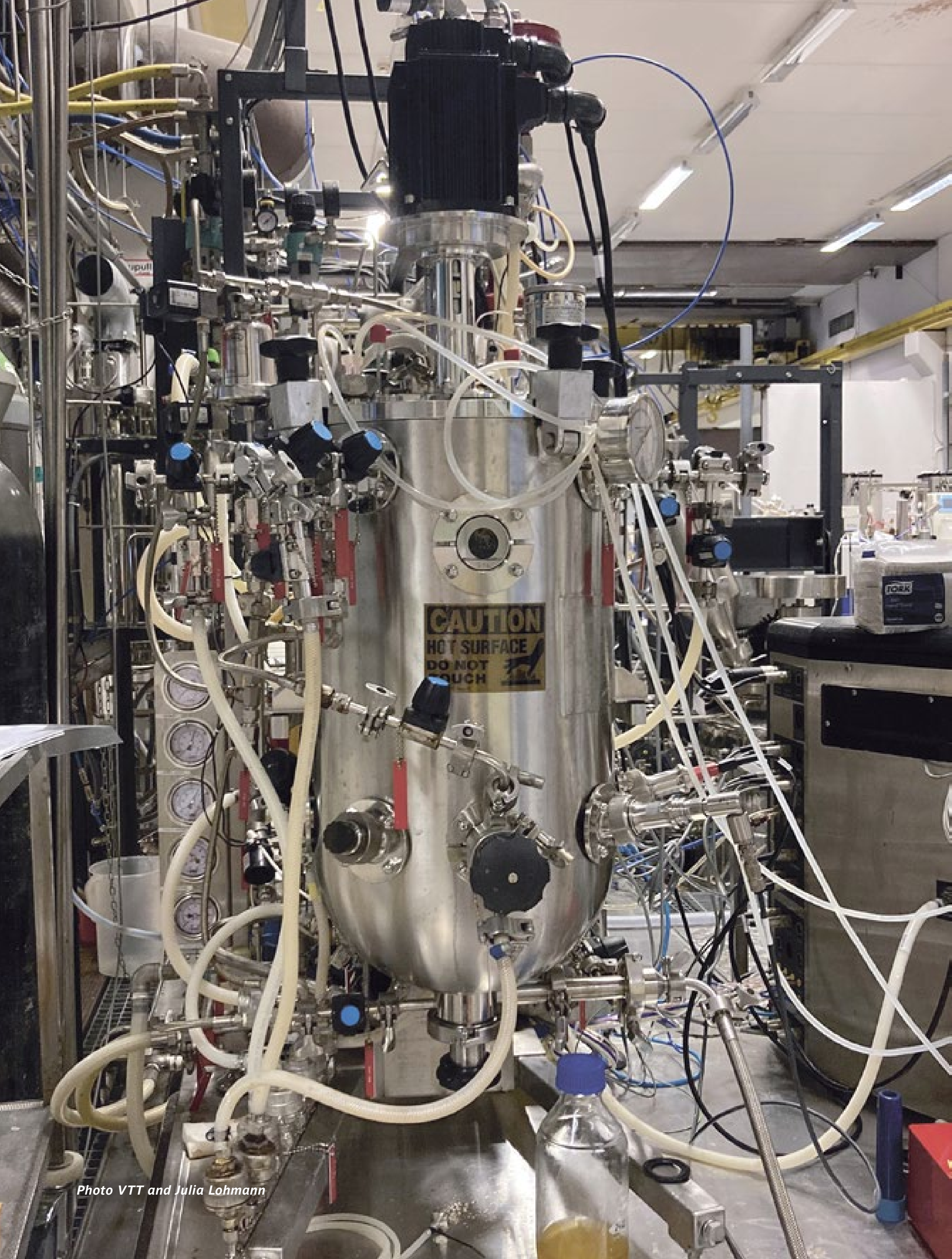


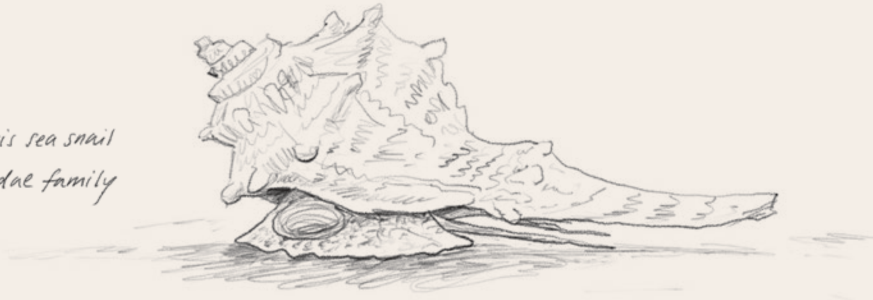
Photo VTT and Julia Lohmann

Tyrian purple
— from sea to bioreactor

Tyrian purple is a pigment of privilege, prized more highly than gold, that dyed the robes of royalty, religious and political leaders. Laboriously sourced from sea snails of the Muricidae family, it took thousands of them to make one gram of pigment, thereby endangering the species.

E. coli bacteria

Today, scientists are teaching E. coli bacteria in bioreactors how to generate Tyrian purple, promising a democratization of the pigment and a reprieve for sea snails.



Bolinus brandaris sea snail from the Muricidae family

Mervi Toivari, Satu Hilditch, Géza Szilvay,
Manuel Arias Barrantes, István Molnár, Merja Penttilä

Synthetic biology and biocolours

ABSTRACT

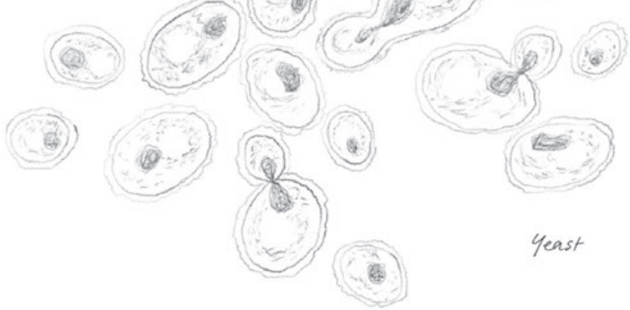
Synthetic biology is accelerating genetic engineering of microbes to produce desired compounds. Currently, there is lot of interest in using synthetic biology for microbial colourant production from basic science to start-up companies. Because of their contained and year-around cultivation, microbes provide a promising system for future colour production. Synthetic biology has already been used to engineer various microbes for the production of colourants. Here, the potential and possibilities of synthetic biology are highlighted with examples such as Tyrian purple, the "royal violet"; the *Monascus* pigments used for food colouring; and the combination of the production of various materials and colourants in the same microbe. We also discuss synthetic biology and colourants in the context of art and design, and provide a future outlook for the field.

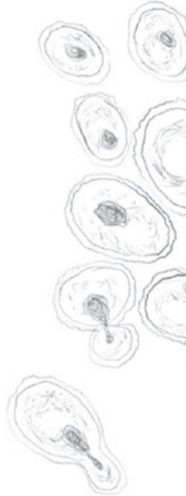
Key words
synthetic biology, microbe, (bio)colour, metabolic engineering, genetic engineering

Pure Tyrian purple extract which consists of a blend from *Stramonita haemastoma* and *Hexaplex trunculus* secretions from Carthage, Tunisia.

Photo Mohamed Ghassen Nouira and Hanen Souhail

Photo VTT and Riikka Räisänen





Introduction

Natural pigments and dyes have been extracted from plants, mushrooms, insects, and mollusks for millenia, and used in traditional dyeing of yarns and fabrics, food colouring, or staining of wooden structures such as in spalting. Biotechnology uses cells and enzymes as catalysts to produce desired products from renewable raw materials. Synthetic biology, the engineering of living organisms by applying engineering principles, is now revolutionizing biotechnology. Large genome datasets, cheap DNA synthesis and sequencing, understanding of biochemical reactions and enzymes as their catalysts, computational modelling of metabolism, automation, and use of artificial intelligence (AI) enable the faster design and building of new cell factories e.g., for production of biobased colourant molecules.

Natural colourants are biobased, and biodegradable. In addition to their colouristic properties, they may have antimicrobial or antiviral activities against different pathogens, anticancer activity, antioxidative activity, or UV protection properties. On the other hand, many of the natural dyes have limited use due to their low stability, and insufficient fastness in textile applications. Plants cultivated for natural dye extraction are available only seasonally, occupy farmland, and compete with food-producing agriculture for water, fertilizers, and other resources. The extracted colourants are often mixtures of many compounds, and it is challenging to standardize or scale their production.

Colours are also produced by microscopic organisms (microbes). Bacteria, fungi, and algae are able to produce a wide range of pigments from yellow carotenoids to dark melanins. These colourants have enormous chemical diversity and can be classified by their chemical structures e.g., as carotenoids/isoprenoid derivatives, flavins/benzopyran derivatives, melanins, quinones, tetrapyrrole derivatives/chlorophylls, and other N-heterocyclic compounds (J. Grewal et al., 2022; Kalra et al., 2020; Orlandi et al., 2022). Microbes can be grown in closed containers in standardized conditions, in large volumes year-round. The processes operate in mild conditions, in ambient temperature and pressure. In addition, microbes can utilize various industrial side streams, such as food processing residues, as raw materials and thus contribute to the circular economy. However, as with plants the colour-producing microbes usually yield a mixture of compounds, and the productivity may be low. In addition, harmful compounds, such as mycotoxins can also be formed as side products.

Synthetic biology can solve these challenges by introducing the colourant biosynthetic pathways to safe, well-known, "domesticated" microbial hosts that are already in use on the industrial scale. Colourant production can be improved e.g., by increasing the productivity (rate, titer, yield) of the process, improving the purity of the products, or by decreasing side product formation. The natural colour palette can be broadened by engineering the production of new-to-nature compounds e.g., pigments with better stability, or better fastness to fabrics. Colourants can also be produced simultaneously with a material component, ie. the microbe can directly produce coloured material such as coloured polyhydroxyalkanoate bioplastics completely omitting the resource-intensive dyeing step. To harness the full power of synthetic biology, multidisciplinary scientific excellence is needed.

Synthetic biology for engineering colourant production in microbes

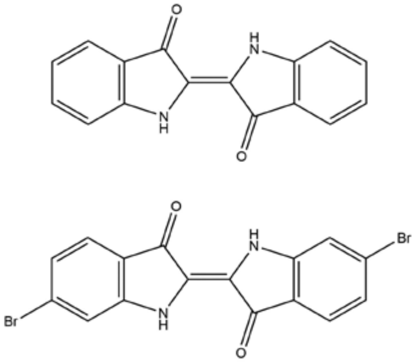
Synthetic biology builds on the metabolic engineering discipline, which is defined as "the improvement of cellular activities by manipulation of enzymatic, transport, and regulatory functions of the cell with the use of recombinant DNA technology" (Bailey, 1991). The pigment biosynthetic pathways may have as many as 10-20 enzymatic steps for the conversion of common, relatively simple metabolic intermediates to the final colour compound with a complex structure, all performed in one unit, the cell. In synthetic biology, functional biosynthetic pathways are routinely built by combinatorial pathway engineering, i.e. by combining the best possible enzymes independent of their sources. Building such a pathway is an iterative process, often referred to as the Design-Build-Test-Learn cycle (DBTL). It starts with designing the production strains and their parts by using computational tools (design); assembling the pathways in the production strains (build); cultivation of the engineered organisms and measurement of product formation (test); and finally, analysis of the data and making decisions for the next round of engineering based on the obtained results (learn). Automated platforms can be used in the build and test phases, and data management and machine learning are increasingly utilized in the design and the data analysis stages.

There are several examples of using synthetic biology to engineer various microbes for the production of colourants. See recent reviews (Ahmed et al., 2021; Jing et al., 2022; Linke et al., 2023; Lyu et al., 2022; Pandey et al., 2016; Sankari et al., 2018; Seo & Jin, 2022; Zha & Koffas, 2017) and Table 1. The potential and possibilities of synthetic biology are highlighted here with three examples. Tyrian purple, the "royal violet" extracted from see snails since ancient times can now be produced in *Escherichia coli* bacteria. This example highlights the capacity of synthetic biology to save natural resources, including animals or plants, by using knowledge on genes and enzymes to transfer the pigment production to microbes. The *Monascus* pigments have been used for thousands of years in East Asia for food colouring. These yellow, orange, and red compounds have an enormous variety of molecular structures, and synthetic biology tools have helped to unravel the biosynthetic pathways and optimize pigment production. Finally, synthetic biology can open totally new production approaches e.g., by combining the production of various materials and colourants in the same microbe. This concept was explored by co-producing spider silk protein and a yellow colourant. These three examples will be discussed in detail below.

Tyrian purple is a reddish-purple natural dye obtained from sea snails (*Muricidae*). This dye was used already 3500 years ago by the Phoenicians and was among the first commercially traded dyes. Due to its distinctive, beautiful shade, and its good stability, this colourant was highly desirable. However, to extract one gram of the dye, 10 000 snails were needed (Mcgovern & Michel, 1990). The laborious snail collection and extraction process led to a very restricted supply, with Tyrian purple fetching three times its weight in gold. Thus, fabrics dyed with this pigment came to symbolize power and wealth, and Tyrian purple was long considered to be a royal colour. More recently, Tyrian purple has been evaluated e.g., in organic phototransistors due to its conductive properties (Kim et al., 2018). The main compound responsible for the colour in Tyrian purple is 6,6′-dibromoindigo. It is similar in structure to the well-known blue natural colour indigo but has bromine substitutions in two positions (Figure 1).

Table 1. Examples of colourants produced by engineered microbes and suggested references. Colour codes are from the Living Color Database (https://color.bio/database), Wikipedia (https://en.wikipedia.org/wiki/), and Encycolorpedia (https://encycolorpedia.com/). The colours of dye solutions depend on the pH.

Compound	Feedstock & organism	References
Indigo (Dark violet, HEX triplet #00416A)	Indigo production has mainly been studied in *E. coli*, with tryptophan or glucose as the raw material. Key enzymes of the pathway include oxygenases. In addition, glucosyltransferases have been used to control the dye forming process.	T. Chen et al., 2021; Fabara & Fraaije, 2020; Hsu et al., 2018; Linke et al., 2023; Ma et al., 2018; Murdock et al., 1993
Indigoidine (Deep blue, HEX triplet not available)	Indigoidine production has been demonstrated in several hosts including *E. coli*, *Pseudomonas putida*, *Corynebacterium glutamicum*, *Saccharomyces cerevisiae*, and *Rhodosporidium toruloides*. L-Glutamine, glucose or glucose and xylose from lignocellulosic hydrolysate have been used as feedstocks.	Banerjee et al., 2020; Wehrs et al., 2018, 2019; Xu et al., 2015
Violacein (Purple, HEX triplet #800080)	Violacein production has been demonstrated in *E. coli*, *C. glutamicum*, *Citrobacter freundii*, *S. cerevisiae* and *Yarrowia lipolytica*, from glucose, glycerol, and tryptophan as feedstocks.	Ahmed et al., 2021; Mitchell et al., 2015; Sun et al., 2016; C. Yang et al., 2011; Zhou et al., 2018
Betanin (Beet red, HEX triplet #7a1f3d)	Betanin production has been demonstrated in *S. cerevisiae* using glucose as a feedstock.	P. S. Grewal et al., 2018; L. Zhang et al., 2023a
Anthocyanins (Pelargonidin 3-O-glucoside – orange, HEX triplet not available; Cyanidin 3-O-glucoside – magenta, HEX triplet not available)	*S. cerevisiae* has been engineered for production of pelargonidin 3-O-glucoside from glucose. *E. coli* was used for pelargonidin 3-O-glucoside and cyanidin 3-O-glucoside production from different precursors.	Levisson et al., 2018; Zha & Koffas, 2017
Carotenoids (β-carotene – orange, HEX triplet #ffa500; Lycopene – red, HEX triplet #ffa500; Astaxanthin – pink-red, HEX triplet #ff9ad2)	β-carotene, lycopene, or astaxanthin have been produced by *E. coli*, *S. cerevisiae*, *Y. lipolytica*, *Komagataella pastoris*, *Kluyveromyces marxianus* using glucose, glycerol, galactose, methanol and other mixed substrates.	Furubayashi et al., 2015; Jing et al., 2022; Park et al., 2018
Carminic acid (Deep red, HEX triplet #960018)	Carminic acid has been produced in *Aspergillus nidulans*, *E. coli*, and *S. cerevisiae* from glucose.	Frandsen et al., 2018; D. Yang et al., 2021; Q. Zhang et al., 2023b



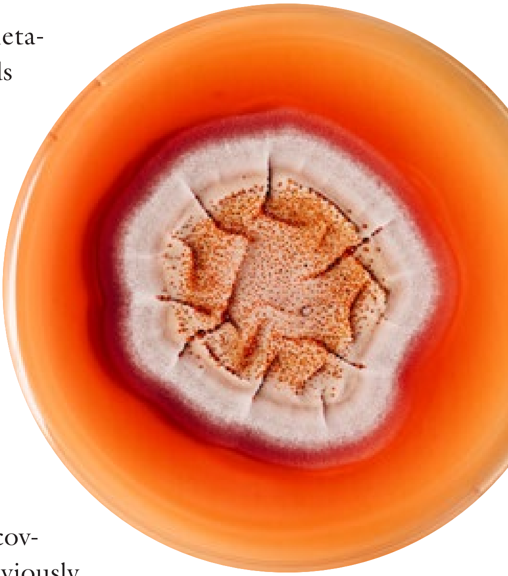
1 Chemical structure of indigo and 6,6'-dibromoindigo.

The natural indigo colour has traditionally been derived from plants (for example, genus *Indigofera* and *Isatis*), but some bacteria also have the capability to produce indigo. In plants, indoxyl is formed from the amino acid tryptophan and converted to more stable indican or isatan B glycosides by glycosylation i.e., attaching a glucose molecule to a hydroxyl group by a glycosyltransferase enzyme. The blue colour is formed when a β-glucosidase enzyme cleaves off the glucose molecule and indoxyl molecules spontaneously dimerize. In bacteria, mainly of genus *Pseudomonas*, tryptophan can be transformed to indole, which is hydroxylated to indoxyl by unspecific enzymes, and indoxyl is again spontaneously dimerized. Enzymes and genes from both bacteria and plants have been discovered, characterized, and transferred to the well-known bacterial production host *E. coli* for indigo production (reviewed in (Linke et al., 2023). An innovative combination of plant and bacterial pathways was used by Hsu et al. (Hsu et al., 2018) where *E. coli* was engineered to produce colourless indican and the β-glucosidase enzyme was used to create the blue colour in the dyeing process. When compared to chemical synthesis from fossil-based raw materials, such synthetic biology approaches offer a possibly more sustainable production route worth considering. Linke et al. (Linke et al., 2023) recently evaluated the feasibility of microbial indigo production, suggesting that although there are still clear needs for development, the approach is attractive also from the business perspective.

The metabolic pathway for the production of 6,6′-dibromoindigo in sea snails is not fully known. Nevertheless, progress in the synthetic biological production of indigo paved the way for a modern age of Tyrian purple, made by microbes. To achieve this, 6,6′-dibromoindigo was produced in *E. coli* from tryptophan (Lee et al., 2021). A flavin-dependent tryptophan halogenase enzyme was used to brominate tryptophan to create 6-bromo-tryptophan, which was further converted to 6-bromo-indole by tryptophanase. This intermediate was converted by a monooxygenase enzyme to 6-bromo-indoxyl, which finally dimerized to 6,6′-dibromoindigo by auto-oxidation. To improve the recycling of the $FADH_2$ cofactor and to increase the solubility of the halogenase enzyme when expressed in *E. coli* a flavin reductase was fused to the halogenase. The conversion of tryptophan to 6,6′-dibromoindigo was performed in a two-strain-system, where one *E. coli* strain produces brominated tryptophan and the other converts it to 6-bromo-indole and finally to 6,6′-dibromoindigo. The final steps, catalyzed by tryptophanase and monooxygenase may also be used to convert halogenated tryptophan or indole precursors to 6,6′-dibromoindigo (Núñez-Navarro et al., 2022; Ullrich et al., 2021).

The synthetic biological production of Tyrian purple opens the way to biosynthesize other, even new-to-nature halogenated indigo derivatives. These may show unique colouristic characteristics for use in dyeing or may display improved properties for semiconductor applications. Further chemical modifications are also possible due to the presence of the halogen moiety.

The yellow, orange and red pigments produced by *Monascus* fungi have a long tradition of use in East Asia, especially in foods such as sausages, or health foods such as red rice. They are considered as healthy food preservatives, but they may also have other properties such as antimicrobial, antiviral, antioxidant and anti-inflammatory activities. The current production volume is about 20,000 ton per year in China alone, and the demand is expected to increase. The *Monascus* pigments belong to the chemical class of azaphilones. Azaphilones are secondary metabolites made via the polyketide biosynthetic pathway. They are also produced by other fungal genera, for example *Talaromyces*, *Penicillium*, and *Aspergillus.* Until June 2018, 111 different azaphilone structures were characterized (Chen et al., 2019), but during the period of January 2020 to March 2021 an amazing number of 100 new compounds were reported (Pimenta et al., 2021). The knowledge on the complex biosynthetic pathways from the central metabolites acetyl-CoA and malonyl-CoA to the various azaphilone compounds have recently expanded through genome sequencing, discovery of gene clusters and characterization of key enzymes such as the multidomain polyketide synthase enzymes. In *Monascus* and *Talaromyces* species the azalophilones are formed through a common trunk pathway leading from acetyl-CoA and malonyl-CoA to the main azaphilone metabolites monascin, ankaflavin, rubropunctatin and monascorubrin. Other pigments are formed by various branch and shunt pathways that channel metabolic "node" compounds of the trunk pathway towards additional azaphilones (Chen et al., 2019). Yet other intermediates may be unstable and are possibly not fully characterized. The enormous diversity of the compounds is created partly by altering the length of the β-keto fatty acyl side chains, spontaneous aldol condensations to generate the tricyclic core, spontaneous *O*-to-*N* substitution of the pyran ring with amines, and modifications by other unspecific cellular enzymes for oxidations and reductions. In this way, a relatively simple compound skeleton can be used to produce a large variety of complex secondary metabolites.


b

New azaphilone compounds are still being discovered e.g., atrorosins from *Talaromyces atroroseus* (previously *Penicillium purpurogenum*) (Isbrandt et al., 2020), and chlorinated azaphilones originating from marine environments (reviewed in Pimenta et al., 2021). Other compounds are still likely to be found through identification of new species and genome sequencing, or by using varied culture conditions (e.g., stress conditions) that can induce the production of novel compounds.

2 **a** Azaphilone colourants produced by *Penicillium purpurogenum* strains VTT D-99740 (liquid culture) or
b VTT D-151592 (growth on agar plate)
c were used for dyeing wool yarn and
d fabric.
Strain VTT D-151592 (= DSM 62866) was originally supplied by DSMZ GmbH.

Yarn and fabric pictures by Monica Louise Gjøderum Hartvigsen

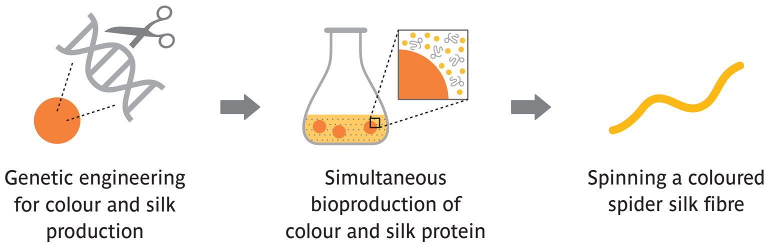
Currently, there are only a relatively few reports on genetic modifications that target azaphilone production. Liu et al. reported improving azaphilone production by 2,3-fold by deleting a gene linked to the cAMP signaling pathway (Liu et al., 2020). In Europe and the United States, the azaphilone colours have not been accepted for food use, due to the potential presence of citrinin, a mycotoxin with hepatotoxic properties, in some *Monascus* azaphilone preparations. However, the genes responsible for mycotoxin production can be removed from the genome, as shown by Ning et al. who deleted the *ctnE* gene from *Monascus aurantiacus* (Ning et al., 2017), abrogating citrinin biosynthesis. In the future, the use of azaphilone dyes for various applications is likely to expand as the pathways, chemical structures and their properties are being elucidated. The use of different side streams as raw materials for azaphilone production is an area of intensive investigations (Srianta et al., 2021) and will further support the sustainability goals of future chemical production.

We examined the azaphilone colourants produced by *Penicillium purpurogenum* or *Talaromyces macrosporus* strains for textile dyeing purposes (Figure 2, (Juuri, 2020)).

Materials and colourants are produced typically in separate processes and combined later in another process, such as dyeing, coating, or compounding. Synthetic biology has the potential to offer streamlining and improved resource efficiency by creating a one-step, one-pot synthesis process where both the material component and the colourant compound are produced by the same microbe in a single bioprocess. Accordingly, the manufactured materials and products would be coloured and therefore a separate dyeing process would not be needed. Considering that textile dyeing is one of the largest consumers of water in the world and produces large amounts of toxic effluents, such combined processes would not only be economically valuable, but may also contribute to a more sustainable industry.

Towards this aim, we studied a concept where a spider silk protein and a yellow pigment could be simultaneously produced by a *Trichoderma reesei* strain. Such an integrated synthetic biological production process was expected to create coloured materials in the form of coloured silk fiber (Figure 3).

The filamentous fungus *Trichoderma reesei* became known when it caused degradation of cotton garments and tents in the Solomon Islands during World War II (Reese, 1976). This fungus can secrete

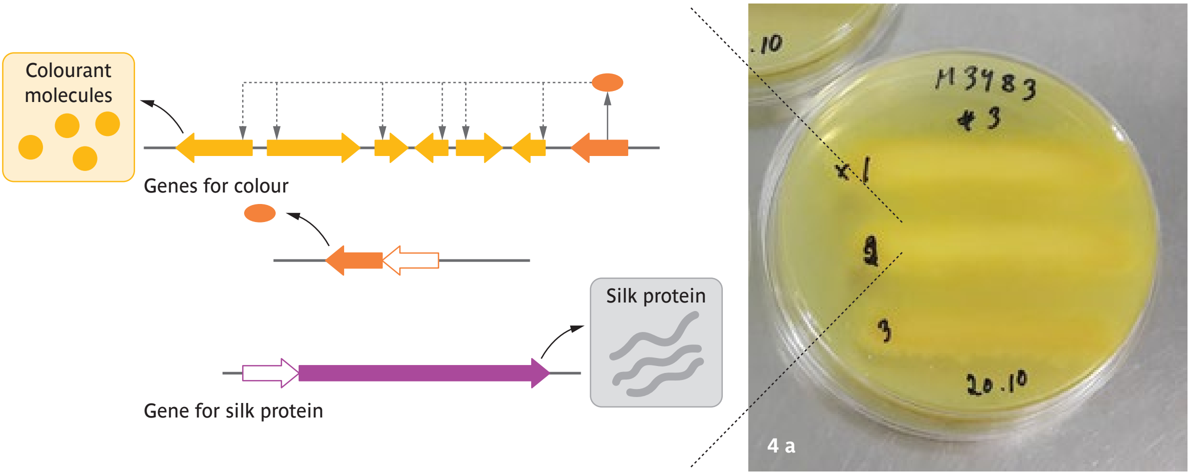


3 Schematic representation of the production of coloured spider silk fiber. Microbial cells are genetically modified for production of colourant and silk protein (left); the strains produce simultaneously silk protein and colourant in closed containers (middle); and coloured silk protein can be extracted and spun to fibers.

large amounts of hydrolytic enzymes such as cellulases and hemicellulases and is now used as an industrial production host for secreted enzymes and proteins. VTT, the Technical Research Centre of Finland Ltd, has a long history of studying *T. reesei* as a production organism of industrial enzymes, human antibodies, and food proteins (Aro et al., 2023; Landowski et al., 2015; Penttilä et al., 1987). Recently, a *T. reesei* strain optimized for industrial protein production was engineered by VTT researchers to produce fusion proteins that are based on the European garden spider (*Araneus diadematus*) silk protein gene ADF3 (unpublished). Such microbially produced eADF3 silk protein fusion proteins had been previously spun into fibers, alone or admixed with cellulose (Heidebrecht et al., 2015; Mohammadi et al., 2019).

In certain growth conditions *T. reesei* strains may also produce a yellow colour, which is an unwanted feature in industrial protein production (Derntl et al., 2016). The yellow pigment consists of various sorbicillinoids, a family of polyketide metabolites with more than 150 known members, each featuring a characteristic sorbyl side chain. In *T. reesei*, the production sorbicillinoids is encoded by a gene cluster that contains genes for two polyketide synthases, a FAD-dependent monooxygenase, a transporter, two transcription factors and a dehydrogenase. It is known that the transcription factor *ypr1* activates all the pathway genes, and that its overexpression results in the production of yellow colour (Derntl et al., 2016; Zhang et al., 2020).

As a starting point, we utilized the *T. reesei* strain that had been previously engineered to produce the eADF3 fusion protein, and overexpressed the *ypr1* transcription factor in this fungus (Figure 4a and b). This enabled the engineered strain to co-produce increased amounts of sorbicillinoids together with the silk fusion protein. The ratio of silk protein



and pigment production varied depending on the level of *ypr1* expression, with some strains producing moderate amounts of yellow colour, but more silk protein, whereas other strains produced more yellow colour, but less silk protein. Co-purification of the silk protein with the sorbicillinoids was also successful via precipitation, but further optimization and upscaling will be required for detailed testing of the products under application conditions. In the meantime, we modelled the spinning of coloured fibers by mixing separately purified silk fusion protein and yellow sorbicillinoid extracts, both obtained from *T. reesei* fermentations. We used hexafluoroisopropanol as the solvent to form the spinning dope, and wet-spun the dope with a syringe pump and an ethanol coagulation bath to obtain silk protein fibers (Figure 5). The resulting fibers were yellow, had a diameter of about 450 µm and were insoluble in water. We were thus able to demonstrate the concept on a laboratory scale, but further studies are needed to improve fiber strength, to optimize the process, and to understand the colour fastness properties of the product.

Co-production of a material and a colourant illustrates the innovation potential of synthetic biology, where current production methods can be reimagined in previously impossible ways. Conceptually similar to our work, a blue polyhydroxyalkanoate (PHA) biopolymer has been obtained by co-production of PHA and indigo in an engineered *E. coli* strain that was supplied with indole as the colourant

4 **a** Schematic representation of the activation of the sorbicillinoid biosynthetic gene cluster by over-expression of the *ypr1* transcription factor, and expression of a gene encoding the spider silk protein.
b Yellow colour produced by engineered *T. reesei* strain.

5 Production of yellow silk protein fiber. The fiber was wet-spun from a spinning dope containing synthetic spider silk protein and yellow sorbicillinoid as the colourant, both produced by *T. reesei*. For this experiment we used separately purified components.

starting material (Jung et al., 2020). Similarly, production of fungal biomass-based materials could be combined with colour production. Thus, different Gram-positive bacteria, mainly *Bacillus* species, were screened for their ability to convert tyrosine to melanin, a dark brown/black pigment. The best performing bacterial strain was then cultured together with mycelium-forming fungi from *Ganoderma* spp. to produce dark coloured fungal material (Meng et al., 2021). Some bacterial species can produce cellulose, which in principle could be simultaneously coloured. Bacterial cellulose has been dyed in situ by providing synthetic dyes to the growth medium (Shim & Kim, 2018), but co-production of bacterial cellulose and biobased colourants is still to be developed.

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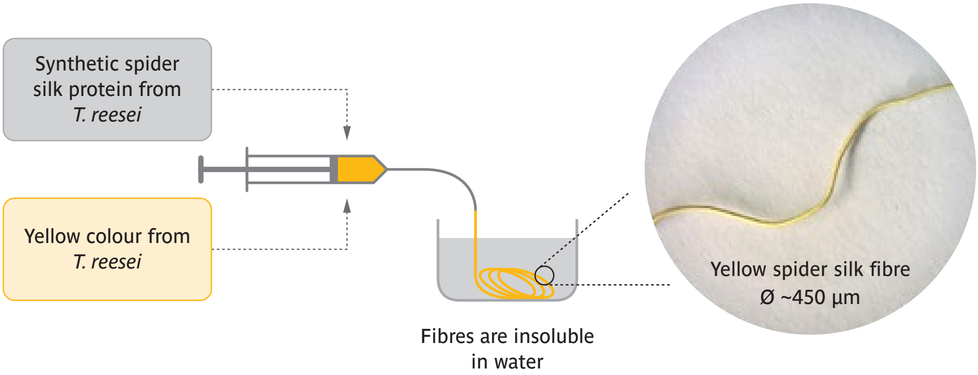

Future colour pathways for art and design through synthetic biology

Colour has always been an important aspect of art and design, playing a crucial role in conveying emotions and ideas. The use of colour can evoke a range of emotions, from calmness and tranquility to excitement and energy. In design, colour is a powerful tool to generate visual interest and build brand or personal identities. With the rapid expansion of synthetic biology in recent years and the need for cleaner and greener processes in the fashion industry, artists and designers have begun to explore new paths to harness fungi, bacteria, or algae to produce microbial pigments (Quijano et al., 2021). By using synthetic biology techniques, designers and artists are able to create unique new biological ways to integrate microbes and their capability to be engineered into our own material world and future products. These microbes are the catalysts for material-driven creativity and new means of production. For example, new bioprocesses for the creation of silk, or leather-like alternatives such as those made from fungal

mycelium will replace both fossil-based fibers and the harmful chemical dyeing processes with bio-based equivalents (Tang et al., 2021).

Given the vast number of microbes on the planet, the colour possibilities are endless. For example, the company PILI Bio is currently developing a technology based on the engineering of microbial enzymes to produce textile dyes from renewable carbon feedstocks, such as sugar (PILI Bio, 2019). Additionally, the field of biosynthetic colours has seen the rise of colour databases such as the Living Colours Database (https://color.bio/database), an online database of bio-based pigments. It contains organisms such as fungi, bacteria, and archaea, along with the pigments they produce by showing the colour expressions by HEX, RGB, and Pantone indices as well as the chemical structure and the biosynthesis of the compounds (Sharma & Meyer, 2022).

In the context of VTT and the BioColour project, art and design have played an important role in three different ways. First, various fungal species were used to produce pigments from the sorbicillinoid, azaphilone, carotenoid, and xylindein chemical classes (Figure 6). Some of these fungal pigments were later tested on textiles

6 Fungal colours produced at VTT.
Photo Manuel Arias Barrantes

by means of a traditional dyeing process (Figure 7). Second, at VTT we have also been envisioning the future of material and colour production, as described above (Figure 5). In this other project, design played an important part as we were exploring the simultaneous production of colour using fungal strains and silk proteins to create fibers with unique colourways, or even ready-made objects. To further examine the concepts of microbial colours and materials, yellow fungal pigments were tested on wood, and with bioplastics and protein films. As a result of these tests, jewelry pieces were created as proof-of-concept (Figure 8). Third, an inspiring development on this topic was the exploration of design education for the development of biobased colourants using synthetic biology. A Masters' thesis work was completed on the use of fungal and bacterial colourants (Juuri, 2020).

By engineering microbes to produce specific colours, designers and artists can create unique and customizable materials that can be grown into specific shapes, size, and structures. These materials can be used in a variety of applications, such as fashion, product design, and even architecture. Such collaborations between designers, artists, companies, and research institutes are crucial as this will result in many innovative applications, including those that may have a positive impact on our environment and society.

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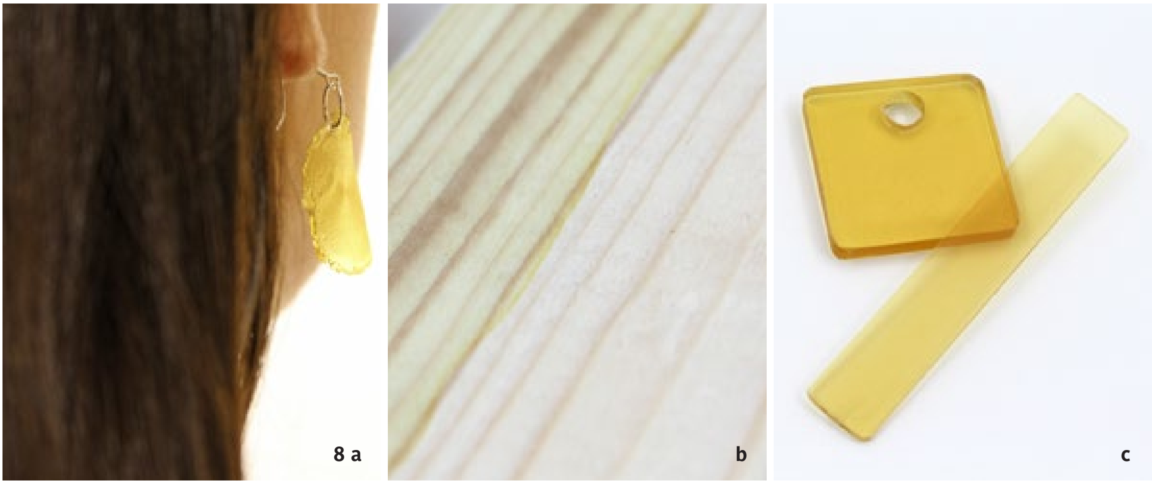

Discussions and Conclusions

Biotechnology, synthetic biology and biomanufacturing are expected to develop rapidly. Synthetic biology is a cross-disciplinary field that builds on collaboration between different scientific disciplines from AI to cell physiology, but an even broader collaboration is needed to apply synthetic biology to specific fields such as the production of colourants or co-production of colours and materials. In addition to investigating the capability of engineered or natural microbes to produce certain pigments, we need to address their safety. Natural colourants need to be carefully evaluated during their different applications for their safety towards the consumers of dyed products, the factory workers who produce the colourants and the dyed products, and the environment where colourants-containing industrial and consumer waste is disposed to. Next, we need to study the colouristic quality of these pigments, and evaluate the techno-economic feasibility and sustainability of the large-scale production processes. The views and needs of application specialists and designers are equally important.

Synthetic biology holds tremendous innovation potential. The variety of chemical reactions carried out in living cells is huge and can even be further extended by chemical catalysis to create

7 Colours produced by fungi were used in a traditional dyeing process.

Dyeing and pictures by Monica Louise Gjøderum Hartvigsen

8 Material samples and prototypes with yellow sorbicillinoids:
a films as an earring prototype
b wood and
c bioplastics

Bioplastic by Kirsi Immonen, prototyping and pictures by Manuel Arias Barrantes new-to-nature compounds based on modelling and design. The use of cell factories can enable totally new production concepts e.g., by integrating several production processes into a single microorganism.

Currently, this innovation potential is being realized both in basic science and in industry. The scientific studies focus on proof-of-concept studies on the production of new colours, elucidating metabolic pathways and enzyme functions, and improving productivity. Various industries have already shown interest in biobased colourant options, and there are several start-up companies that try to bring microbial colourants to the market. Thus, companies like Colourifix, Vienna Textile Lab, PILI Bio, Chromologics, Phytolon, Lycored, Michroma, Spira, and DDW use native microorganisms or engineered microbes to produce various pigments. Although many of these companies are in the early development phase, they have already gathered significant investments. Their concepts vary from producing purified dyes for food colouring (Chromologics) to growing pigment-producing microbes and using the resulting dye liquor directly to stain textiles (Colourifix).

Synthetic biology is accelerating the development of cell factories, including those that produce colourants, to create more sustainable but still economically feasible production processes. This technology offers benefits in terms of contained production in existing fermentation facilities, independent of land use, growth seasons, weather events or climate change. It does not require harsh conditions, and offers solvent-free production. Synthetic biology-based processes may use various industrial side streams or even CO_2 as the raw material, supporting circular economies. Although development is still needed to improve colourant productivities and processes, there are many inspiring opportunities to create a colourful future with microbes.

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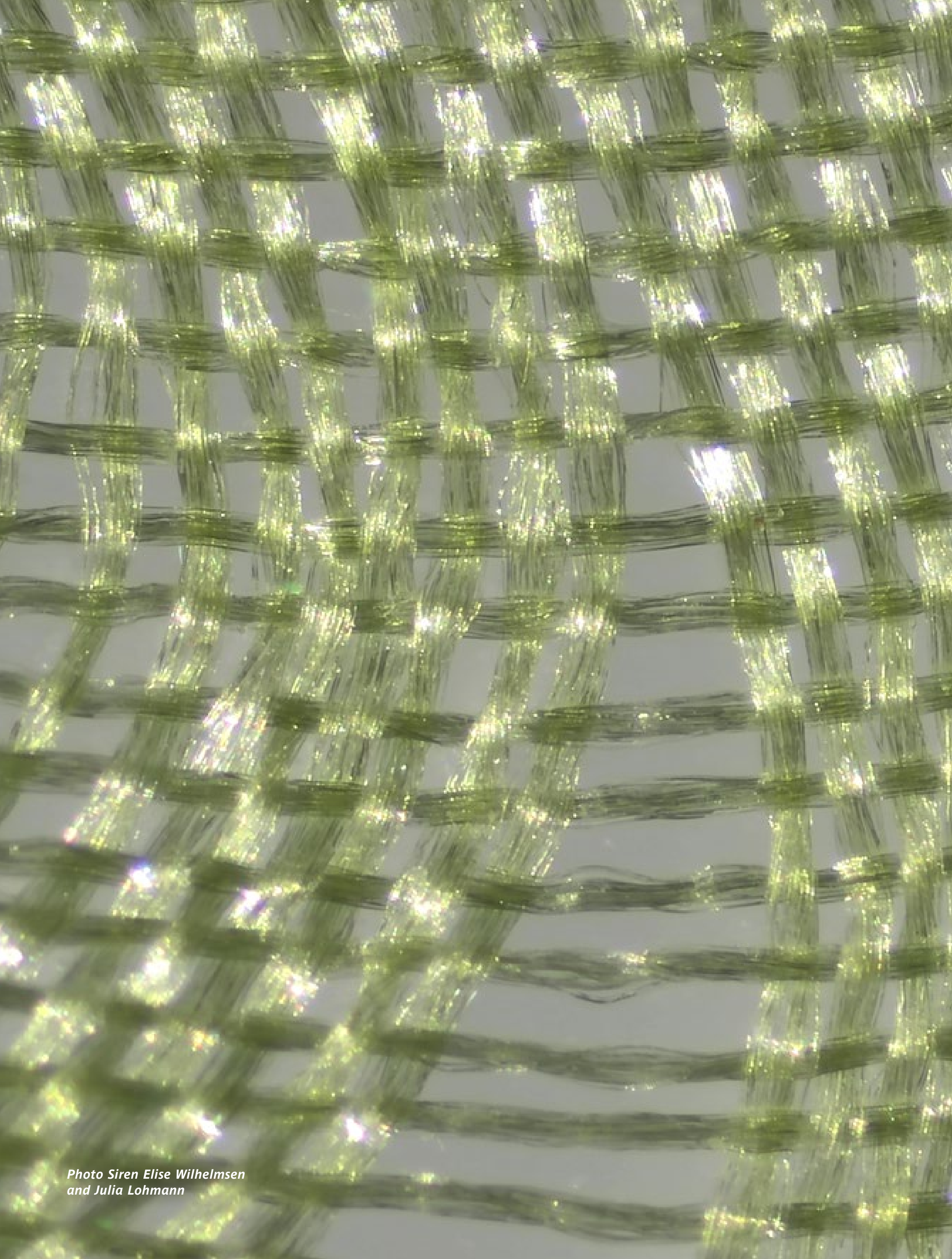
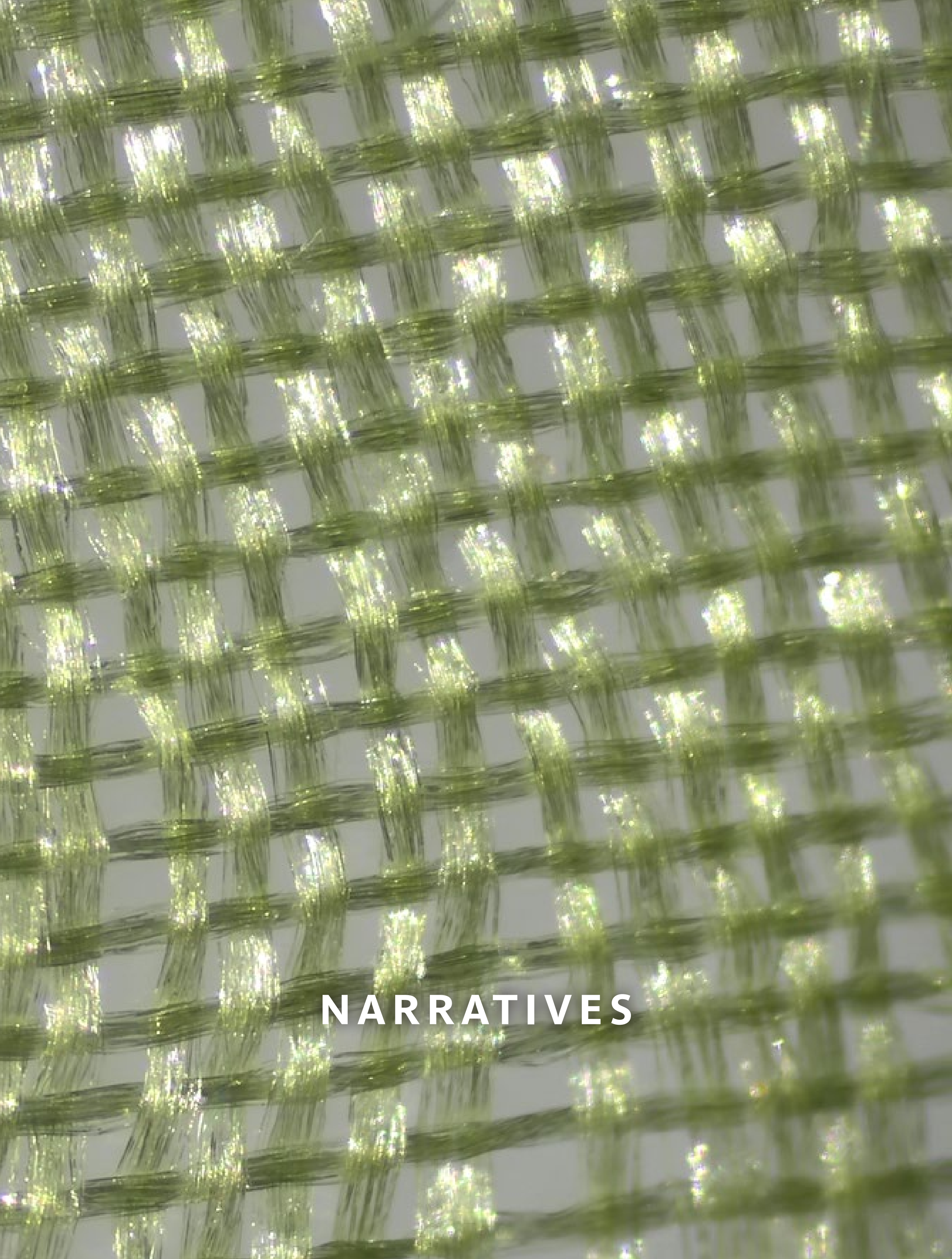


Photo Siren Elise Wilhelmsen
and Julia Lohmann

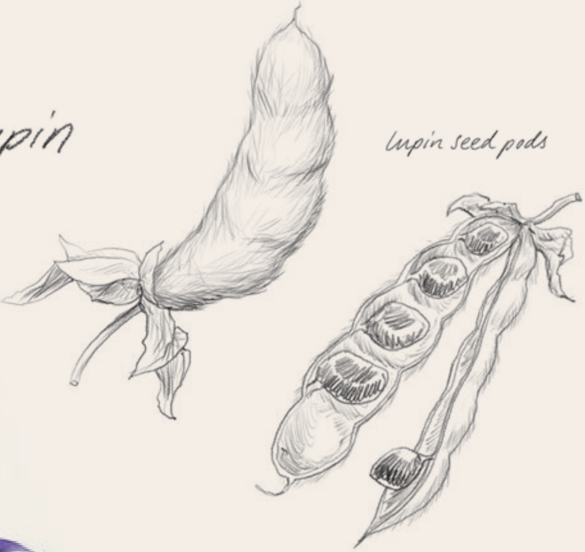


NARRATIVES

Photos Leonardo Hidalgo Uribe (left), Julia Lohmann (right)

Large-leaved Lupin

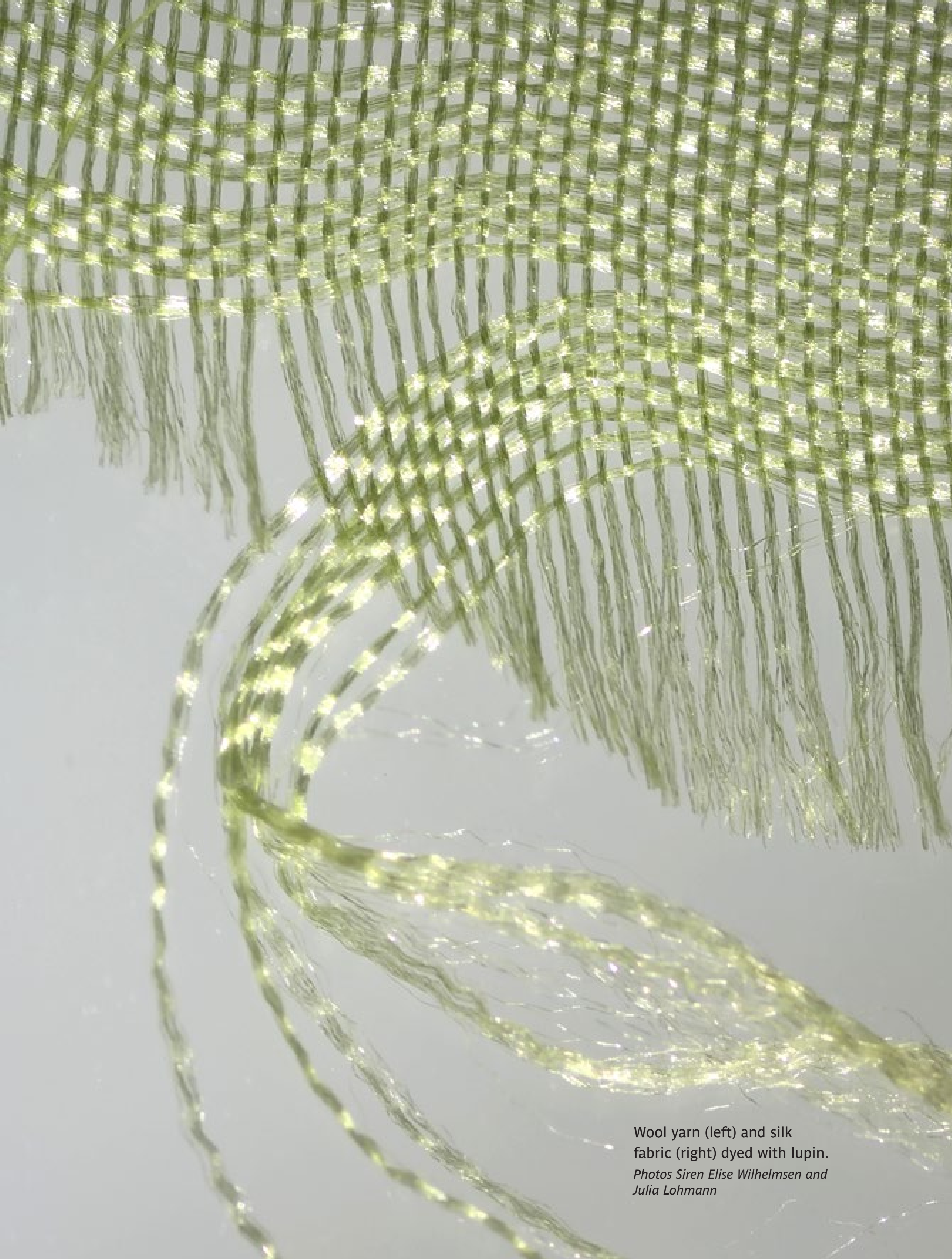
(Lupinus polyphyllus)



Lupin is a herbaceous perennial plant of the legume family, also known as Lupinus, Lupine, or bluebonnet. They are native to the Americas and annual varieties exist in the Mediterranean. Beyond their native ranges, lupins are considered invasive species.

Lupin seeds have been used as food, as well as animal feed. They have also been cultivated to improve soil fertility because they fix nitrogen from the atmosphere.

Lupin blossoms can be used as a natural dyestuff, producing colours ranging from yellows to lime greens.



Wool yarn (left) and silk fabric (right) dyed with lupin.

Photos Siren Elise Wilhelmsen and Julia Lohmann

Photo Siren Elise Wilhelmsen

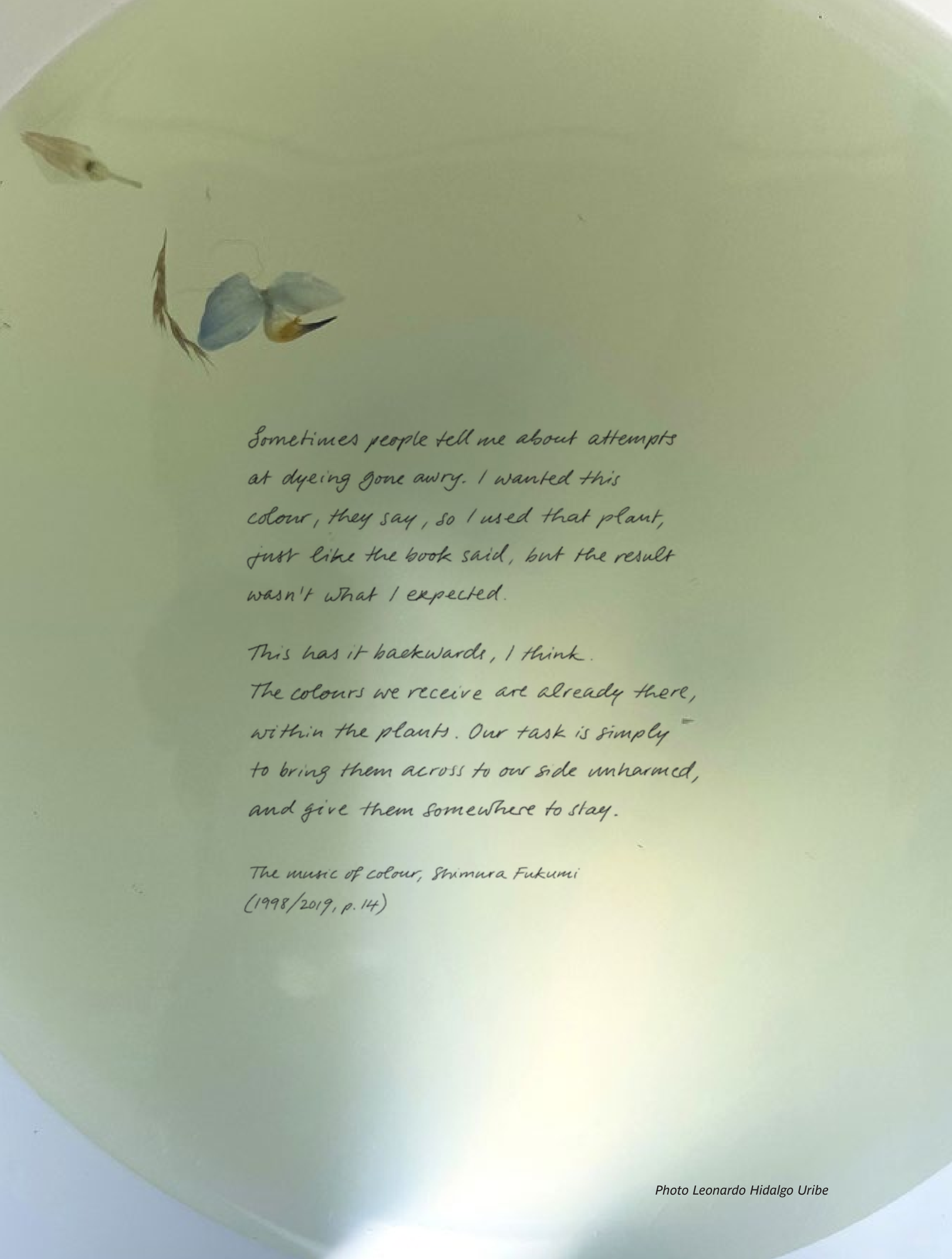
Leonardo Hidalgo Uribe

Making colour a relational practice: correspondence between materials and local environments in natural textile dyeing processes

ABSTRACT

In contrast to biocolourants, the standards of colour production and manufacturing with synthetic dyes ensure that the desired colours meet the expectations of both the designers and the market. However, these models reduce colourants to static, stable categories, detaching the dyeing materials from the complex relations between the practitioners and the environment that arise during dyeing. Using Ingold's processual perspective on materials and making, Berleants' concept of aesthetic engagement and Saito's aesthetics of imperfection, this article proposes a way of understanding the dyeing practice in which colour emerges from the correspondences between the dyers and the environment, by involving the practitioner's openness and capacity to follow the flow of materials in the process of making colour. It aims to open up a discussion on the current colour practices in the field of crafts and design and offers a theoretical perspective on dyeing that involves the influence of organisms and environments on colour.

Keywords
natural dyes, textiles, making colour, correspondence, wayfaring, entanglement, aesthetic sensibility, aesthetic disappointment, aesthetic engagement



Sometimes people tell me about attempts
at dyeing gone awry. I wanted this
colour, they say, so I used that plant,
just like the book said, but the result
wasn't what I expected.

This has it backwards, I think.
The colours we receive are already there,
within the plants. Our task is simply
to bring them across to our side unharmed,
and give them somewhere to stay.

The music of colour, Shimura Fukumi
(1998/2019, p. 14)

Photo Leonardo Hidalgo Uribe

Introduction

The textile industry uses several colour standards and colour management tools to ensure a controlled manufacturing process in which colours meet the designer's intentions and satisfy consumers' expectations (Setchell, 2017). Colour libraries containing swatches with dyeing recipes and standards for colour nomenclature (e.g. Pantone) are used to match and reproduce any desired colours for yarns and fabrics (Best, 2017). These tools have influenced the way in which colours are thought about and used in weaving practice (Albers, 1965/2017) in line with, for example, Chevreul's (1839) principles of colour mixture (Boeri, 2012; Ng & Zhou, 2013; Nicklas, 2014). As a consequence, colour preferences in textile design are linked to unchangeable and predictable outcomes. However, dyeing textiles in artistic or other smaller-scale practices does not necessarily follow such strict models of control, although it still relies on similar tools to those that guide colour selection.

Due to the environmental impact of dyeing in the textile industry (Niinimäki et al., 2020), interest in researching biocolourants as an alternative to synthetic dyes is increasing (e.g. Biocolour, 2023; Chieza & Ward, 2019; Datta et al., 2022). The use of bio-based sources of colourants faces the challenge of variation in the outcome, compared to the control that can be achieved with synthetic dyes. The difficulties of accuracy and control in natural dyeing have been discussed in different studies (Falls & Smith, 2011; Lowengard, 2001; Perret, 2020; Sengupta, 2019; Talman, 2018). Natural dyes obtained from plants are directly connected to what archaeologist Holt (1991) calls 'botanical artefacts', which are 'defined and conceived of as any floral element which is utilized or impacted by [humans]' (p.48). These are characterized by their limited availability due to geographical and seasonal conditions and by being sensitive to environmental changes (Holt, 1991). This issue requires the development of different ways of using colour in textile design, and the exploration of aesthetic qualities that address the cycles of ecosystems and elements in the places from where dyes come.

Dyeing with biobased materials involves the activities of gathering and growing parts of organisms to obtain colours. Growing implies establishing conditions for nurturing, which is a notion that anthropologist Tim Ingold (2000) connects to the idea of making. According to Ingold, the forms that other creatures or materials take 'are neither given in advance nor given from above; they emerge within the context of their mutual involvement in a single continuous field of relationships' (p. 87). From the perspective of dyeing textiles, 'giving form' or 'making' can be understood as the activity of developing colours from dyes that are extracted from materials and transferred into fibres or fabrics. This activity entails an embodied relationship between the dyer, the dyeing material and the different elements of the environment that participate in the process.

Current models of colour production and coordination detach the dyeing of materials from the complex relations between practitioners and the environment that form during dyeing because colourants are reduced to static and stable categories that are heavily controlled to meet the designer's expectations. This article acknowledges the fluidity of biobased materials and proposes a way of understanding dyeing as colour emerging from the correspondences between the dyers and the environment, by involving the practitioner's openness and capacity to follow the flow of materials in the process of making colour. It aims to open up a discussion on the current colour practices in the field of crafts and design and to offer a perspective on dyeing that includes the influence of other organisms and landscapes on colour.

The text explores the role of the dyer in the process of developing colour with natural dyes by first discussing the act of making a colour in textile practice and its relation to the materials and environments. I examine the dyeing practice using Ingold's (2000; 2010; 2013) concepts of wayfaring and correspondence and his processual perspective on making, materiality and relationality. This perspective sees dyers as wayfarers who follow the movements and flows of materials, and dyeing and developing colour works as an act of corresponding to — answering to — the materials on the move, instead of imposing a preconceived idea into inert, raw and static matter. The next section explores the limits of control in the dyeing process and how colour expectations can be examined under Quacchia's (2020) notion of aesthetic disappointment and Saito's (Saito, 1997; 2017) aesthetics of imperfection. Here, expectations of colour are related to ideals of beauty and production standards that do not necessarily correspond to the cycles of plants, land or water. Quacchia and Saito argue for openness and appreciating things on 'their own terms'. Based on this idea, the final section explores how dyers engage with the environment and appreciate the correspondences of making through aesthetic sensibility and aesthetic engagement.

Making colour

The development of colour systems and colour standards has influenced the way in which colours are understood and used in textile design practices, particularly in the textile industry (Best, 2017; Blaszczyk, 2012; Goodman, 2017). Colour-matching systems such as Pantone have enabled textile designers and manufacturers to quantify and communicate colours, allowing them to match and replicate colours according to their expectations (Goodman, 2017, p. 419). Designers create and coordinate palettes using colour identification tools that ensure that certain colours are consistent during production to maintain the desired combinations (Best, 2017, p. 462). To avoid confusion and mistakes, colour quality standards follow tools such as colour names, reference numbers, and swatches compiled in libraries, which are used as a way to communicate colours to dyers during the different stages of design and production. Swatches are pieces of cloth or yarn that are dyed according to a specific formula that can be replicated, and they are kept in special conditions to prevent colours from changing over time as much as possible (ibid).

In these cases, the production of coloured textiles using dyeing processes is considered something that can be quantified, replicated and objectively communicated. This is not exclusive to synthetic dyes. For example, historian Sara Lowengard (2001) explains how natural dyes also followed notions of quantification and order during the eighteenth century in France. Lowengard describes a criterion for balancing aesthetic and manufacturing qualities, which was established by industrial committees. These models focused on the preference for bright and saturated colours, the pleasant tactile and draping qualities of the fabric after dyeing, and the colour permanence and cost efficiency during its production (Ibid, p. 93–94). Also, colour charts and standard colours (e.g. Richard Waller's tables in 1686) were implemented and validated by institutions such as the Royal Society in England or the Conseil de Commerce and Academie Royale des Science (ibid).

This way of understanding colour and dyeing in terms of measurement and repetition follows what Ingold (2013) calls the hylomorphic model. Based on Aristotle's theory, Ingold explains hylomorphism by thinking of making as a project, in which 'practitioners impose forms internal to the mind upon a material world out there' (p. 20). This means that the maker starts with an idea and uses raw material to transform this idea into a finished artefact. This model understands materiality as 'form-receiving passivity rather than form-taking activity' (p. 28). When designers dye textiles, they search for specific shades that can be found from samples, moodboards or colour forecasts, for example. Then they choose the desired colour, which is matched using a colour library containing recipes that allow the designer to reproduce the colours that they have in mind (Best, 2017). According to Ingold's argument, here, the dyes are the raw material, which plays a passive role in the process of making colour, and the desired shades are imposed on the fabric or, as Ingold puts it, 'given in advance' by the designer (p. 25). So the designer's expectations are met by repeating the colour recipe, which involves the use of measuring instruments for the dyeing process, but more importantly, by the use of standardized colour samples that are 'specified colorimetrically with very narrow variation tolerances' (Fridell Anter, 2015, p. 63). Physical colour samples use what Fridell Anter calls 'nominal colour' which is defined as 'perceived colour under standardized viewing conditions' (Ibid). This method of making colour considers the standardized colour sample to be a static, stable entity and forces the dyeing process to develop the specific shade that should be matched with the nominal colour to meet the designer's expectations.

Ingold (2013) criticizes the form-receiving passivity of matter viewed under the hylomorphic model in his theoretical work on making, matter and form. The author proposes that instead of understanding making as a form-giving activity, it should be considered a process of growth (p. 21). Here the maker joins forces with the materials in a form-generating process within a field of constant relations, transformation and movement (p. 22). Growing implies an ontological transformation and when Ingold refers to making as growing, he sees the maker as someone who intervenes with the materials in a play of forces and relations (Hallam & Ingold, 2016). Makers may have a form in mind, but it is their engagement with materials that creates the work, not the form (Ingold, 2013, p. 22). By citing Deleuze and Guattari (1987), Ingold (2013) explains that the hylomorphic model assumes a fixed form that is accomplished by the maker, ignoring the possible 'tensions and elasticities, lines of flow and resistance'(p. 25).

Natural dyeing processes involve a set of relations between dyers and the environment (Perret, 2020; Sengupta, 2019). Dyers engage with different environmental conditions to create colours, such as water quality, seasonal changes, and the lifecycles of plants, among many others. For this reason, the control of the dyer becomes compromised by multiple factors that play an active role in the dyeing process. Perret (2020) has explored these relations in the work of artisans from the Chaco province in Argentina and examined how 'the heterogeneity of materials and times leads to thinking of colour less in terms of quantities and more in terms of growth processes' (p. 380). Deleuze and Guattari propose that matter is in constant movement and variation, which requires makers to be wayfarers who can follow the flow of materiality (Ingold, 2013). Ingold highlights that following the materials is not a passive activity; it requires the maker to engage with them through coordinating action and perception (Ibid). I explain the notion of the maker as a wayfarer in the following section.

The dyer as a wayfarer

Materials, for Ingold, do not exist as static entities with defined attributes waiting to be shaped by an external force. Instead, they are considered 'substances-in-becoming' which cannot be restricted to established concepts or categories (Ingold, 2013, p. 31). Materials are on the move and continue with their own ongoing stories, and practitioners know them by understanding what they 'do and what happens to them when treated in particular ways' (ibid). According to Ingold, during the act of making, practitioners couple their 'own movements and gestures' with the becoming of the materials, allowing them to join and follow the 'forces and flows' that make their work possible. For example, dyers from the Coromandel region in India work in relation to the salinity of coastal water and rely on ecological and circumstantial factors that influence the colours they develop from chaya roots (Sengupta, 2019). The different shades of red that dyers in Coromandel achieve cannot be described in terms of

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colour only without ignoring the cultural and ecological relations that make them possible. Chaya roots were first exported to Europe in the eighteenth century, however, even though the dyeing process was well documented, scholars failed to achieve the colours and qualities they wanted outside the Coromandel region (Ibid, p. 11).

The movements of practitioners and materials can be understood as different trajectories 'traced along a continuous wayfaring line' (Laterza et al., 2013), which meet along the process of making a field of entanglements (Ingold, 2013). The maker learns to follow the lines of materials as well as a hunter or a gatherer follows different tracks or signs along their way, requiring active engagement with their surroundings. This act of following is what Ingold calls wayfaring, which involves the embodied experience of the maker (Ingold, 2011, 2013).

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During the indigo dyeing process, for example, dyers use their sense of smell and vision to follow the state of the dyeing liquor (Wiseman, 2013). Using perceptual skills for dyeing requires the capacity to not only distinguish colours but also to move within the environment, as happens when dyers gather wild plants: they have to be able to recognize species and know the right times to collect them (Perret, 2020).

The act of making involves wayfaring lines where 'materials flow and bodies move', and their entanglements are described by Ingold (2012) as a 'meshwork'. Instead of interacting as separate entities, the lines of makers and materials mesh together by 'sustaining relations of contiguity and resemblance, as well as 'constantly overlapping with each other' (Laterza et al., 2013,

1 Collage of foraging experience when searching for spruce cones.

2 Collage of foraging experience when searching for reeds.
Photos Leonardo Hidalgo Uribe

p. 167). Making, then, can be seen as a process of 'correspondence' (Ingold, 2013) which involves ongoing interaction between maker and material in a movement that is sentient and happens in real time (p. 105). Ingold draws a distinction between interaction and correspondence, in which the former makers and materials are placed on opposite sides which have been clearly defined in advance, while the latter involves both parts being mutually constituent, bringing into each other along the way (Ingold, 2017, p. 10). By corresponding, makers are not imposing preconceived forms on raw materials. Indeed, it is through this correspondence that form emerges as the result of maker and material entanglements, as occurs with coloured fabrics when dyers answer to the dye materials and the environments in which they are gathered. It is important to note that these relations are not always in harmony, on the contrary, material flows and bodies can also overlap, resist, restrict, and contradict each other (Laterza et al., 2013, p. 189).

During the dyeing process, colours emerge from the correspondence between dyers, the dyeing materials and the environment. Red dyes from chaya roots in Coromandel 'emerge, disappear and reappear' during the mordanting, washing and boiling processes (Sengupta, 2019, p. 15). The appearance and disappearance of colour during the dyeing process is evidence of their movement. Moreover, colours in textiles vary according to the recipes used as well as the qualities of the dyeing materials (Perret, 2020, p. 380). Dyes are not static and neither are the colours that they achieve. Dyes follow a path that takes the same direction as the lines of the dyer and the environment. Dyed materials cannot consider their colours to be a result of their shades also changing when we expose them to light, wash them or rub their surfaces. Standardized colour samples are based on colour systems that define and describe colours using static models (Arnkil, 2015, p. 68), and their function is to facilitate the identification and reproduction of colours. However, this way of dyeing expects colour to be static and isolates the colour-making process from its multiple correspondences. Dye processes do not result in a finalized colour that has been previously defined, instead they mesh different materials and bodies into colours that are constantly becoming. For this reason, the role and intentions of the dyer cannot ignore the multiple relations that make colour possible. The following section will explore the role of the dyer when dyeing is considered a practice of correspondence.

Imperfection and disappointment in making colour

Dyeing with natural materials involves a level of uncertainty. For example, dyers in Coromandel find it challenging to make black because they may make unexpected colours even if they follow a proper process and use all the required ingredients (Sengupta, 2019, p. 17):

> *Once the ingredients are mixed in a pot, there is not much the dyers can do to enhance the quality of the solution. The solution can either turn into the dye, which the dyers eagerly wish for, or it can bring disappointment to the dyer's efforts* (Sengupta, 2019, p. 18).

Perret (2020) argues that making colour is relational and that the control of colour is distributed among the different actors that play an active role in the dyeing process. The author calls these unexpected results 'surprises', which reveal the material and temporal variations that influence the dyeing process and are not under the dyer's control (p. 379). However, Perret also claims that unexpected colour results are a problem in the production of handicrafts in Chaco. In this case, expectations are mediated by market dynamics in which consumers or commissioners are seeking a specific colour that has been defined before the process starts. In both cases, dyers from Coromandel and Chaco may be disappointed when the outcome of their work does not match the colours they are expecting.

Quacchia (2020) sees the role of expectation as the basis of aesthetic appreciation. According to the author, expectations hold an 'anticipatory component' which relates to 'our level of hope or confidence over the likelihood of the desired outcome being realized'. Quacchia's argument claims that anticipations are a 'form of prospective belief' that accounts for a prediction of how things might be or look. This belief is based on normative ideas of beauty which judge the aesthetic experience against an ideal of beauty. For example, the dyer may prefer bright colours and be disappointed when the process results in dull or pale colours. As Lowengard (2001) examined in her historical analysis of the French dyeing industry in the eighteenth century, committees pushed colour preferences towards certain shades that fulfil both beauty expectations and production feasibility. Here I consider that the notion of 'ideal' colour – which can be kept as a sample in a standardized colour card– reflects Ingold's critique of the hylomorphic model that assumes that makers give form to passive matter according to what they have in mind. In the case of dyeing, the dyer already has an ideal colour that they hope to achieve at the end of the process. This ideal colour is static, as any variation is considered wrong and thus disappointing. To obtain the expected colours, the dyeing process is subject to meticulous control that calculates and measures every material and movement. However, as has been explained before, dyers need to negotiate with a myriad of forces entangled within the process of making colour.

Saito (1997; 2017) examines the role of control in making practices from the perspective of the aesthetics of imperfection, and accounts for appreciation of objects that do not fit the determined norms of perfection and beauty and argues that 'perfectionism impoverishes our aesthetic lives because it limits the range of sensuous qualities for appreciation' (2017, p. 2). In the case of pottery-making, for example, Saito explains how raku potters in Japan have to submit to factors beyond their control, such as the precise temperature during the firing process or the 'exact response of the clay and glazing to the particular fire' (Saito, 1997, p. 383). Saito emphasizes the stance of the maker, who assumes an attitude of submission, resulting in the materials taking the lead in the process (ibid). This point of view contradicts the hylomorphic model, in which the makers are the ones who take total control over the raw material. However, as was explained in the previous section, Ingold (2017) argues that neither the maker nor the materials take a passive role; they continuously correspond, or answer, to each other.

On the other hand, Saito (2017) develops a way of appreciating imperfection in objects by adopting an attitude of 'open-mindedness and receptivity' and valuing things 'on their own terms'. For Saito, this form of appreciation involves recognizing the limitations of human agency and acknowledging the transience of life and materials. Accepting something on its own terms resonates with Ingold's idea of the maker as a wayfarer, following the materials along with their

3 Failing to obtain blue shade with fermented alder buckthorn berries.

4 Failing to obtain blue shade with fresh alder buckthorn berries.

Photos Leonardo Hidalgo Uribe

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actions and sensory attention. Similarly, acknowledging our limitations in making implies recognizing the flows that play an active role in the process. This form of appreciation involves considering colours part of the flows and movements between the makers and dyes: the dyeing process does not finish with a colour outcome but continues as a *colour-becoming*. In addition, by appreciating the colour of a dyed fabric on its own terms we learn to perceive the relations between our bodies and forests, water, plants, minerals, and air, amongst the many other elements entangled within the dyeing process.

Dyeing practice and environmental sensibility

As was mentioned before, by following the flow of materials, practitioners are wayfarers 'whose skill lies in their ability to find the grain of the world's becoming and to follow its course while bending it to their evolving purpose' (Ingold, 2010, p. 92). This skill involves movement and feeling and requires a practice of correspondence in which the practitioners learn to go along with the materials by responding to them and being responded to (Ingold, 2013, p. 4). Crafters and researchers Latva-Somppi and Mäkelä (2020) argue that making can be considered an aesthetic practice that entails 'multi-sensorial meaning-making by hand'. The maker can cultivate material sensibility through their practice, which is guided by emotional and experiential knowledge (p. 33). The aesthetic theory of Arnold Berleant (2012) expands on the notion of sensibility as a 'perceptual awareness that is developed, focused, and informed' and 'requires perceptual knowledge and skills that we are continually enhancing through our encounters and activities' (p. 55).

As it occurs in different craft practices, dyeing involves perceptual awareness of the environment in which the materials are gathered or cultivated, and this environmental perception entails a 'multi-sensory bodily engagement' (Berleant, 2012, p. 55). Berleant does not understand the notion of the environment being something that is separated from humans and does not consider it an object or surroundings. Instead, humans are an integral component of the environment, which is 'acting and reacting as part of its constant flux' (p. 56). This resonates with Ingold's (2000) view of the environment being forged through the activities of living beings and being

continually under construction through a process of growth (p. 20). Makers are also part of the environment and for this reason, Latva-Somppi and Mäkelä (2020) argue that craft practitioners engage with it when working with materials in a 'close and attentive observation and perceptual acuity' (p. 43). If we understand the dyer as a wayfarer, the act of following the flow of materials involves engagement with the different lines entangled within the dyeing process.

Berleant (2013) describes aesthetic engagement as a way in which to reject the dualism ingrained in the traditional perspectives of aesthetic appreciation, which sees the aesthetic object and the appreciator as opposite entities. On the contrary, aesthetic engagement 'emphasizes the holistic, contextual character of aesthetic appreciation', and also entails a 'perceptual involvement' and an 'active

5 Collage of foraging experience when trying to identify alder buckthorn shrubs.
Photos Leonardo Hidalgo Uribe

participation in the appreciative process' (Berleant, 2013). Some views on ecological aesthetics (Berleant, 2016; Cheng, 2013; Koh, 1988) emphasize the contextual character of environmental aesthetic experience, as well as the unity of humans and the environment through aesthetic engagement (Berleant, 2016). Berleant argues that appreciation and aesthetic values are grounded in perception, and it is through the understanding of the environment that our perceptual experience is enhanced (p. 132). According to this perspective, aesthetician Perullo (2019) argues that developing knowledge about the environment involves 'participating with an active and always emerging movement' that is entangled with other beings and materials. For example, dyers in Coromandel relate to coastal water resources in their practice and dyeing techniques, as well as the ecological knowledge involved in the process (Sengupta, 2019).

Dyeing as a process of itineration and improvisation

Working with dyeing processes can be seen as what Ingold (2010) calls *itineration* and *improvisation*. Understanding dyers as wayfarers involves thinking of their work as itineration rather than iteration. Iterations are repetitions of the same process over and over again whereas working around an itinerary means that the practitioner has a path that they take every time they perform an activity. Paths unfold during the process of making and entail a movement that goes forward, which requires improvisation. Citing Ingold, 'to improvise is to follow the ways of the world, as they open up, rather than to recover a chain of connections, from an end-point to a starting-point, on a route already travelled' (p. 97). Dyeing processes use recipes and dyers document steps, measurements and interactions to achieve the same results. Repeating a dyeing recipe could be seen as an iteration of the process. However, I argue that every time a practitioner working with natural dyes follows a recipe they are improvising, as they have to constantly respond to changes in the environment in, for example, temperature, water quality, the lifecycle of plants, and seasons. Recent work with natural dyes has explored in situ how colours and dyes emerge in local environments and how practitioners learn to follow and understand these processes. In the next paragraphs, I illustrate how itineration and improvisations are involved in the documentation and reflective work of artist Sally Blake, designer Hannah Elizabeth Jones, and master weaver and dyer Fukumi Shimura.

The dye diary of Australian artist Sally Blake (2015) compiles visual, material and written documentation of dyes prepared from several local plants grown and gathered in the Inner North of Canberra. She documented seasonal changes in the availability of colours and plants. In her observations, Blake noted how the intensity of the colours she obtained varied according to environmental conditions. For example, when collecting flowers on rainy days, the colours she obtained were more 'diluted', and this highlights how 'these uncontrollable variations relate to the poetic possibilities and mysteries of nature, a wonderful reminder that much of what happens in nature is beyond human control'. Blake also archived the plant materials she used for dyeing to gather information about the physical conditions of these materials and to create a relation between their unique qualities and colours. Similarly, Welsh designer Hanna Elizabeth Jones (2020) has developed a database of dyes from wild plants. This database follows seasonal changes and the geographical location of the dye materials that Jones gathers in North Wales. She displays the plants and colours in graphs that show how they vary according to time and place and how the dyes and colours are entangled with the local environment.

Master dyer and weaver Fukumi Shimura has extensive experience of working with plant-based dyes and tsumugi-ori weaving techniques. She has also written essays and poems that describe her thoughts about and experiences of dyeing and collecting materials from her surroundings. In her writings, Shimura (2019) describes how colours emerge from her interaction with plants and her knowledge about places and seasons. For example, she mentions in her essays that cherry tree extracts must be taken in early spring when there is still snow and the branches show their first buds and describes how she uses the ashes from the same tree as a mordant to make her colours. Shimura works with the colours she obtains from the environment rather than searching for specific shades. For her, the colours are already there and the work of the dyer is to bring them to light. As she describes it: 'the plum, the peach, the grapevine: without fail, each one birth its own colour (...) Whatever assistance we provide in bringing this heavenly dew to earth, the silk yarn drinks these natural essences into the fullness of its being with astonishing stillness' (p. 19).

Dyeing Process

Norway Spruce Cones

Dye extraction:

April 19th, 2022

Dyeing:

June 13th, 2022

Shimura works on her loom with the colours she obtains and builds compositions of yarns and shades that tell the stories of the plants and their environments. About a project with students from Fujiwara Junior High School in Gunma prefecture, Shimura writes:

> *On my visit to the school, I gave each of the students one bundle of yarn and asked them to dye it with the colours of Fujiwara's forests, fields, and grasses, and then send it back to me. Around the end of spring, the skeins began to return from the students. Horse chestnut, apple, peach, cherry birch, sawagikyou (Lobelia sessilifolia): they were like handfuls of spring itself.*
>
> *I set up the yarn on my loom and began to weave. I did not need any design. The colors that the children had found became stripes and I used white yarn to add horizontal lines. When I was finished, I named this piece "The snows of Fujiwara" (Fujiwara no yuki). Then I wove another, with the same warp but different weft: green for spring, indigo for summer, brown for autumn, and white for winter.* (p. 94)

The relations she sees between warp and weft and colour, her collective gathering of materials and her attention to seasonality highlight Shimura's sensitivity to the places and people that are involved in her artistic practice. Her colours are not independent of these encounters.

Conclusion: Dyeing as a relational practice

This article explored how dyeing and making colours can be seen as a relational practice between dyers, materials and the environment. This perspective questions the role of the practitioner's expectations and control of the emergence of colour. Hylomorphism assumes that 'making involves the imposition of preconceived form on matter' (Ingold, 2012, p. 439), and in the field of textiles and dyeing, this perspective understands colour as the result of a dyeing process in which the practitioner uses colour-matching systems as a static reference and forces the dyeing materials into a desired shade. However, dyes from plants and other organisms are difficult to control in comparison to synthetic dyes and their laboratory conditions. These dyes are influenced by

6 Measuring colour of dye liquor while dyeing with spruce cones.
Photo Leonardo Hidalgo Uribe

several environmental factors, including the lifecycles of organisms and the quality of water, as in the dyeing practice of artisans from the Coromandel region described by Sengupta (2019), and in the practices in the Chaco Province described by Perret (2020). Working around a way of making colour that is dynamic and relational requires textile practitioners to change their attitudes towards the dyeing process and their appreciation of colours.

From a processual perspective, (Ingold, 2010; 2012; 2013) materials and bodies are porous and in constant movement. Instead of being fixed and static entities, they trace paths and leak in relation to each other, as happens when trees produce chemicals known as tannins to defend themselves from herbivores and influence the quality of the water and soil in their surroundings (Kohn, 2013, p. 82). Dyers extract these tannins from bark or bog and river water and use them as mordants to fix colours and prolong their light fastness (Räisänen et al., 2016, p. 233). Colour belongs to an ecosystem and emerges through the correspondences between dyers, organisms and the environment. Thus, dyers can be considered wayfarers who follow the paths of materials and processes in which colour unfolds from the intertwining of maker and material.

From the perspective of aesthetic disappointment (Quacchia, 2020), dyers hold determined expectations of the colours they aim to achieve at the end of the process. According to Quacchia, expectations involve anticipations that are tied to ideals of beauty and perfection. In the case of colour, this can be influenced by production dynamics as well as historical, local and cultural factors, as has been examined by Lowengard (2001). These colour palettes work with different shades that are balanced by the practitioner's choices. However, when colour results do not meet expectations, colour combinations are also compromised (Best, 2017). Saito (2017), in contrast, proposes appreciating things on their own terms, which means adopting an attitude of receptiveness and open-mindedness by recognizing the transience of the materials and the limitations of the maker. This point of view sees colour as not only the result of the interaction between the dyer and the materials, but also as a process of mutual response, or correspondence. In my opinion, openness to colour and dyeing processes results from following the material flows within the environment during the process of making, which entails environmental sensibility as well as aesthetic engagement. Following the materials involves perceptual skills and is an active practice that requires attention and engagement with the environment (Ingold, 2010). This relates to the notion of aesthetic sensibility described by Berleant (Berleant, 2012): perceptual awareness that is informed and continually enriched by the relations between the perceiver and the environment. Aesthetic engagement brings a perspective that breaks the separation of appreciator from object: it entails 'perceptual involvement' and 'active participation' (Berleant, 2013). The relation and intimacy that develops between dyers and local environments highlights the way they actively participate and become entangled in the movements of other beings and materials.

Seeing the dyer as a wayfarer requires seeing dyeing as an act of correspondence. This does not mean that dyeing and other making processes occur harmoniously. On the contrary, the entanglements between dyers and materials can also make this difficult or restrict the actions of the practitioner. Dyeing is a process of negotiation with the environment, involving, for example, sunlight, water, soil, lifecycles, perceptual skills, and practice. We can re-examine colour development and its expectations by seeing the act of dyeing as a continuous path that the dyer follows, on which colours emerge during the process, instead of a segmented line that has a starting point — a colour sample that the dyer wants to repeat — and an endpoint — the resultant colour after dyeing. Colour emerges not only from the work of the dyer but also from the multiple entanglements of organisms and ecosystems. Corresponding to, and thus engaging with, these different forces that operate in the process of making colour enables practitioners to expand their expectations of colours: they come to understand colour and dyes as relational processes that do not have to force preconceived ideas into materials. As Blake (2015) Jones (2020), and Shimura (2019) examined in their textile work, this perspective does not compromise techniques and methods that require experience and expertise. Ingold (2010) argues that making is not a process of iteration but of *itineration*. Dyers always have to improvise, even when following a recipe, as they are constantly answering to environmental circumstances as well as the transformation of the dyeing materials. Thus colours can be followed instead of being forced.

The worrying environmental impact of dyeing in the textile industry on land and water in different parts of the world (Niinimäki et al., 2020) is an example of the consequences of continuing a model that forces materials and ecologies to supply shades and quantities that markets and designers expect. Colour practices need to attend to the materiality of dyeing processes and become involved in the entanglements of the lifelines that bring dyes to fibres, that is, craftspeople, designers, studios, and factories. The perception of colour is a relational phenomenon (Arnkil, 2015) and so is its manufacturing. Attending to the environmental challenges of dyeing through biobased colourants also involves attending to the webs of forests, rivers, mountains, and coasts. The craftspeople in Coromandel are experts in dyeing techniques but they are also masters of the waterways that flow through the land in which they live. Seeing dyers are wayfarers entails extending colour design knowledge to the apprehension of life processes and the world that we inhabit together with other organisms.

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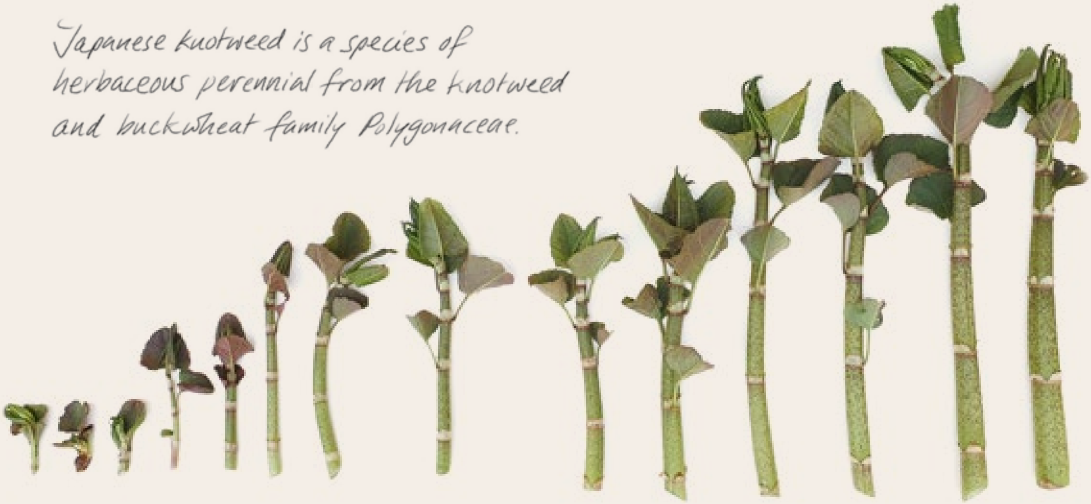
Photo Leonardo Hidalgo Uribe

Photos Siren Elise Wilhelmsen (left), Julia Lohmann (right)

Japanese knotweed / Asian knotweed

(Reynoutria japonica / Fallopia japonica / Polygonum cuspidatum)

Japanese knotweed is a species of herbaceous perennial from the knotweed and buckwheat family Polygonaceae.



A native of East Asia, it was brought as a decorative plant to North America and Europe, where it is classified as an invasive species. It spreads via far-reaching rhizomes in the soil and through seeds.

Japanese knotweed has large, alternating trowel-shaped leaves and may grow up to three meters tall, sometimes up to 20 centimeters in a day. It can suppress native plants by depriving them of light and nutrients and its strong roots and shoots may damage roads and building foundations.

Rhizome with old and new growth

However, Japanese knotweed is also a source of nectar to bees and birds eat its seeds. Japanese knotweed can be foraged as food and prepared like rhubarb. Its leaves and rhizome can be used to create a natural dye in yellow and orange colours.

Siren Elise Wilhelmsen

Fieldnotes from the "forbidden garden"

A journey through the colour palette of a group of "invasive alien plant species" in Norway.

ABSTRACT

This essay explores a design-driven study on colours and approaches concerning invasive alien plant species. While outlining the colour palette of textile dyes represented by plants considered invasive to Norway, it also presents both a personal story and a collective perspective for future production and consumption. The "forbidden garden" refers to the author's childhood playground in her grandmother's garden, which has gradually become inhabited by plants that are now considered unwanted or forbidden. The author questions the traditional approach of removing and eradicating invasive plants and advocates for a more holistic approach that takes into account the complexity of the ecosystem in combination with human impacts. Colour discoveries demonstrate the potential of an alternative approach and focus specifically on the possibilities of using Japanese knotweed rhizomes as a textile dye. This plant has become known as one of the world's most invasive species, although it has been valued as a useful plant for centuries.

Keywords
colour palette, invasive alien plant species, Japanese knotweed, new local flora, natural resources, holistic approach

On the left, wool yarn dyed with Japanese knotweed.

Photo Siren Elise Wilhelmsen and Julia Lohmann

Photo Niklas Sebastian Alveberg

Siren Elise Wilhelmsen

Introduction

To begin this essay, I would like to introduce you to the concept of a rhizome. Botanically, a rhizome can be described as a “mass of roots”. Unlike the root of a tree, where the branches and roots grow from one central point, the rhizome is structured as a network. What makes rhizomes unique is their ability to allow new root-shoots to grow upwards and become a plant stem instead of a root-stem. Any shoot can become a new plant, making rhizomes highly adaptable. Additionally, if a rhizome is separated, each piece can give rise to a new plant. These complex structures demonstrate impressive survival mechanisms, producing clones through highly effective vegetative reproduction systems. One of the very first rhizomes I ever held in my hand belonged to a plant called Japanese knotweed, *Fallopia japonica* (synonyms *Reynoutria japonica* and *Polygonum cuspidatum*). Its rhizomes can reach lengths up to seven meters, and its shoots can work their way through concrete, while root fragments as small as one centimetre can give rise to new plants. These are probably some of the reasons why this plant has become famous as ‘one of the world’s most invasive plants’. However, in my grandmother’s garden, where I first became familiar with it, it was never an enemy. My sister and I used to explore its vast territory of expansion, what we called ‘the jungle’, making paths and clearings across the area. The tall stems of the Japanese knotweed became swords, flutes, and building material for our imaginative play.

The house and garden were built by my great-grandparents in the 1920s on a wind-swept island on the Norwegian west coast. Any plant that would provide shelter from the wind was an appreciated feature (Figure 1). The suggestion to use knotweed probably came from the garden architect, who was hired to plan a large fruit and berry garden with beds of flowering perennials and herbs. The goal was to create a garden that was both useful and beautiful, providing shelter from the wind and adding a variety of colours to the landscape.

1

The introduction of Japanese knotweed to Europe can be traced back to the first half of the 19th century when Philipp Franz von Siebold, a German physician, botanist, and adventurer, brought over 1000 living plant specimens to Europe from Japan between 1823 and 1841 (Bailey & Conolly, 2000). Among these specimens were hosta, hortensia, and Japanese knotweed. While in Japan, Siebold learned about the edible young stems of knotweed and the medicinal value of its roots in Japanese and Chinese medicine. However, in Europe, knotweed was primarily valued as an ornamental plant, and it was even awarded a gold medal for being the most interesting ornamental plant of the year in 1847 by the *Society of Agriculture and Horticulture* in Utrecht (Bailey & Conolly, 2000). As a result, it quickly became a popular choice among garden and park owners throughout Europe. The plant most likely arrived in Norway in

1 The bare landscape surrounding the house and garden, 1930.
Photographer unknown

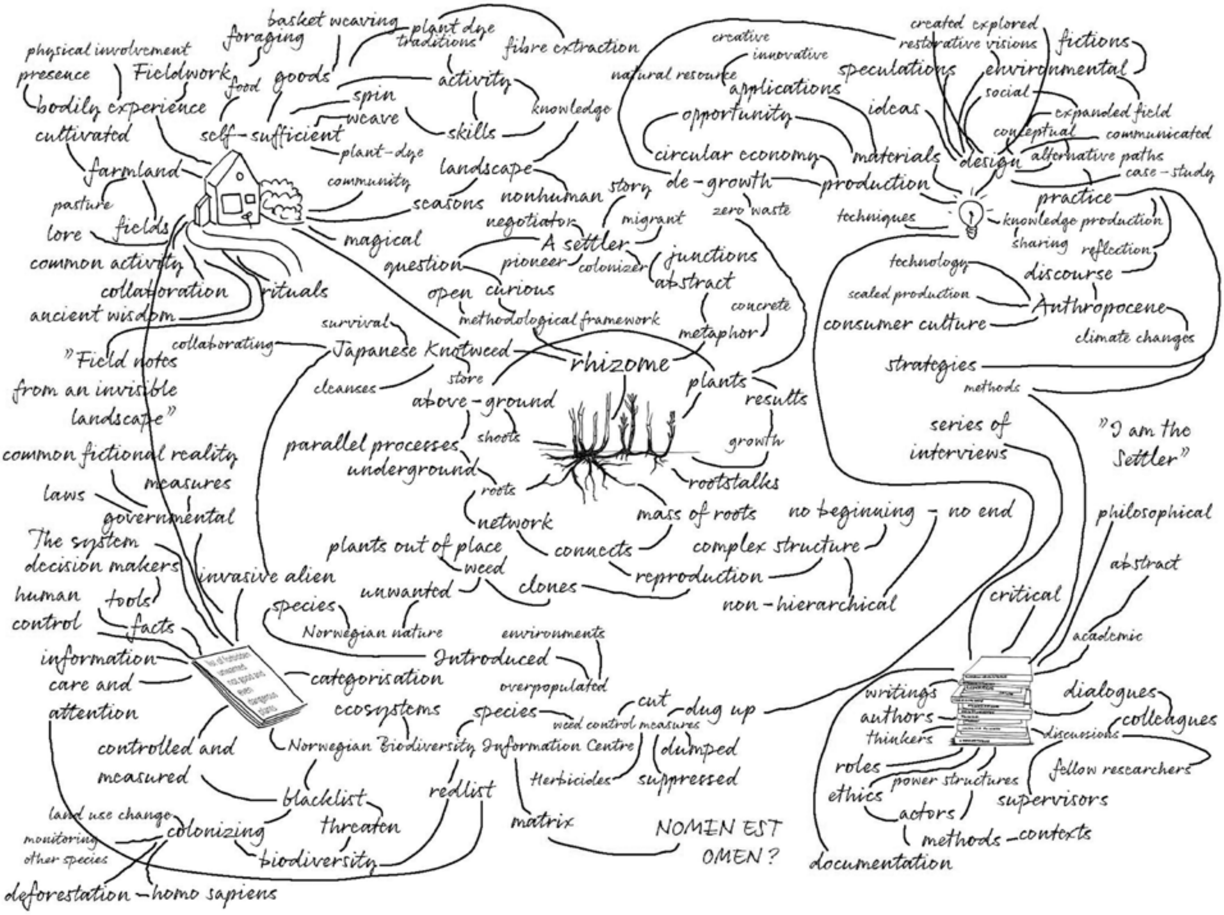
2 The author working with Japanese knotweed in her grandmother's garden, 2019.
Photo Niklas Sebastian Alveberg

2

the 1860s or 1870s (Elven et al., 2018), and by the time the garden architect suggested using it in my great-grandparents' garden, it had already become an established newcomer.

It is somewhat unclear which other ornamental plants were part of the original garden plan, and which were added later. Lupins and lilacs are visible in a photograph dating back to 1938. Today, the garden includes not only fruits, berries, roses, knotweed, and lupins, but also several plants listed as invasive alien plant species (IAPS) in Norway, including yellow loosestrife, *Lysimachia punctata*, beach rose, *Rosa rugosa*, Sitka spruce, *Picea sitchensis*, goat's beard, *Aruncus dioicus*, red elderberry, *Sambucus racemose*, hollyberry cotoneaster, *Cotoneaster bullatus*, and Scotch broom, *Cytisus scoparius.*

While the term "weed" can refer to any plant growing in an undesired location, IAPS specifically describes non-native plants that become overpopulated and negatively impact their new environments, causing economic or ecological harm (Orion, 2015). Invasive plants



can displace particular native species, reduce biodiversity, and alter ecosystem functions, resulting in negative impacts on wildlife and essential ecosystem services such as water purification and pollination. In addition, invasive plants can have economic impacts, such as reducing crop yields, damaging infrastructure, and increasing management costs. Yet, the question remains whether removal and eradication is the best solution, or if the complexity requires a different and more holistic approach. The current state of the world, including the climate crisis, biological mass extinction, growing human population, pandemic, and unstable political landscape, calls for a fundamental rethinking of production and consumption practices. Perhaps we need to start by addressing the underlying issue of our relationship to the natural world?

3 A conceptual (rhizomatic) mind-map of Siren Elise Wilhelmsen's PhD project.

Over the years, my grandmother's garden has become a place for reflecting upon the changing attitudes towards nature and the environment. What was once a barren and windswept landscape has evolved into a thriving habitat that supports a diverse range of species. For me, the garden serves as a reminder of our impact on the natural world, both positive and negative, and highlights our responsibility to make informed decisions about how we interact with nature.

My childhood memories of encountering Japanese knotweed have inspired me to view the "forbidden garden" as a place of opportunity, rather than a graveyard for poor choices, and to leverage my profession as a designer to explore these possibilities (Figure 2). Design is a field that bridges industry, crafts, and science and has the potential and responsibility to be a driver of transformation through functionality, creativity, and storytelling. In my PhD project in artistic research, called "The Settlers – Towards New Territories in Design", I approach IAPS as new local plants from which we can learn. By gathering stories about their edibility, environmental benefits, health benefits, colourants, fibre, and wood applications, we can create a new landscape of knowledge and understanding.

The following pages present the preliminary findings on colourants for textile dyeing derived from invasive alien plant species (IAPS) in Norway, with a particular focus on the results of the Japanese knotweed. These findings were first presented at the "XVII CONFERENZA DEL COLORE" in Florence in September 2022 in the presentation and paper "Plants out of place? A design-driven investigation of colour and material possibilities within a group of "invasive alien plant species" in a Norwegian context" (Wilhelmsen, 2022).

Plant dye as a historical local possibility

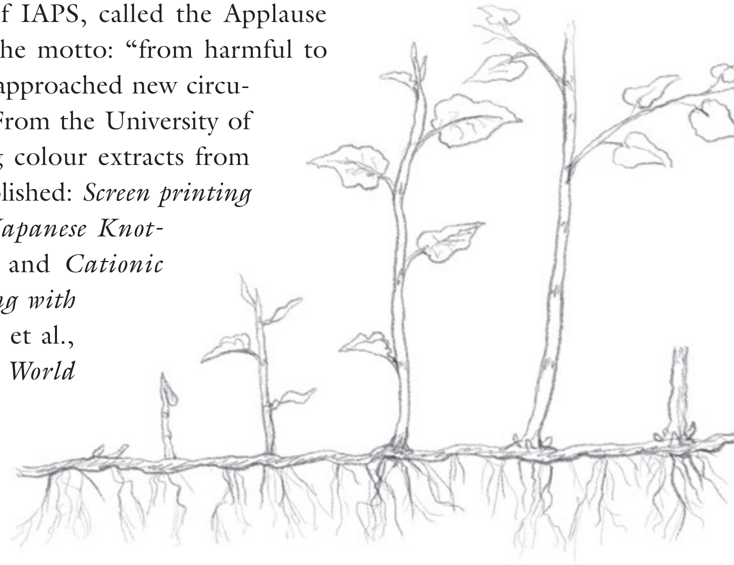
In Norway, as in most parts of Europe, the knowledge of dyeing with natural pigments has a long history. Early findings of plant-dyed cloth date back to the Late Roman Iron Age (Lukešová et al., 2017). It is assumed that mostly local plants were in use at this time, although imported colourants such as the red alizarin and purpurin from madder, *Rubia tinctorum*, and the blue indigotin from woad, *Isatis tinctoria*, have been identified in various textile samples (Bender & Walton, 1986). Woad seeds from 834 A.D. were found at the Viking Age ship burial site at Oseberg (Sagberg, 2017). It has also been proven that local variations of madder-like red dyes have been used, such as bedstraw, *Galium verum L.*, and Northern bedstraw, *Galium boreale L.*, as well as a whole range of local, unidentified, yellow dyestuff (Bender & Walton, 1986).

For centuries, natural dyes were the main colourants accessible for textile dyeing. However, with the development of synthetic dyes at the beginning of the twentieth century, the interest in and further development of natural dyes stagnated (Bechtold et al., 2003). In Norway, Hilda Christensen was one of the first to gather and preserve the knowledge of the old dye traditions (Christensen, 1924). Her textbook *Lærebok i farging med planter* ("Textbook on dyeing with plants") on natural dyeing was published 1908. In it, she presented recipes containing imported dyestuffs, like cochineal, indigo and madder. But, her focus was mainly directed towards local barks, leaves, twigs, herbaceous plants, and lichens, most of which are still viable in the Norwegian flora today. Despite this rich history, a hundred years of industrial production has had a huge impact on the environment and humans.

Over the years the landscape and flora has been drastically transformed, making the starting point for gathering and harvesting today very different than it was for Hilda and her contemporaries. Visible changes such as expanded urban, agricultural, and industrialized areas, infrastructure, and electrical power systems are evident even at a distance. Other changes must be experienced, such as certain climatic changes, or discovered up close, like the range of new species (UNEP, 2021). Since 1800, over two-thousand non-native alien plant species have settled in the Norwegian flora (Artsdatabanken, 2018). This new point of departure makes it apparent that we need to rethink, restructure, and re-establish our relationship with the environment.

Although most IAPS in Norway have been introduced as ornamental plants, some have long histories as cultural and useful plants elsewhere. Plants which are labelled as invasive in one place may be appreciated or protected in another context. Dyer's woad, *Isatis tinctoria*, has for instance been a sought- after resource throughout history. Today it has pest status in some western states of the United States (Weyl, 2022), while in the UK it is being reintroduced as a commercial dyestuff and cultivated as a such (TheWoadCentre, 2012). Similarly, Japanese knotweed is today known as one of the world's most invasive species yet valued in countries where it has cultural purposes. In Japan, it is known as *Itadori*, which translates to "tiger cane". This name may refer to the plant's vigorous growth and resilience, similar to the strength and power of a tiger. It has been used as a traditional medicine for centuries. Its root is a rich source of resveratrol and is still sold in nutritional supplements, and its young shoots are consumed as a vegetable (Shaw, 2013).

As the PhD project "The Settlers – Towards New Territories in Design" started at the University of Bergen, Faculty of Fine Art, Music and Design in 2018, the first case study and following exhibition, *Interpreting Fallopia japonica* presented a design perspective on Japanese knotweed, focusing on materials and colours. A range of warm yellows to ochre and golden brown were achieved by boiling its rhizomes without mordants. At the time, little research was found on colours and materials from IAPS. But in the following years an increased focus on the topic has resulted in interesting studies and projects world-wide. To mention some: NYC based artist Ellie Irons has through her project "invasive pigments" made watercolour from local IAPS (Beans, 2018), Alyssa Dennis based in Maryland (US) has started the "Invasive Apothecary", where she works with IAPS as part of her multidisciplinary art and clinical herbal pharmacy practice (Dennis, 2022), UK-based designer Marina Belintanis devoted her MA degree to material research on Japanese knotweed (RCA, 2020), and the city of Ljubljana has made a major investment concerning the handling of IAPS, called the Applause project (UIA, 2022). Based on the motto: "from harmful to useful", citizen-led activities have approached new circular economic and social systems. From the University of Ljubljana, two papers concerning colour extracts from Japanese knotweed have been published: *Screen printing with Natural Dye Extract from Japanese Knotweed Rhizome* (Klančnik, 2021) and *Cationic Pretreatment of Cotton and Dyeing with Fallopia Japonica Leaves* (Gorjanc et al., 2019). The book, *True Colors: World*



Growth stages of
Japanese knotweed

Masters of Natural Dyes and Pigments (Recker, 2020), presents the story of Avani, a non-profit organization in India. Their mission is to bring back community-driven, local textile production and responsibly made goods. Research on regional dyestuff revealed that a local pest plant, *Ageratina adenophora*, could yield a range of yellow and green dyes. Through regular harvesting, thereby removing the plant from the woods, the community helps balance the local ecosystem, which was suffering by the invasion of this plant. At the same time, the community accesses a wild growing dyestuff which is plentiful.

These examples are intriguing indications of a shifting mindset towards sustainable economic and social systems, based on holistic handling of IAPS as natural resources.

Outlining the palette – an experiment

The colour research presented here has focused on forty-five of the IAPS labelled with the "highest risk assessment" in Norway. A mapping of historical and present-day usage, descriptions, and indications of colour extraction became the starting point for the practical colour study. Availability constraints resulted in some plants being recorded based solely on the mapping without being tested in the studio, while others underwent multiple tests focusing on different parts of the plant. The tests were performed as dyes for textile, still the palette can hopefully be useful for a broader field.

Hilda Christensen's textbook formed the basis for all recipes and the process of generating the dye samples. It must be emphasized that these were studio experiments and not lab-tests. Chemical components, light fastness, wash fastness, and a systematic treatment of each single dyestuff have not been examined. In this early-stage study, the focus was on outlining the palette.

A broad range of shades and colour depths has been achieved by applying natural dyestuffs in various mordants. Alum was used as a pre-mordant in a separate immersion bath for the fibres, while vinegar, ammonium chloride, iron, and potash were used as separate post-mordants. The dyeing process involved boiling the dyestuff in tap water in a stainless-steel pot, with various plant materials like stems, twigs, leaves, petals, bark, fruits, and roots, which had been cut into small pieces. Dyestuff was boiled in water and allowed to soak for twenty-four hours before adding the fibre and heating it for an hour. The textile material was then split into 4 parts and treated with different post-mordants before being air-dried. Some mordants used by Christensen, such as tin and copper, are toxic and have been left out of this study. Others, such as cream of tartar, citric acid, or baking soda, will be considered for further development.

Results

The study employs four distinct mordants and showcases a total of 132 swatches, including frequent examples of yellows, greens, greys, beiges, and browns. However, apricot, rose, and orange are less common, while purple is only found twice, and one outcome displays turquoise and one red (Figure 4).

Approximately two-thirds of the high-risk group and two percent of the total group of IAPS in Norway have been mapped. Despite the limited scope, the results showcase a diverse and vibrant palette, providing a starting point for further exploration. Some colours stand out for their vivid and brilliant hues, such as the yellow shades extracted from crack willow, *Salix × fragilis*, and goat's beard, *Aruncus dioicus*, the yellow, green and turquoise tones obtained from large-leaved lupine, *Lupinus polyphyllus*, and the rose shades derived from meadowsweet shrub *Spiraea × billardii*. Other noteworthy findings include the various shades of green produced by Scotch broom, *Cytisus scoparius*, which shift from yellow-green in April-May to deeper greens and browns throughout the season. Iron proves to be a powerful colour shifter, yielding dark browns, grays, and greens. Further exploration is needed to fully understand the range of hues and develop a reproducible scheme. Alkaline additives like ammonium chloride and ash water tend to produce warmer nuances.

Some dyestuffs, such as the Sitka spruce, *Picea sitchensis*, show minimal reaction to changes in acidity, while others, like the dyestuff derived from Japanese knotweed rhizomes, are pH-sensitive. The study found that this dyestuff revealed the most significant colour shifts when exposed to varying levels of acidity or alkalinity in the dye baths. Previous research on Japanese knotweed had exposed warm yellow, ochre, and brown hues. However, this study uncovered

4 Following pages:
Overview of colours, with information about the plant sources, condition of dyestuff, mordants, and range of colours. The fibre used for testing is 100% neutral white sheep wool. Related plants, where the results are expected to be similar, are placed under the same number in this overview. The first name is the plant that was actually tested.
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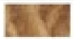
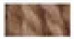
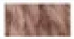
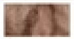
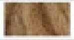
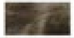
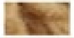
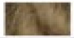
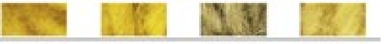
PLANT	PART	CONDITION	TESTED	COLOUR (INDICATION)	ALUMINUM SULFATE	AMMONIUM CHLORIDE	POTASSIUM CARBONATE	IRON(II) SULPHATE	PLAIN VINEGAR
1. ALASKAKORNELL / Red-osier Dogwood / *Swida sericea*	Twig	Fresh	June	Yellow / Grey	x				
2. ALPEASAL / Mougeot's Whitebeam/ *Sorbus mougeotii*	Bark	-	-	Yellow / Brown					
3. ALPEFURU / (buskfuru)/ (Swiss) Mountain Pine / *Pinus mugo* (**VRIFURU** / Lodgepole Pine / *Pinus contorta)*	Needle Cone	- -	- -	Green Brown					
4. ALPEGULLREGN / Scotch Laburnum / *Laburnum alpinum*	Flower / Leaf	-	-	Yellow					
5. BLEIKSPIREA / Meadowsweets / *Spiraea ×rubella*	Twig	Fresh	June	Apricot	x				
6. BLÅHEGG / Juneberry, Serviceberry / *Amelanchier spicata*	Berry	-	-	Purple					
7. BLÅLEDDVED / Fly Honeysuckle/ *Lonicera caerulea (var. Edulis)*	Berry	-	-	Purple					
8. BOERSVINEBLOM / Narrow-leaved Ragwort / *Senecio inaequidens*	Leaf Flower	- -	- -	Green / Yellow Brown / Orange					
9. BULKEMISPEL / Hollyberry Cotoneaster/ *Cotoneaster bullatus* (**BLOMSTERMISPEL** / Showy Cotoneaster / *Cotoneaster multiflorus)*	Leaf	Fresh	May	Beige / Brown	x				
(**DIELSMISPEL** / Diels' Cotoneaster/ *Cotoneaster dielsianus)* (**SPRIKEMISPEL** / Spreading Cotoneaster / *Cotoneaster divaricatus)*	Root	Fresh	May	Rose	x				
	Berry	-	-	Beige / Rose / Brown	x				
10. FAGERFREDLØS / Dotted Loosestrife / *Lysimachia punctata*	Flower	Fresh	July	Yellow / Green	x				
	Root	Fresh	July	Beige / Brown	x				
11. GRØNNPIL/ Crack Willow / *Salix × fragilis (Salix × rubens)*	Leaf	Fresh	July	Yellow / Green	x				
12. GULLREGN / Laburnum / *Laburnum anagyroides*	Bark Flower	- -	- -	Brown Yellow/ Orange					
13. GYVEL / Scotch Broom / *Cytisus scoparius*	Stem w/ buds	Fresh	April	Green	x				
	Flowering stem	Fresh	July	Green	x				
14. HAGELUPIN / Big-Leaf Lupin, Lupine / *Lupinus polyphyllus* (**JÆRLUPIN** / Sundial Lupine / *Lupinus perennis)*	Blue flowers	Fresh	July	Green/Turquoise	x				
(**SANDLUPIN** / Blue Lupine / *Lupinus nootkatensis)*	Stem / Leaf	Dried	July	Yellow	x				
15. HYBRIDBARLIND / Anglojap Yew / *Taxus x media*	Stem / Bark	Fresh	June	Apricot / Brown	x				
16. HØSTBERBERIS / Japanese Barberry / *Berberis thunbergii* / green leaves	Stem / Leaf	Fresh	July	Yellow / Grey	x				
– / red leaves	Stem / Leaf	Fresh	July	Apricot / Yellow	x				
17. JAPAN PESTROT / Sweet Coltsfoot, Butterbur / *Petasites japonicus*	Leaf	-	-	Yellow / Orange					

18. KANADAGULLRIS / (Giant-)Goldenrod / *Solidago canadensis (+ gigantea serotina)*	Flowering stem	-	-	Yellow / Green/ Grey	x	
19. KJEMPESPRINGFRØ / Himalayan Balsam / *Impatiens glandulifera*	Stem/ Leaf/ Flower	-	-	Ginger/ Brown		
20. KLASESPIREA / Meadowsweets / *Spiraea ×billardii*	Twig	Fresh	July	Rose	x	
21. KLISTERSVINEBLOM / Sticky Groundsel / *Senecio viscosus*	Leaf Flower	- -	- -	Green Yellow / Brown		
22. KRYPFREDLØS / Creeping Jenny / *Lysimachia nummularia*	Root	Fresh	Sept	Brown / Grey	x	
	Leaf / Stem	Fresh	Sept	Yellow / Beige / Grey	x	
23. MONGOLSPRINGFRØ / Smallflower Touchmenot / *Impatiens parviflora*	Leaf / Stem	-	-	Yellow		
24. PARKGULLTVETANN / Yellow Archangel / *Lamiastrum galeobdolon galeobdolon*	Leaf / Stem	-	-	Green / Beige		
25. PARKSLIREKNE / Japanese Knotweed / *Reynoutria japonica, Fallopia japonica*	Leaf	Fresh	May	Yellow / Ochre / Grey	x	
(**HYBRIDSLIREKNE**, Bohemian Knotweed / *Reynoutria x bohemica)*	Root	Fresh	July	Yellow / Orange Red / Green	x	
26. PLATANLØNN / Sycamore / *Acer pseudoplatanus*	Bark / Twig	Fresh	June	Beige	x	
	Leaf	Fresh	June	Yellow	x	
27. PRAKTMARIKÅPE / Lady's-mantle / *Alchemilla mollis*	Leaf / Stem	Fresh	May	Yellow / Green	x	
28. PURPURSPIREA SPIREA (Bjarkøyspirea) / Meadowsweets / *Spiraea x rosalba*	Twig	Fresh	July	Rose	x	
29. RYNKEROSE / Beach Rose / *Rosa rugosa*	Hip	Dried	July	Beige	x	
	Petal	Dried	June	Beige / Brown	x	
30. RØDHYLL / Red Elderberry / *Sambucus racemosa*	Berry	Dried	August	Beige / Green	x	
31. SKOGSKJEGG/ Goat's Beard / *Aruncus dioicus*	Leaf / Stem	Fresh	June	Yellow / Green	x	
32.SNØBÆRBUSK/ Common Snowberry /*Symphoricarpos albus (L.) S.F.Blake*	Twig	Fresh	June	Yellow / Grey	x	
33. SITKAGRAN (+Lutzgran) / Sitka Spruce/ *Picea sitchensis (+Picea ×lutzii)*	Needle / Twig	Fresh	June	Beige / Brown	x	
34. TROMSØPALME / (Persian) Hogweed / *Heracleum persicum, Heracleum tromsoensis*	Leaf / Stem	Fresh	June	Yellow / Grey	x	
35. VESTAMERIKANSK HEMLOKK / Western Hemlock / *Tsuga heterophylla*	Bark	Fresh	May	Brown	x	
36. VALURT / Comfrey / *Symphytum officinale*	Leaf / Stem	-	-	Green		
37. ULLBORRE / Woolly Burdock / *Arctium tomentosum*	Root	-	-	Green / Beige		

dramatic colour changes in the dyestuff based on the pH of the solution. For instance, adding iron produced an olive-green colour, while alkalic agents generated an array of reddish hues. Furthermore, a test conducted without alum-treated fibres resulted in orange colours with ammonium chloride and rose shades with potashes. Additionally, the dyestuff was tested in a cold-dye for a week, which produced softer and paler tones of the same variety of colours. The experiments resulted in a wide range of hues achieved with Japanese knotweed (Figure 5). Although further testing is necessary to determine wash fastness, rub fastness, and light fastness for all samples, the Japanese knotweed swatches from 2018 remained unchanged after washing, and retained their colour quality, albeit slightly darker.

Conclusions

My childhood experiences from the ‘forbidden garden’ and my acquaintance with the Japanese knotweed have influenced the direction of my career path and research interests. Not only has this plant fascinated me with its range of applications, such as medicine, food, and colours, but its rhizomes have taught me something even more important. The flexible and open structure of the rhizomes provides a perspective, or even a recipe, for a way of being in the world. The rhizomatic network prioritizes collaboration and interdependence over hierarchy and control, challenging the dominant linear and vertical structures of modern society that prioritize individualism and competition. By valuing the interconnectedness of all things, we can create more sustainable and equitable systems that prioritize the well-being of both people and the living planet. Through this perspective, the rhizome offers a powerful metaphor for understanding our place in the world, embracing a holistic approach to production and consumption, with the goal of moving toward a more collaborative, interconnected, and sustainable future.

By approaching the group of IAPS with this mindset, a new narrative can be articulated. The group of invasive alien plant species

(IAPS) in Norway must be adaptable and robust to thrive in this harsh environment. They do not require fields, as they often grow in urban areas where native plants cannot survive, which provides an opportunity to activate abandoned and unmanaged areas of the city for material harvesting, combining it with maintenance of vulnerable areas (Orion, 2015). Harvesting in this way could be time-consuming

5 Dye swatches of Japanese knotweed.
Photo Siren Elise Wilhelmsen

since it might involve moving from site to site. On the other hand, cultivating dye crops in a field would involve ploughing, seed bed preparation, and weed control (Bechtold et al., 2003). Furthermore, replacing harmful and labour-intensive measures, used to combat IAPS, with knowledge and care could result in natural reduction and balance based on utilisation, local production, and circular economy.

Creating new plant-based palettes and site-specific recipes makes it possible to generate dyes from renewable natural sources, as opposed to synthetic dyes produced with substances from non-renewable and non-local sources. The process can be a social practice, a local business, or a forager's way of reducing consumption and collecting colourants for personal use. The harvest and preparation of dyestuffs from local plants connects us to the plants, the environments and landscapes in which they grow. It is also a way of reconnecting with the past and traditions passed on from artisans through history, while also paving the way towards a balanced and fertile coexistence in the future.

The colour study demonstrates that IAPS can be promising dye plants for the future. Although the results should be seen as indicators rather than absolute answers, potential applications include textile dye production, development of inks, lake-pigments, and food-colourants, as well as paints for architecture and design, natural stained paper, and colourants for cosmetics and pharmaceuticals.

The aim of these fieldnotes from the "forbidden garden" has been to add new knowledge and insight from involvement with a group of invasive alien plant species in a Norwegian context, with transfer value to other communities and ecosystems. This can hopefully contribute to widening the range of information available and draw further attention to the potential of pushing the boundaries of local resources and a holistic approach to colour production at any scale.

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Photos Ingvill Fossheim and Julia Lohmann (left),
Julia Lohmann (right)

Beetroot (Beta vulgaris)

Beetroot, used as food and medicine since ancient times, can provide colours that are intensely vibrant yet highly unstable. Stains from the freshly cut vegetable will colour human skin and materials like textiles in bright reds and magentas. Adapting the dyeing process and ingredients can change these colours into yellows, purples and greens. They may fade into shadow-like beige traces.

> "I explored beetroot vegetable colour in the context of costume and performance praxis, experimenting with colour extraction, manipulation and application onto and with costumed human bodies.
> This investigative creative process was shaped by the unstable and impermanent qualities of biobased colourants, inviting critical reflection on how biobased colour can be understood and appreciated as a performative agent."
>
> — Ingvill Fossheim

Beta vulgaris, lemons, and dancer Jussi Suomalainen in the performance *As time goes by* (2023) produced by Zodiak – Centre for New Dance and Jenni-Elina von Bagh / Open-ended ry. Costume design by Ingvill Fossheim
Photo by Katri Naukkarinen

These video stills, from Juhani Haukka's short film *Värjäys / Farging / Colouring* (2021), produced by Väkevä Collective, show the costume designer-researcher at work.

Details of beetroot-stained costumes by Ingvill Fossheim.
Photos Ingvill Fossheim and Julia Lohmann

Photo Hung Jui Tsao

Carole Collet

Towards a life-conducive system reset for textile colouring

ABSTRACT

How can new bio-informed textile colouring practices participate in the process of regenerating our soils, our oceans and our biodiversity? We are on the cusp of a colour revolution in the textile sector. Two key factors are driving this. First the relatively recent emergence of biodesign – the integration of biological tools into the design process – is expanding our approach to colouring textiles. Second, a deeper understanding of the environmental impact of the fashion and textile industry is rapidly stimulating radical innovations. Start-ups are increasingly developing nature-positive colourants made with microbes, algae and biomass waste. Although for millennia, we relied solely on natural ingredients derived from plants, minerals, soil, metals and insects to pattern fabrics, the twentieth century advancement in oil-based chemistry has made prevalent synthetic dyes that are harmful to life. Today, the development of alternative bio-informed dye technologies is opening up a whole new landscape of possibilities. Some of these techniques rely on fermentation, bio-assemblage or bioengineering. Understanding their ecological contribution and limitation is critical in the context of our planetary emergency. This chapter proposes a framework centred on living-system thinking to position bio-colouring processes in relation to life-conducive environmental and ethical principles.

Keywords
biodesign, living systems, life-conducive, microbial colourants, bio-informed strategies

Colouring textiles in a planetary emergency

International scientific evidence shows us that human activities have led to a rapid decline in our planetary health. Today, one million species are at risk of extinction (IPBES, 2019) and we have reached a climate 'code red for humanity' (Guterres, 2021). Intensive farming methods have depleted our soil nutrients (FAO, 2019). Our oceans' life-sustaining capacity is threatened by plastic pollution (UNESCO, 2022). Our rivers and underground water reserves are directly compromised by intensive farming and industrial pollution (Soil Association). The fashion and textile industry is part of this toxic legacy and its detrimental impact on the natural world is well established (Global Fashion Agenda & Boston Consulting Group, 2017, Ellen MacArthur Foundation, 2017). Our modes of textile fabrication are threatening our climate, our biodiversity, and our soils. We urgently need to reverse this decline: we need to transition from a linear, extractive textile economy into a circular bioeconomy that helps restore planetary health. This will require the imagination of new manufacturing systems and exploring new modes of textile colouration will be core to this shift.

Can we imagine viable, scalable alternatives for a post-petrol textile colouring system? Textile colouration today has two main paths: traditional natural dyeing processes, or using synthetic dyes derived from the petroleum industry, a non-renewable resource. The latter is the de-facto standard process used in the global commercial textile industry, whilst natural dyes are only valued as part of small scale, artisanal and local systems. Both processes have a direct impact on the environment. The use of non-renewable synthetic dyes promotes the extraction of oil, which in turn generates large amounts of greenhouse gas emissions, and their disposal in water or soil is hazardous to life (Lellis, B. et al., 2019). Natural dyes are derived from plants, insects and minerals. Contrary to common belief, they can also have a negative impact on our environment when used with traditional metallic mordanting (i.e. chromium, iron, copper salts). These

Automating Violacein,
Charlotte Werth
Photo Paul Cochrane for Maison/0

mordants are toxic (Thacker et al., 2022) but in some cases can be replaced by renewable plant-based biomordants (Ashis, 2020; Grande et al., 2023). Plant-based natural dyes can also require large amounts of land to grow. In a context in which climate change is jeopardising our capacity to grow food, producing dye plants on a much larger global scale is not an alternative. Natural dye plants can, however, be grown as part of local holistic regenerative agriculture systems, a form of farming that promotes the restoration of biodiversity and captures carbon (Textile Exchange, 2022). The Fibreshed network promotes this nature-positive approach, as a regional soil-to-soil fashion farming network (Burgess, 2019). Both synthetic and natural dyes require the use of large amounts of water, a commodity at risk in today's context of increased climate-induced draughts. Developing solutions that radically reduce water usage should also be a priority. In this context, we note the development of waterless $C0_2$ dyeing by Dyecoo, a system that uses reclaimed $C0_2$ as a dye carrier instead of water. This technology is based on synthetic dyes, but directly addresses the need to reduce water usage and pollution.

International cooperation negotiated via the United Nations such as the COP 21 Paris Agreement signed in 2015 or the more recent COP 15 Global Biodiversity Framework (2022) drive new regulations and initiatives. In the European Union, a new Digital Product Passport is being prepared as part of the European New Green Deal and will require the environmental impact of every product circulated in the union to be much more transparent. The ZDHC (Zero Discharge Hazardous Chemicals) roadmap for sustainable chemical management within the fashion industry is also driving progress. However, in the context of a critical planetary emergency, beyond optimising existing textile colouring systems, there is also a need to pose new research questions and explore disruptive models. Can we imagine an efficient alternative textile colouring system that benefits the environment instead of depleting life on Earth? What renewable colour processes can be derived from applying bio-circular principles? Can colour obtained from microbial fermentation replace the use of synthetic dyes at scale? Today, we are witnessing the emergence of such alternative bio-circular or bio-informed design research, be it derived from scientific inquiries or led by new design practices. Although not mainstream, nor yet developed on a global scale, they offer a new imaginary for a post-petrol textile colouring process.

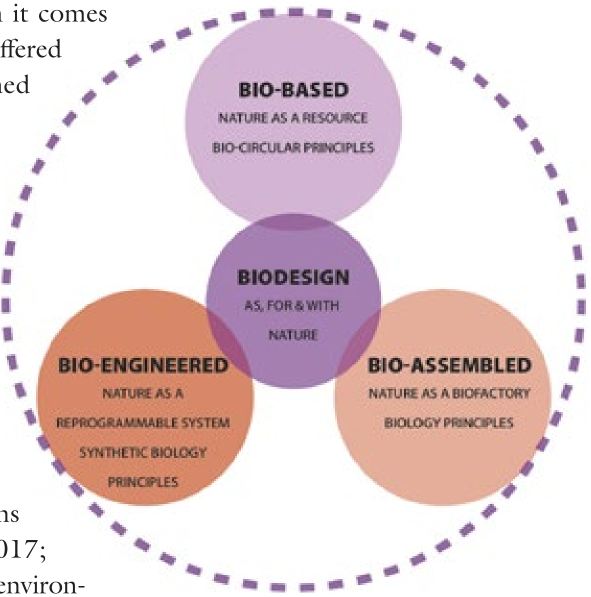
The first section of this chapter proposes a framework centred on living-system thinking to position these emergent bio-colouring processes in relation to environmental principles. The following sections discuss a range of design-led projects and examine the potential of these new colouring systems, be they bio-based, bio-assembled or bioengineered.

Positioning a taxonomy of bio-informed strategies for textile colouring

Why should we develop bio-informed design and manufacture strategies for textiles? We cannot transition into a nature-positive circular bioeconomy without recalibrating our design practices. Design specifications directly influence material sourcing and manufacturing tools. Nature has been a key inspiration throughout human cultures, as is evidenced in our craft and design history. The concept of the circular economy derives from biomimicry, the emulation and adoption of nature's strategies in human systems (Biomimicry Institute, 2020) and it coincides with the emergence of biodesign, defined as the integration of biological tools and organisms into the design process (Myers, 2012). Biodesign is actioned in both the design and scientific fields and has radically transformed our approach to designing with and for the natural world. In addition to inspiration and imitation, biodesign learns from biological protocols to drive new inquiries into sustainable practices. In the field of textiles, this applies to the development of new bio-informed materials as well as to alternative colour technologies.

The biological world has evolved to function at ambient temperatures, using local resources for energy and nutrients without generating harmful toxic waste (Benyus, 1997). Living systems are by default life conducive: they operate in dynamic, complex and interconnected networks in which the waste of one species becomes the nutrient of others. Learning how to biofabricate as nature does is therefore essential if we are to shift away from our current extractive, linear and oil-centric economy. However, as the field of biodesign and biofabrication expands, diverse practices and narratives are evolving in which the prefix 'bio' is often used as a signifier of sustainability. We need to clearly distinguish the meaning behind the use of terminologies such as bio-based, bio-informed, bio-integrated, bio-assembled, biofabricated or bioengineered. ‘It is not safe to assume that bio is better’ (Biofabricate, 2020, p. 5). In the same way, the term ‘natural’ does not mean ecological: qualifying a material or a pigment with the adjective ‘bio’ does not imply that it is environmentally positive at scale. Cotton is a good example. Cotton grown in conventional intensive agriculture leads to serious environmental damage: water pollution, CO_2 emissions, high-level use of chemical fertilisers, soil depletion, and biodiversity loss (Textile Exchange, 2018). Cotton is a natural plant that captures carbon as it grows and contributes to its ecosystem when in its native wild environment. Once exploited in monoculture, human-engineered systems, its production becomes toxic: natural does not necessarily mean sustainable. Equally, a ‘bio’ material or pigment may stem from toxic intensive agriculture, contain limited amounts of biomass or even be a mix of petro-chemicals and bio-based ingredients (Biofabricate, 2020). In addition, some biofabrication processes include genetic engineering, often referenced as a proprietary biotechnology. This lack of transparency and mixed use of terminologies can lead to confusion when it comes to identifying the ecological advantage offered by the adoption of biologically-informed processes in design and biomanufacture.

We need to ensure that we do not simply replicate our extractive approach to the natural world with these new ‘bio’ narratives and toolsets. Instead we must truly transform our ways of making and transition into a life-conducive circular, regenerative textile economy. Therefore, we need to frame these emergent practices using a critical environmental lens. Cross-referencing existing classifications (Biofabricate, 2020; Camere et al., 2017; Collet 2017; 2021) with life-conducive environmental criteria, figure 1 proposes a taxonomy of interactions with living systems in three parts to articulate the key thresholds across bio-informed approaches in biodesign practice.



1 Bio-informed strategies for design: a taxonomy of interactions with living systems.
Carole Collet 2023

Strategy 1: Designing bio-based materials (see examples in Section 3):

In this framework, the design of bio-based materials entails the adoption of bio-circular principles. By promoting the uptake of biomass waste as a new source for material or pigment production, we remove the need to extract virgin resources, i.e. living space for Nature to recover (Ellen MacArthur Foundation b). This design and fabrication approach uses inert biomass from the leftovers of agricultural systems to create biodegradable and compostable material solutions. In today's linear economy, the management of waste is guided by cost and convenience, not by the laws of nutritious decomposition in nature. In some parts of the world, agricultural waste is burnt (Uma et al., 2022), leading to CO_2 emissions and air pollution, and untreated textile wastewater is released directly into rivers (Athira, 2018). Embracing the concept of biodegradability and designing with and for decomposition should be central to the next generation of bio-based materials (Biomimicry Institute, 2020). However, two main environmental challenges should be considered. This bio-based material design approach should rely on regional and local waste streams, and not promote the global energy-hungry circulation of materials before transformation. Sourcing biomass waste from organic farming systems should also be a priority to support farming models that work in harmony with nature.

Strategy 2: Designing bio-assembled materials (see examples in Section 4):

In contrast to the bio-based approach above, bio-assembled materials harness the active metabolic function of organisms to directly grow materials. They rely on living micro-organisms such as algae, microbes, or mycelium to function as biofactories in closed environments. These organisms naturally generate materials or pigments in their endemic wild ecosystems, but here, their biological capacity is optimised in controlled nutrient baths to be harvested at scale. Using fermentation techniques or cellular agriculture, we can create the relevant parameters for these organisms to live in optimum conditions, by carefully monitoring their temperature, humidity and nutrient levels to enable their best performance. Different methods can be used with different organisms, but they all entail the destruction of the living microorganisms

Bio-informed strategies for the circular bioeconomy	Principles	Environmental benefits	Environmental challenges
1 – Designing bio-based materials Biomass waste as a renewable circular resource	Bio-circular: using biomass waste as a starting point	– Renewable – Biodegradable – Compostable – Reduced need for raw virgin materials/leaves space for nature to recover – Promotes local regional upcycling of biomass waste	– This works for local/regional economies – but is questionable if biomass waste has to travel long distances (CO_2 emissions) – Should not support intensive farming systems by creating value streams for their toxic waste. – Unclear 'bio' terminology: need more transparency and legislation related to actual bio-based content – Knowledge gap: need further research to develop materials that match current industry quality standards.
2 – Designing bio-assembled materials Nature as a biofactory	Biology: relying on living metabolic self-assembly principles to grow materials	– Works at low or ambient temperature in the growing phase – Renewable – Biodegradable – Leftover biofabrication waste can be reused in composting schemes – Promotes the reduction of traditional land use for material production – Growing in controlled environment removes risk of climate-related crop failure	– Requires energy for sterilising feedstock and containers – Feedstock needs to be sourced from organic origins – Limited life-cycle analysis data available – Knowledge gap: need further research to develop materials that match current industry quality standards.
3 – Designing bioengineered materials Nature as a reprogrammable system	Synthetic biology: fine-tuning existing biological functions with genetic engineering to improve and expand biological fabrication capacity	– Works at low or ambient temperatures in the growing phase – Biodegradable – Renewable – Promotes the reduction of traditional land use for material production – Growing in controlled environment removes risk of climate-related crop failure	– Must operate within ethical guidelines – Requires energy for sterilisation of feedstock and containers – Use of GM: Must operate in closed-loop environment in manufacture stage to avoid contamination. – Feedstock needs to be sourced from organic origins – Limited life-cycle analysis data available – Knowledge gap: need further research to develop materials that match current industry quality standards.

in the final stages, (via heat or sterilisation processes) to render the harvested material biologically inert. Using biodesign, we can radically alter creative practice, with the notion of working with dynamic living systems as opposed to inanimate matter. ‘Designers are now able to expand their roles from scripting the form-shaping of existing inanimate materials, to creating and growing new biological materialities’ (Collet, 2017, p. 25), they can design, as, for and with Nature.

Strategy 3: Designing bioengineered materials (see examples in Section 5):

This biodesign strategy relies on biological assemblage protocols, but also involves the use of genetic manipulation designed to optimise or increase the natural biofabrication capacity of existing microorganisms. Using synthetic biology tools, we can reprogram their metabolic function and tune their performance with precision. This biotechnology needs to be applied in closed-loop systems to prevent any contamination and must operate within strict ethical guidelines. The world of bioengineered materials is rapidly expanding and opens up radical and disruptive possibilities that can fundamentally reshape our relationship with the natural world. We need to cross-examine these possibilities in the context of ethical and just future systems (World Economic Forum & Faber Futures, 2022).

Both strategies 2 and 3 relate to biofabrication, which uses organisms as living biofactories to create materials. Both rely on feedstock, such as sugar, to nourish the selected microorganisms. The provenance of these feedstocks is one of the key challenges in upscaling biofabricated materials and pigments. Here again, we need to prioritise sources from organic and/or waste streams so as not to add value to the leftovers from intensive toxic agricultural models.

The table on the left highlights the key principles of each strategy associated with environmental benefits and challenges. These bio-informed material strategies are recent, and their availability on a commercial scale is limited. Their life-cycle analysis is also limited, and we need to continue monitoring their performance to ensure that their environmental benefits are maintained when produced at scale.

In this section, we have discussed how working with living systems principles can help us transition towards a life-conducive, bio-circular textile economy. We have posited a framework that situates a taxonomy of bio-informed strategies in relation to environmental benefits and challenges. In the following sections, we discuss how biodesign textile colouring practices are beginning to reshape the sector, be this at the proof-of-concept stage or on a commercial scale.

Bio-based approaches to colour

In this section, we review a range of creative textile propositions as well as new dye technologies that rely on biomass waste as a primary resource to produce colour. These circular initiatives offer a range of inquiries into bio-based colouring other than ancestral natural dye techniques and thus increase their potential.

Colour/Matter, a design research studio led by Rebecca Hoyes and Jo Pierce at Central Saint Martins UAL is dedicated to exploring alternative print concepts for textile colouring. Their project *New Natural 02* (Figure 2) examines the use of undervalued and overlooked food waste as a resource for natural dyes and asks: Can food waste increase the use of bio-based colour?

For this collection, they developed original dye recipes that exclusively use food waste for both dye and print techniques. Interest in using waste streams from the food industry as a resource to produce new materials and extract colour pigments is growing. In 2019, Kaiku, a start-up founded by Nicole Stjernsward developed a process of turning agricultural waste from avocado, pomegranate and onions into powdered textile pigments. Dye manufacturer Archroma has developed Earthcolors®, a range of commercial GOTS-certified (Global Organic Textile Standard) textile pigments made from agricultural waste such as nutshells, leaves, and herbal residues. Wasting food entails wasting large amounts of energy, water and labour required for its production. 'Globally, around 14 percent of food produced is lost between harvest and retail, while an estimated 17 percent of total global food production is wasted' (United Nations, 2022). This is no negligeable amount and represents a potential alternative circular source for pigment production. However, the colour range obtained from food waste is fairly limited (pastel pink and green, orange, brown, purple and greys) and is not a realistic alternative to the full colour palette achievable with synthetic dyes.

In a similar approach, Living Ink, a bioscience research company based in the USA produces Algae Black™ on a commercial scale,

a carbon-negative textile ink. Using the leftover biomass of algae-farmed food colouring production from a neighbouring company (Figure 3), they have developed a unique process to manufacture an OEKO-TEX certified water-based ink for printed textiles. Algae grow rapidly and capture carbon as a source of energy, thus providing a raw material that contributes to reducing our carbon footprint.

Algae waste stream from the food and cosmetic industries are also the primary resource claimed by Zeefier, a natural seaweed textile dye brand launched by Dutch designer Nienke Hoogvliet, in 2021. After nearly a decade of design-led research into the use of algae, Hoogvliet established key protocols to repurpose algae into textile dyes.

Food waste can also play the role of a catalyst to help clean up synthetic dye waste streams. Excessories (Figure 4), a project developed by designer Cassie Quinn, started from the ambition to explore the issue of textile dye wastewater using biodesign tools. Legislation differs from country to country, and the release of synthetic dye

2 *New Natural 02* collection, by Colour/Matter studio, 2019.
Photo Atton Conrad

3

wastewater into rivers is still allowed in some parts of the world with varying permissible limits, even though these dyes contain non-biodegradable pollutants that are harmful to life (Castillo-Suárez et al., 2023). As biological, physicochemical, and advanced oxidation processes can be used to remove such toxic pollutants from synthetic dye effluents, Quinn wanted to explore the recovery of coloured particles as a means to create a new bio-based material.

4

3 Algae production for food colouring.

Photography courtesy of Earthrise Nutritionals

4 Excessories, by Cassie Quinn, 2020, part of a collaborative Maison/0 project with LVMH and the MA Biodesign course at Central Saint Martins UAL.

Photo Paul Cochrane

The project was initiated by Maison/0 as a collaboration between the environment team at the luxury group LVMH and the MA Biodesign course at Central Saint Martins UAL. In the quest for a system reset and the transition towards a fully circular bioeconomy, the project explored the potential of biodesign for future luxury products. By developing a unique bio-based recipe using ingredients derived from food waste, Quinn successfully developed a technique that can clean textile dye wastewater. The process results in a leftover material from which she has produced sequins as an alternative to plastic sequins. The colour of the material is the colour of the wastewater used at the start of the process, which potentially enables a full spectrum of colours.

In this section, we have explored a range of projects that activate carbon capture and circular textile colouring systems. These examples showcase diverse inquiries into bio-based processes, some are still at the prototype level, others are commercially available. Although they do not individually address the scale of the issues linked to textile colouration, they increase and diversify our current options. Reusing waste is core to our transition into a circular textile industry and these projects demonstrate that a new roadmap is possible. However, we also need to ensure that by creating new dye processes we do not incite or sustain the production of waste, but simply offer propositions relevant to unavoidable forms of waste. It would also be useful to source biowaste from organic origins as opposed to creating added income for intensive farming food systems.

Bio-assembled colour

Learning from the natural biological world is key to biodesign. In this section, we focus on examining the development of alternative colouring processes that rely on working with living organisms to produce pigments, be they extracted from organisms or directly grown onto cloth. One of the key principles of biology is self-assembly: cells directed by their DNA codes will grow, evolve and self-assemble in a range of active structures and behaviours. In the natural world, many organisms rely on local ingredients such as solar energy, rainwater and macronutrients to produce colour at ambient temperatures without generating toxic byproducts. We can learn from these biofabrication principles. Some bacteria, algae and fungi are indeed able to produce pigments using their intrinsic biological capacity. Working with bio-assembled colouring processes is now a realistic emergent form of textile colouring, driven by both biodesigners and scientists alike.

More than a decade ago, pioneer designer Natsai Audrey Chieza, founder of Faber Futures, prototyped textile printing with bacteria in collaboration with Professor John Ward at UCL. The Coelicolor project has since been further developed as an inquiry into design-driven protocol for bacterial printing. Today, we are witnessing the development of promising new microbial dye technologies, now reaching commercial scale. Microbial research has shown clear environmental benefits, including biodegradability and significant water-saving in comparison to synthetic dyes (https://faberfutures.com/projects/project-coelicolor/). Bacterial colours also work across fibre types (cellulose, keratin or synthetic) without needing toxic mordanting.

For textile designers, the application of bacterial colour onto cloth is more than an environmentally beneficial technical process; it is also a new platform for creativity. Every new technique calls for imaginative applications. This was the focus of Charlotte Werth's *Automating Violacein* produced for her design residency at Maison/0 (Figure 5).

With the bacteria printing machine she developed for her MA Material Futures graduation project at Central Saint Martins UAL, Werth has further explored the potential of this automated technique to develop a range of printed textiles using *Janthinobacterium lividum*, a wild soil-dwelling bacterium. By experimenting with folding, pleating, resist techniques and multiple dye run throughs, Charlotte has created a variety of patterns. The challenge for the designer is to orchestrate a life-support nutrient system for bacterial growth, whilst at the same time engineering a patterning process by controlling the areas of the fabrics exposed to the activity of live organisms.

In addition to bacteria, fungi can also be used as a cellular pigment-producing organism, as demonstrated by Liene Kazaka in her Myco Colour project, developed for her MA Material Futures graduation thesis at Central Saint Martins, in 2021. Using *Chlorociboria aeruginascens*, a green elfcup fungus, to release a turquoise pigment directly onto fabric as it grows, Kazala eliminates the need for chemicals by relying on the active biological properties of this fungus to fix pigment into fibre. According to her research, the

5 Automating Violacein by Charlotte Werth, 2023. A Designer in Residence Maison/0 project at Central Saint Martins UAL.
Photo Paul Cochrane

pigment produced by this mushroom has shown equal colour fastness to commercial dyes (https://lienekazaka.com). Although this project is a proof of concept, it has established new knowledge in the field of textile colouring and demonstrates the potential of exploring further principles of living colours found in nature.

The world of fungi also informed Julia Jueckstock's Hyphea Hues project, part of the collaborative Maison/0 project mentioned above, in 2020. Referencing the culinary recipe of grain fermentation traditional in Japan, China and Korea, Jueckstock used a red yeast fermentation process to cultivate a living pigment for textiles. Using waste from a local distillery as feedstock, she developed an original yeast-based recipe to either dye fabric in live fermentation batches, or to produce a print paste by extracting the red pigment. Figure 6 shows a scarf first dyed with live red yeast, then screen printed with a yeast paste.

Although the projects above exemplify the potential of working with living organisms to develop bio-assembled protocols for textile colouring, they remain limited in their industrial applications to date. Bacterial colours derived from natural organisms found in nature, also called 'wild type', offer real ecological advantages: they remove the need for the mordanting used in traditional natural dye recipes to fix pigment into fibres. They also work across fibre types (cellulose, keratin and synthetics) and require less water than both natural and synthetic dyes. They are biodegradable and their nutrients can also be derived from waste sugar feedstocks. However, their colour and light fastness is limited, and this presents a real barrier to achieving an industry standard for large-scale applications. The colour range of wild type is also very limited bacteria (mainly purple-pink and grey hues). These limitations can be addressed by using biotechnology and genetic engineering, examples which we discuss in the next section. Using live fungi and yeast to dye textiles is less developed than bacterial dyes but represents yet another path to explore further.

Whilst there is an established body of literature on the use of natural dyes, there is a knowledge gap concerning the use of organisms as living cellular pigment factories. Yet we are very experienced in working with organisms such as yeast for the production of beer, wine, cheese and other culinary traditions. Perhaps we can explore the transferability of such knowledge to establish a new kind of textile colouring process derived from natural fermentation protocols. This

approach to bio-assembled colouring with wild type microorganisms, in which the production of colour is directly controlled by cell factories, is still at a nascent stage and requires further research to establish its full potential in terms of scalability.

Bioengineered colour

A growing number of designers are experimenting with the creative potential of wild type bacterial dyes, but above, we have established their limitations in terms of industry performance and colour range. In parallel to biodesign research, an increasing number of start-ups led by scientific research are dedicated to using biotechnology to improve the performance of microorganisms for textile colouring. Their mission is to develop biodegradable dyes that can replace harmful non-renewable synthetic dyes and be competitive in terms of quality performance and price range. A leading company in this field is Colorifix in the United Kingdom. Using

6 Hyphea Hues by Julia Jueckstock 2020, part of a collaborative Maison/0 project with LVMH and the MA Biodesign course at Central Saint Martins UAL.
Photo Paul Cochrane

7

8

DNA sequencing and digital tools (not real specimens), Colorifix is able to identify colour-triggering genes in nature and translate them into microorganisms to produce an extended colour range. In a recent Life Cycle Analysis impact assessment, Colorifix established that their dyeing process uses 77% less water, 80% less chemicals, and a 31% reduction of global warming contribution compared to conventional synthetic dyeing processes (Colorifix, 2022). Their microorganisms are bioengineered, grown in bioreactors, then destroyed in a closed loop extraction process. What remains is effectively a brewed natural pigment that can be used in existing dye manufacturing systems. Colorifix is in the process of developing this technology at scale and is actively collaborating with design brands and textile manufacturing such as Acatel (Figure 7) to retrofit the use of microbial dyes into existing manufacturing

7 Microbial printed textiles by Acatel using Colorifix dyes.
Image courtesy of Colorifix and Acatel

8 This is GMO by Jen Keane, founder of Modern Synthesis, in collaboration with scientist Marcus Walker.
Photo Ed Tritton

systems. Colorifix has also recently launched a collaborative doctoral research project in collaboration with the Living Systems Lab at central Saint Martins with designer Ruth Llyod to develop a new framework for microbial textile printing and to accelerate the adoption of biofabricated colours in the global textile industry.

Pili in France has also industrialised the production of biofabricated coloured pigments and is a proactive leader in the decarbonisation of the textile industry due to its use of efficient, scalable biological solutions. Huue in the USA is focusing on the development of a biosynthetic indigo dye that could replace synthetic indigo, thus potentially radically reducing the environmental impact of the denim industry.

Bioengineered colour production presents a paradox. On the one hand these technologies use bioengineered organisms, but on the other hand, the resulting process is a form of natural biodegradable pigment that radically reduces the use of water and energy. These engineered microorganisms also allow us to bypass the use of heavy metals and harmful chemicals normally required to fix colour onto fibre. Biotechnology enables us to tune existing biological performance and to adapt them to a fermentation process akin to brewing for large-scale production. As these alternative renewable biofabricated colour technologies develop into industrialised systems, we need to remain vigilant in terms of ethical practice. Ongoing environmental audits will also be critical to further demonstrate their benefits, but so far they have proven to outperform conventional synthetic dyes in terms of environmental criteria with a reduced impact on water, and less chemicals and CO_2 emissions.

Traditionally, we manufacture textile materials before we colour them. With biofabrication tools we can also converge these two steps into one. *This is GMO*, a black bacterial cellulose shoe prototype (Figure 8) is a project led by Jen Keane, founder of Modern Synthesis, in collaboration with scientist Marcus Walker.

The colouration of materials in situ during growth is a regular occurrence in nature. This principle was applied in the production of the upper part of the shoe, and black melanin pigment growth was engineered into bacterial cellulose production (Walker et al., 2023). Bacterial cellulose is a natural biomaterial produced by a range of bacteria and is cream coloured in its natural state. *This is GMO* demonstrates the potential of biofabricating both textile material and colour at the same time and opens the door to radical, disruptive innovations for the future of the biotextile industry.

Above, we have shown that bioengineered colour technologies are able to leverage the colour production of natural living organisms to outperform petro-chemical colouring processes in terms of environmental criteria. They are renewable, biodegradable, and considerably reduce the amount of water and chemicals needed for the colouring process. They can also potentially enable us to converge material and colour production into one single biofabrication stage. However, the range of colours these processes can produce is still limited and so far cannot compete with the spectrum provided by synthetic dyes. Bioengineered colour production is also a very new industry with limited datasets in terms of Life Cycle Analysis. We must continue to monitor the performance of bioengineered colours once implemented on an industrial scale to ensure that they fulfil their original mission, that of shifting from a harmful oil-based to a life-conducive textile colouring system.

Rewilding textiles: a post-petrol colour palette

In the sections above, we explored three different bio-informed colour strategies: bio-based, bio-assembled and bioengineered. Although these can all offer environmental benefits; their respective colour capacity is limited in comparison to cost-effective, versatile synthetic dyes. The Rewilding Textiles project set out to explore the intersection of these colouring processes and to establish their potential when combined (Maison/0, 2022).

Recognition that regenerative textile farming can help the fashion and textile industry meet its climate and biodiversity objectives is growing (Textile Exchange, 2022). Fibres grown in regenerative agriculture contribute to drawdown carbon and to restoring biodiversity, but once absorbed in the global textile manufacturing system, they are treated with conventional synthetic dyes. The project

DYE SOURCES

● Algae

● Food Waste (Avocado)

● Bacteria

● Bacteria

● Bacteria

● Algae

● Bacteria

● Algae

● Food Waste (Turmeric) + Algae

● Food Waste (Pomegranate)

● Food Waste (Turmeric) + Bacteria

● Food Waste (Turmeric)

Regenerative Fabrics: Wool (Chargeurs)

9 Textile collection from the Rewilding Textiles project by Maison/0 Central Saint Martins UAL, 2022.
Photo Hung Jui Tsao

asks: Can we align a colouring textile system with these regenerative fibres? (Maison/0 2022: 9)

The final output consists of a series of textile collections and a publication that contextualises regenerative textile design practice from fibre to colour. For the project, new dye and print protocols were developed to combine the use of microbial dyes (both wild type and bioengineered), algae, food waste and biomordants. Figure 9 shows a twelve-colour set of textile samples screen-printed on regenerative wool. Some of the colours come from one origin (for instance algae), others are achieved by combining two sources (such as algae and bacterial dyes). One of the key challenges was to gather the relevant expertise to work across these different bio-informed colour recipes. A team of six designers with diverse textile dye knowledge and the support of biologists and a natural dye expert was required to achieve the range of expanded colour palettes. All the colours of the spectrum were successfully produced when bio-based, bio-assembled and bioengineered dyes were combined, except fluorescent colours. Rewilding Textiles is the first prototype collection entirely produced using regenerative fibres and printed using a mix of bio-informed colour processes. This proof of concept demonstrates the need to further develop these emerging colour technologies at scale, so as to complement the current progress achieved in regenerative textile fibre production.

Conclusion

In this chapter we have established that in the context of a planetary emergency, the textile industry needs to transition towards a bio circular and regenerative model. This entails considering post-petrol colouring systems and breaking away from using non-renewable, polluting, synthetic dyes. Learning from how living systems operate in the natural world, at ambient temperatures with local nutrients and without the release of toxic byproducts, we can envisage new bio-informed dye technologies beyond the use of natural dyes. Natural dyes do not offer a realistic alternative to synthetic dyes at scale but are beneficial when grown in regional regenerative agriculture, using biomordants as opposed to traditional toxic heavy metals. The circular bioeconomy provides a new context for re-imagining a bio-informed textile landscape and coincides with the emergence of biodesign practice and the integration of biological protocols in the design process.

As the field of biodesign and biofabrication is expanding rapidly, the flurry of 'bio'-related terminologies can lead to assumptions and confusion. We need to position bio-informed design and material strategies in relation to life-conducive environmental and ethical criteria. This chapter posits such a framework and defines a taxonomy of interactions with living systems in three parts to articulate key thresholds across bio-informed practices. It examined a range of new, nature-positive dyes and colour projects in relation to the proposed framework (bio-based, bio-assembled or bioengineered) and their respective colour range capacity. As they stand, bio-informed colour innovations offer a limited colour palette, but the option to combine dyes from mixed bio-origins could expand the colour range to a full spectrum, except for fluorescent tones. Bio-informed colour research is conducted via different streams: it can stem from design-led inquiries, scientific research or start-ups, which are beginning to scale up on a commercial scale. Although key knowledge gaps need to be overcome before bio-informed dye technology can truly compete with synthetic dyes in terms of cost and versatility, there is clear evidence that biocolours can outperform chemical dyes in terms of environmental benefits. We have seven years left to meet both our climate and biodiversity deadlines, so it is imperative that the development of these nascent bio-informed dye technologies is accelerated. The textile industry we know today was at the heart of the industrial revolution in the 18th and 19th centuries. The textile sector can once again lead the biorevolution and offer a system reset to revitalise the natural world with life-conducive fibre and colour systems. This will take more collaboration across sectors than ever before, but the promise of scalable nature-positive colour dye technologies is real.

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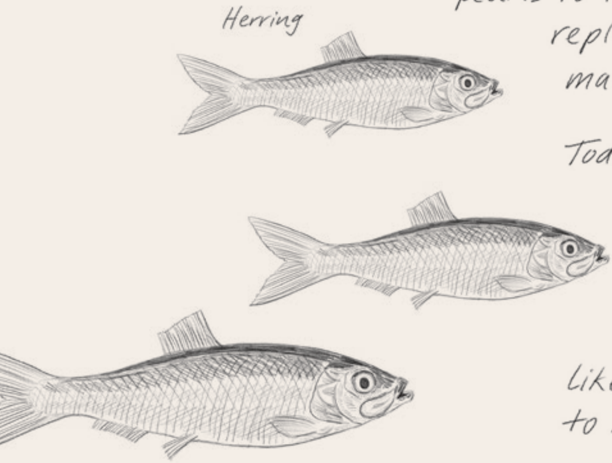
Car illustration Bernd Reuters Archiv
W. Schollenberger Ober-Ramstadt

Iridescence

Humans have always been fascinated by shimmering colours: Butterfly wings, hummingbird feathers, fish scales, the iridescence of shells. We want to be able to shimmer just like these creatures.

The 17th century brought the discovery of fish silver, a pearlescent pigment extracted from the scales of Ukelei and Herring. The scales of about 40 000 herrings were needed for 1 kg of the pigment. The material was used to coat items ranging from artificial pearls to 1930s luxury cars before it was replaced by plastic and metal-based materials.



Today, less environmentally harmful materials and methods are emerging. We can change the structure of wood to recreate durable, reflective nano-surfaces like those giving colour and iridescence to butterflies and fish.

Photo Esa Naukkarinen

Noora Yau, Konrad Klockars, Kirsi Niinimäki

Designing experimental aesthetics with structural colour

ABSTRACT

Structural colour based on cellulose nanocrystals (CNC SC) can be used to create shiny and iridescent colour, using plant biomass, such as wood. CNC SC is envisioned to replace current iridescent and glittery dyes that are harmful to the environment and to people. The development of CNC SC is still ongoing and no industrially manufactured products yet utilize this technology. One of the challenges for widespread use of the colourant is the challenges related to achieving a perfectly uniform colour. While the technical features of CNC SC have been thoroughly studied, their aesthetics and appearance have received little attention.

In order for CNC SC to be more widely introduced in the field of design and art, it is necessary for the users of colours in these fields to understand the mechanisms of structural colour formation. In addition, the visual possibilities and qualities of these colourants need a closer examination in the field of design. In our interdisciplinary research - Shimmering Wood - a collaboration between design and materials science, we have aimed to understand this colourant's behaviour and uncover the characteristic visual features of CNC SC. By analysing constructed material samples and prototypes with CNC SC, we have tried to understand: What can CNC SC look like?

Keywords
structural colour, visual features, colour aesthetics, cellulose nanocrystals

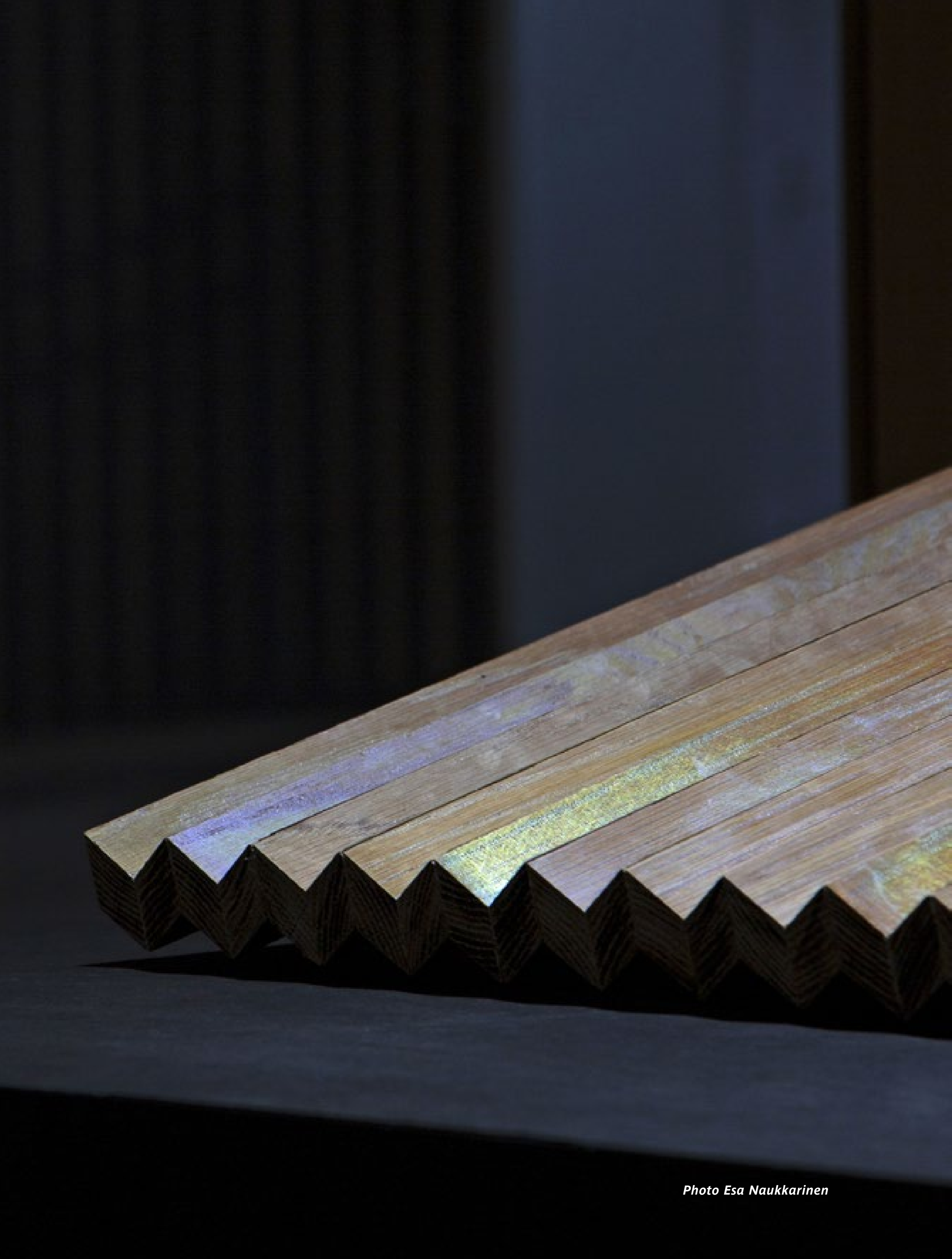


Photo Esa Naukkarinen

Introduction

The colours in morpho butterflies' wings, peacocks' feathers, and soap bubbles are all examples of structural colours (Sun et al., 2013). Structural colour refers to the colour formation mechanism that arises when nano-sized structures reflect light in a certain way, and we perceive colour (Glover & Whitney, 2010). Structural colours have become famous for their shimmering, sparkling, and iridescent colours, but they can also be matte and non-iridescent. Structural colours have been extensively studied in the context of biology (Glover & Whitney, 2010; Sun et al., 2013; Parker, 2000; Doucet & Meadows, 2009; Parker, 1995), optical physics (Kinoshita et al., 2008), and materials science (Zhao et al., 2012; Shang et al., 2019), but a certain degree of vagueness still surrounds the subject and especially the terminology used to describe the appearance and aesthetics of these colours.

The concept of structural colour itself is unknown to most designers and artists, and there is little literature on the subject in the field of art and design. The terminology commonly used to describe colourants and colour effects linked to structural colouration is not established. Terms such as "holographic colours", "pearlescent colours", and "iridescent colours" are used to describe these effect colours, although definitions for these terms may be unclear, or there might not be a proper scientific basis for these descriptions. The above-mentioned colour effects are popular and widely used in design due to their eye-catching appearance (Silvia et al., 2018). However, manufacturing these effect colours usually requires the usage of materials containing plastic or metal, or toxic compounds (Green et al., 2021).

Discussion about the impact of materials and colourants on the environment and people has been ramping up in the field of design. The search for new, better alternatives for the current "traditional" colourants (and technological developments in materials science) have slowly brought structural colours into the conversation (see for example: Lifescaped and "pure Structural Colour" "pigment" in Rothenberg (2021), and collaborative project between fashion designer Stella

McCartney and Radiant Matter in Finney (2023), both colour innovations are motivated by sustainability). Structural colours can have technical properties that make them potentially less harmful to the environment than traditional paints. For example, structural colours do not fade like absorption-based pigment colours (Klockars et al., 2019), and for this reason, these colour surfaces might not need to be renewed as often. Paints developed from structural colours may also be significantly lighter than traditional paints, which could lower the weight of airplanes and thus reduce the amount of fuel needed for flying (Cencillo-Abad, 2023). In recent years, the effort to avoid plastic and metal-based toxic materials has aroused interest in structural colours derived from renewable resources like cellulose nanocrystals (CNCs), a type of nanocellulose.

CNCs are colourless and transparent, but through certain processes, they can form iridescent and metallic colours. In 1992, researchers Revol et al. discovered the tendency of these nanocrystals to organize into nanostructures that create structural colours. Research on structural colour from cellulose nanocrystals (CNC SC) has mainly focused on the technical properties and applications of the nanostructure, such as in optical sensors (Zhao et al., 2021), whereas the colourant's visual features and appearance has not yet gained widespread attention in art and design.

Here, we focus on understanding the visuality and aesthetics of nanocellulose-based structural colour. We have developed and studied this colourant in an interdisciplinary research project between design (Aalto School of ARTS, Department of Design) and materials science (Aalto School of CHEM, Department of Bioproducts and Biosystems). In this collaboration, we have been developing CNC SC for decorative applications and envisioning its possibilities in the art and design field. The research follows research through design practice (Gaver, 2012). By combining design methods, like prototyping, and materials science methods, like laboratory experiments, we aim to build new knowledge about CNC SC and its possibilities in the context of design.

We have observed the difference in visual behaviour between structural colour and pigment colours based on the absorption of light. The materiality aspect and the working principles of the nanostructure emerge as important themes in structural colour, as they can significantly determine the aesthetics and visual features of the perceived colour. For example, the properties of the surface to be coated with CNC SC must be optimal so that the particles can create long-range ordered nanostructures essential for colour formation. By understanding this relationship between the nanostructure and the base material, one can predict (up to a certain point) what colours will be achieved.

In this chapter, we aim to shed light on the visual characteristics, appearance, and aesthetics of CNC SC. We address questions such as: What can it look like? Which are the characteristic visual features? We analyse our material experiments from 2017 to 2023 conducted in the context of "Shimmering Wood" project, and aim to determine characteristic visual features of CNC SC through them.

Background

Structural colours have existed in nature for millions of years (Parker, 2000). They have been used in ornaments and objects in design and art throughout history by incorporating things like beetle elytra, pearls, and the shimmering feathers of birds (Sun et al., 2013). The first scientific writings about them can be found in the writings of Robert Hooke already from the 17th century (Hooke 1667 in Newton 1952). Yet, still in 2008, Kinoshita et al. wrote that the scientific definition of structural colour has not yet been fully settled. For this reason, these colours are often examined in comparison to pigmentary colours.

When structural colours are defined by comparing them to pigment colours (Kinoshita et al., 2008; Shang et al., 2016; Zhao et al., 2012; Glover & Whitney, 2010), the word "pigment" refers to a colour that is produced by absorption of light (sometimes called chemical colour) (Glover & Whitney, 2010). Sun et al. (2013) described structural colour as "the result of selective reflection of light, whereas pigment colours originate from the selective absorption of light by electrons". Almost all colours in the animal kingdom are either pigment colours or structural colours. Colours based on pigments are formed when light and the electrons of a substance interact at the atomic level. Electrons absorb specific wavelengths of light, that is, part of the energy of light. Doucet and Meadows (2009) explain this process through the colour formation of carotenoid pigments, which create red, orange, and yellow in animals. Carotenoid absorbs shorter wavelengths of light (e.g., shades of green and blue) and reflects and transmits longer wavelengths (red, orange, and yellow). (ibid.) On the other hand, structural colour is created through a physical interaction between light and a nano-sized structure. In this case, the light is reflected and/or transmitted by the structure before it reaches the eye of the viewer. There is little loss of light energy in the process. The sources of structural colours are thus optical processes such as reflection, refraction, interference, diffraction, and light scattering (Kinoshita et al., 2008). Structural colours are sometimes characterised as "colour without pigment" (Saito, 2012), although a more accurate definition could be "colour without absorption".

In general, when categorizing structural colour, the topic is usually divided into coherent and non-coherent light scattering according to the operating principles of the nanostructures (Glover & Whitney, 2010). In this chapter, we focus on structural colours based on nanocellulose, which are caused by coherent light scattering, and to be more precise, they are structural colours based on helicoidal reflectors. (Nguyen et al., 2018) We are not focusing on the visual features and the aesthetics of structural colours based on incoherent light scattering. Most of the sparkling and shimmering colours, as well as all iridescence in nature, are based on coherent light scattering (Glover & Whitney, 2010).

Structural colour categorization

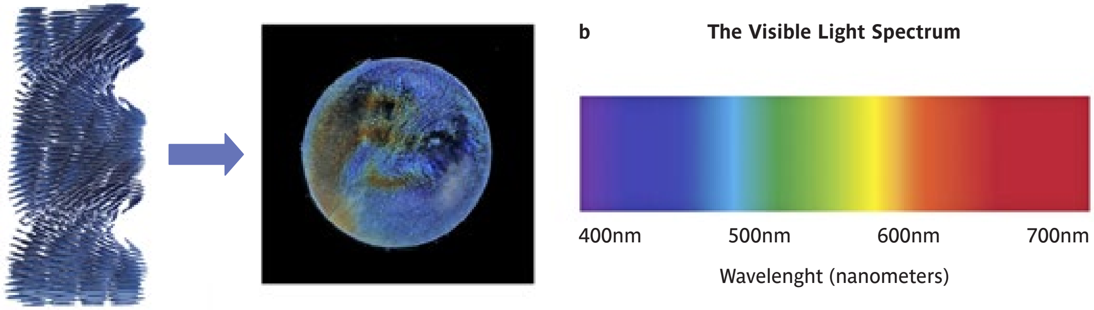
Structural colours, which arise from coherent light scattering, can further be categorised based on the exact mechanism of scattering. These mechanisms depend on the nature of the nanostructure that scatters the light and thus generates the colour. The breakdowns of the categories may vary slightly depending on the author, but one common way to categorize these subcategories is: 1) Thin-film interference and multilayer reflectors, 2) diffraction gratings, and 3) three-dimensional photonic crystals. This division has been used, for example, by Glover and Whitney (2010). Structural colours based on different mechanisms may appear visually similar, and it may not be possible to distinguish which mechanism underlies a certain observed colour (Schenk et al., 2013). A closer look at the nanostructure is often needed in order to connect the observed colour and the colour formation mechanism. Nevertheless, each category does have some characteristic visual features.

Structural colour based on helicoidal reflectors (Vignolini et al., 2012), such as that of CNCs, is remarkably reminiscent of the structural colour created by multilayer reflectors. The operating principle of helicoidal reflectors is very close to that of multilayer reflectors. Because of this, for example, the iridescent blue structural colour of the fruit *Pollia condensata* may sometimes be categorised under multilayer reflectors, as Sun et al. (2013) have done.

Multilayer reflectors are a form of structural colour commonly found in nature, for example on the wings of morpho butterflies and in Japanese jewel beetles (Glover & Whitney, 2010), and there is a lot of scientific literature on them. Therefore, the studied visual characteristics of multilayer reflectors are also included here as a point of reference when discussing CNC SC. In the next section, we present the formation and visual characteristics of CNC SC.

Structural colour from cellulose nanocrystals

Structural colours can be created with cellulose nanocrystals (CNC SC) (Schütz et al., 2020). Cellulose nanocrystals are rod-like nanoparticles extracted from biomass, such as wood, by various chemical treatments, but generally by sulphuric acid hydrolysis (Vanderfleet et al., 2021). The choice of biomass also includes algae and agricultural waste such as coconut shells, wheat straw, and sugarcane bagasse (Vanderfleet et al., 2021). Here, we focus on CNCs made of wood. They are usually about 100–200 nm in length and 3–10 nm in cross-section (Beck et al., 2011). They come in the form of aqueous suspensions, where they can self-assemble into a chiral nematic structure that resembles a left-handed helix structure (Figure 1a) (Revol et al., 1992). The assembly occurs above a critical concentration, which depends on the CNC size (Honorato-Rios & Lagerwall, 2020) and charge (Abitbol et al., 2018) as well as the properties of the liquid medium (pH, ionic strength, electrolyte type, solvent, presence of other molecules, etc. (Dong et al., 1996; Bruckner et al., 2016; Bardet et al., 2015). The chiral nematic structure remains when the suspension is dried into coatings or films and is responsible for the structural colour generated. CNCs themselves form transparent materials, but when they are organised into a helicoidal nanostructure, they selectively reflect a narrow spectrum of light, giving rise to structural colours.



The perceived colour hue, or in other words, the wavelengths which are reflected from the dried CNC film, can be controlled to some extent by adjusting the pitch size of the chiral nematic structure when it forms in CNC suspensions. The pitch describes the distance of a 360° rotation of the helix (De Vries, 1951). It can be adjusted, for example, through ultrasound treatment (Parton et al., 2022) or by adding electrolytes to the CNC suspension (Pan et al., 2010).

It is noteworthy that structural colour reflections based on the multilayer interference mechanism rely on sharp periodic boundaries, while the CNC SC arises from a helicoidal stacking of CNCs, which is a continuous periodic structure without boundaries.

Iridescence, shiny and metallic colours

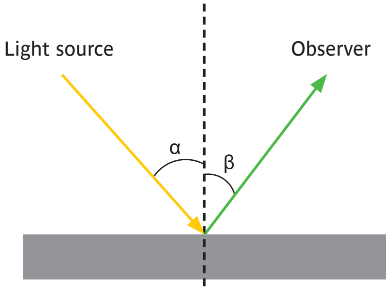
Iridescence is one of the most used keywords when describing structural colours (Kinoshita et al., 2008), and it can only be found within structural colour. The word originates from the Latin and Greek word iris, meaning 'rainbow', but also refers to the ancient Greek goddess Iris, who is the personification of the rainbow and a mediator of the gods' messages (Doucet & Meadows, 2009). Generally, iridescent colours can be defined as colours that change depending on the viewing angle (Seago et al., 2009; Meadows et al., 2009; Glover & Whitney, 2010). This rather loose definition leaves plenty of space for many visually different colour effects. It also makes it challenging to conclude what actually falls within its scope. Nanostructures with periodicities of constant

1 **a** Cellulose nanocrystals in suspensions can self-assemble into a chiral nematic structure that resembles a left-handed helix structure. The chiral nematic structure remains when the suspension is dried into coatings or films and is responsible for the structural colour generated.
b The visible light spectrum
Photos Noora Yau

sizes and ones with continuously changing periodicity sizes generate iridescence where the colour change follows the exact order of the visible light spectrum (Figure 1b), i.e., violet, blue, green, yellow, orange, red. This effectively limits colour changes that jump from, e.g., blue to red.

The structural colour that originates from multilayer reflectors is usually pure and intense with a narrow wavelength spectrum (Glover & Whitney, 2010). This usually means strong individual shades such as the blue of the wings of morpho butterflies, which are also often iridescent. Colours from multilayer reflectors may also appear metallic, silvery, mirror-like, or pearl-like, with a corresponding broad wavelength range (Seago et al., 2009). Some golden and silvery beetle colours, which are based on multilayer reflectors, have been reported with metallic (mirror-like) and possibly non-iridescent colours (Seago et al., 2009).

The iridescence of CNC SC has been studied in depth by Frka-Petesic et al. (2019). Due to the natural origin of the CNCs, there is generally a large dispersity in their dimensions. This leads to a large distribution in the dimensions and the relative orientations of the periodicity (pitch) in a single dried film or coating. This makes the nature of the CNC SC iridescence complicated, but it also offers a wider variety of unique visual effects that can be achieved. It is noteworthy that in the context of iridescence, the observed colour depends on the relative position of the light source and the observer and on the orientation of the nanostructure in relation to the previous two. Frka-Petesic et al. (2019) showed that the direction of the iridescence along the visible spectrum depends on whether both the colour source and the observer move equally, or whether only one of them moves (Figure 2).



When α and β increases equally:
the colour changes towards green/blue

When α and β increases while
the other is fixed: the colour changes
towards green/red

2 The direction along the visible spectrum depends on whether both the colour source and the observer move equally or whether only one of them moves.

The coffee ring effect

The coffee ring effect (Deegan et al., 1997) occurs during the drying of suspensions and also applies to CNC suspensions. When applied on a surface, the suspension dries faster at the edges of the coated area, which results in a capillary flow of particles towards the edges. This leads to thicker coatings at the edges compared to the centre. Interestingly, the coffee ring effect has a secondary consequence in CNC SC: The effect produces a gradual redshift in the structural colour towards the edges of the coating, which coincides with the increase in thickness (Mu & Gray, 2014). In our previous work, we have suggested using this effect as a visual effect in the context of design and art (Klockars et al., 2019).

Intensity of the colour (background effects)

Absorption pigments are able to both enhance and reduce the intensity of the structural colour created by nanostructures. An example of a synergistic enhancing effect can be seen in the wings of morpho butterflies. The wings of morpho butterflies are pigmented brown, but the surface of the wing also has a nanostructure that produces an intense metallic blue colour. The dark pigmented background increases the intensity of the structural colour from the nanostructure (Kinoshita et al., 2002). The same affect is expected to happen for CNC SC.

Hygrochromicity

Some structural colours are hygrochromic. Hygrochomicity refers to a “reversible colour change” (Seago et al., 2009) from exposure to water or changes in humidity. In essence, the periodic distances of the nanostructures are affected by related changes, and this leads to an adjusted reflected colour. In the case of CNC SC, the colour shifts from smaller to larger wavelengths in seconds and usually ends up reflecting infrared wavelengths, which appear transparent to humans. The shift in wavelengths follows the spectrum of visible light. Therefore, the redshift follows this sequence: transparent (ultraviolet) – blue – green – yellow – red – transparent (infrared).

UV resistance

After millions of years, some fossils still have iridescent colours on their surface, because the structural colour does not fade like pigment colours (Parker, 2000). Structural colours can remain vivid and intense as long as the nanostructure remains intact. Therefore, in theory, these nanostructures could be used to create non-fading colours. In our previous work, we compared the colour fading of pigmentary colours and CNC SC by exposing both colourants to UV light (Klockars et al., 2018).

Appearance and aesthetics: the visual features of structural colour

In order for CNC SC to reach its full potential – in addition to its technical qualities – its visual features and aesthetic dimensions need to be considered. Aesthetics and visual features are topics which might have not been seen as relevant research subjects in the field of material science, as they are typically difficult to measure (Koskinen et al., 2011). However, these features can play an essential role when we encounter new materials, for example in the form of products (Karana et al., 2008). Wastiels et al. (2013) have noted that architecture students' experience of material properties is mostly determined by what they see, and Fenko et al. (2009) have noted that when buying new products, consumers are mostly guided by their vision. The perspective of designers and artists, who actively use colour in their work, can contribute to this understanding.

The visual characteristics of colours and materials are only one piece of the puzzle when it comes to aesthetics of CNC SC. To our knowledge, research focusing specifically on structural colours and their aesthetics has not yet been conducted. Research on the aesthetics of glittering and shiny things has been done, for example by Leddy (1997). Also, Meert et al. (2014), Gaydarska and Chapman (2008), Silvia et al. (2017), and Doucet and Meadows (2009) have studied the aesthetics of glittering and shimmering colours and the reason for their appeal to humans. For example, Leddy (1997) discusses how the aesthetics of sparkle and lustre are understood differently depending on their cause, and reactions can be strong for and against. For example, precious stones are cherished due to their glitter, whereas glitter used in kids' classroom art projects might be seen as "glitzy", unwanted, and temporary. While these findings are relevant to the overall meaning-making process and development of CNC SC, we leave these themes out of this chapter and focus specifically on the appearance of coatings of CNC SC.

The meaningful/high-quality use of structural colours in the context of design and art would require a broader understanding of how these colours differ from pigment colours. Some distinguishing factors may be technical properties, but these colour formation mechanisms can also produce a wide variety of different colour effects. Glover and Whitney (2010) pointed out that compared to absorption pigments or "chemical colours", structural colours have slightly different visual properties. In particular, they highlighted the intensity and stability of the colour: When comparing chemical colours to structural colours, chemical colours are often slightly dimmer than structural ones. Chemical colours also usually look the same from every angle of view, meaning they are not iridescent. Structural colours, on the other hand, can be very intense since the nanostructures can reflect very precise bandwidths of light. They can also form colours that change depending on the angle of view, meaning they are iridescent. Iridescence is a unique property of structural colour, although not all structural colour is iridescent. Knowing the formation mechanisms of structural colours on a general level contributes to understanding the colour's characteristic behaviour. (Glover & Whitney, 2010)

A lot has been written about the relationship between nanostructures and light, for example, in the field of optical physics. However, for designers, this information is often too complicated and challenging. Few designers know the principles of absorption in such a profound way. Still, designers have to be able to paint pictures, mix colours, envision colours for spaces through mental images, etc., and these activities require a sufficient understanding of how pigment-based colours work. For this reason, we believe that by knowing the operating principles of structural colours in general, we could expand our possibilities for their usage.

Method

This research has two different phases. First, we have constructed knowledge about nanocellulose-based structural colour and its behaviour through interdisciplinary and experimental collaboration, resulting in different kinds of prototypes. Secondly, in this current study, we analyse the prototypes produced and their appearance, visual features, and characteristics. Through this approach, we want to provide new knowledge, especially about how designers can understand and work with these colours.

Research through design:

The study is an interdisciplinary collaboration between materials science and design with a Research through Design (RtD) approach. Design processes are usually iterative, and it is often difficult to give general guidelines for how RtD should be implemented (Gaver, 2012). In our research, we use materials science practices and complement them with design methods. The approach for our collaboration has been constructive design research, in which building things, prototyping, and experimenting with the materials have been the key means of constructing knowledge (Koskinen et al., 2011). We have gathered knowledge about nanocellulose based structural colour (CNC SC) appearance and behaviour by material tinkering and constructing laboratory experiments and prototypes. The research question has been: What kinds of colours can be created with CNC SC? What kind of recurring visual characteristics can be identified from the Shimmering Wood samples?

Research design:

This exploratory study is based on the material samples we have conducted in the Shimmering Wood project during the years 2017-2023. The research focuses on examining and identifying the visual properties of the material samples in question. The focus has been on examining the samples produced based on their appearance characteristics that can be observed with the human eye, as designers mainly work based on these observations (as opposed to colour measurement with a spectrometer). We have reflected on the colour theory of structural colour through our material experiments.

We analysed 99 material experiments with CNC SC and selected samples with clearly visible colours for analysis. The base materials for the colour coating in these samples were: wood (28), textiles (28), glass (8), 3D-printed PLA and Wood-filament (14), and free-standing CNC Films (21). The analysed characteristics were: iridescence and shiny metallic colours, non-uniform colours (coffee ring effect), the intensity of the colour (background colour effect), and hygrochromicity.

We investigated:

1. What shades of colours can be seen in the samples, and how do they change depending on the viewing angle? (iridescence)
2. What different hues of colour can be observed in the samples? (metallic, shiny colours/colour hues)
3. How uniform/uneven are the colours? (non-uniform colours/coffee ring effect)
4. How does the background colour of the samples affect the perceived colour?
5. Does the colour change repeatedly? How is hygrochromicity visible in colour samples?

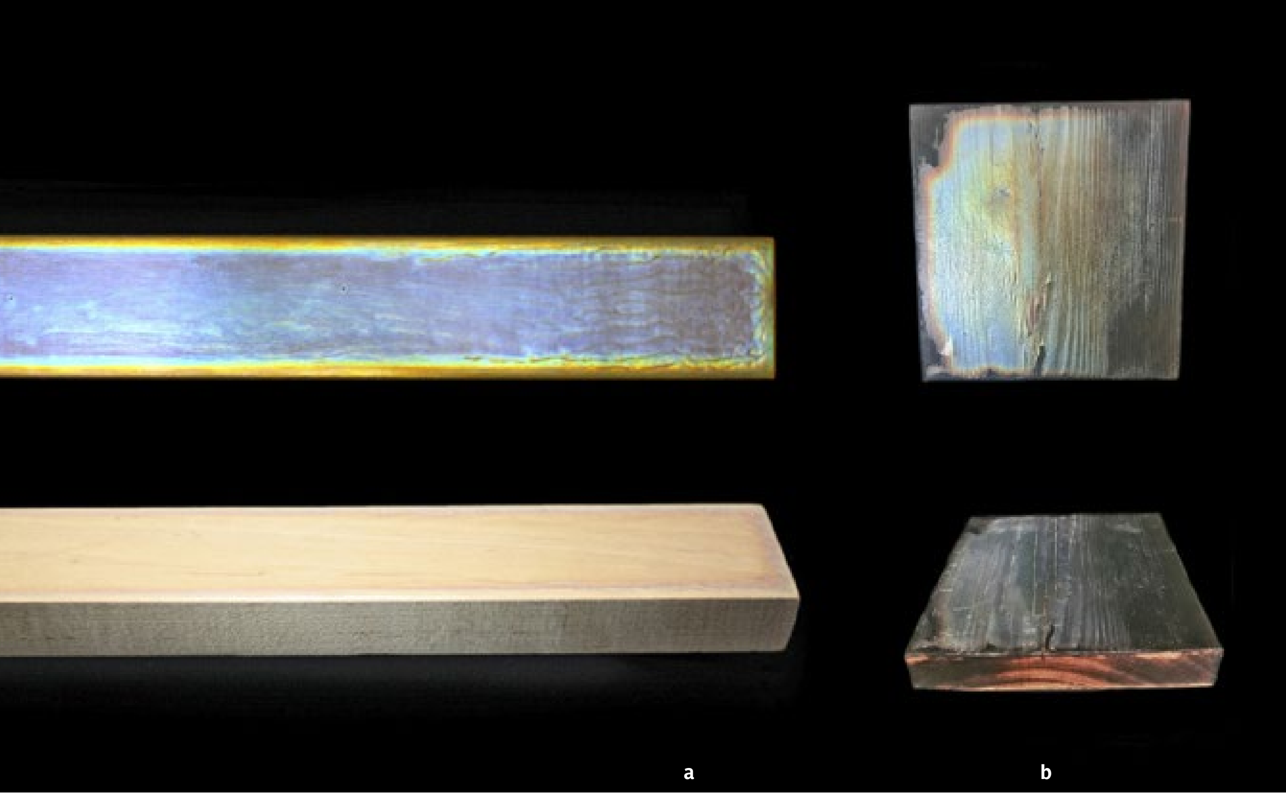
We present visual examples of the experiments in the results. In addition to the points mentioned above and other visual features, it is important to note the CNC SC resistance to UV light, which we have researched earlier (Klockars et al., 2019). UV resistance cannot be detected instantly in the same way as other properties of CNC SC colour, but it is an essential part of the colour's appearance in the longer term and distinguishes CNC SC from pigment colours formed through absorption.

Results

Iridescence, shiny and metallic colours:

Shiny and sparkling metallic colours as well as iridescence were noticeable in all the samples analysed. The hues in all the samples corresponded to colours from the visible light spectrum, both in terms of the "main colour hue" and iridescence. The degree of gloss and iridescence of the colour surfaces may vary in appearance. Gloss and iridescence are affected by several factors, for example, the material of the surface to be coated, the smoothness, the thickness of the coating, and the type of CNCs.

The most common main colour in the samples was blue. Depending on the viewing angle, the colours always change in the same order according to the spectrum of visible light: red, orange, yellow, blue, indigo, and violet. In addition to the fact that the colour of the samples vary and several different hues can be observed in one sample, there is also variation in the iridescence that the eye

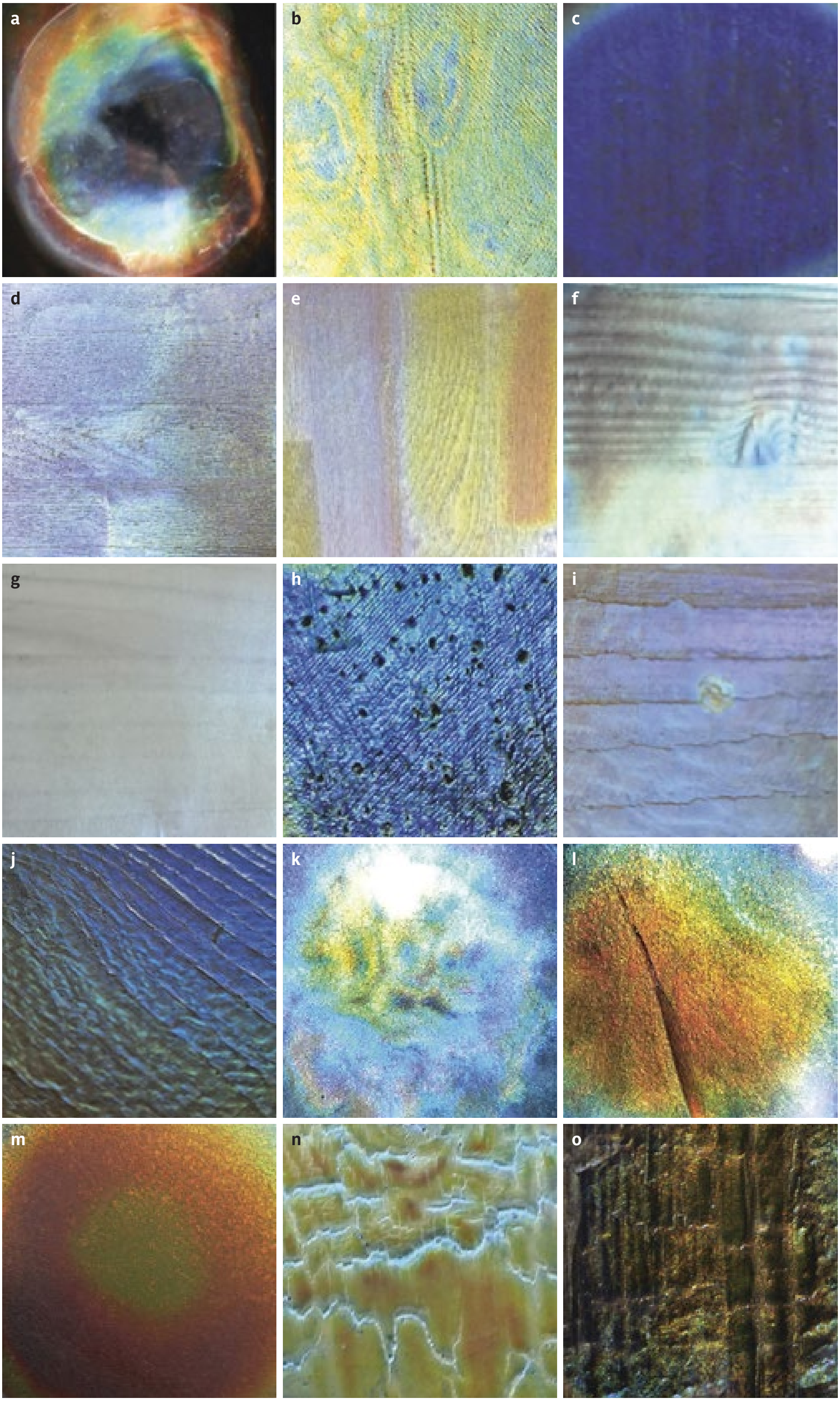


3 **a** Example of a “dramatic” and “fast” iridescence where colour changes from vivid blue to almost transparent.
b Example of another kind of iridescence: Colours of this sample do not become completely transparent, but change to greyish, dull colour shades.
Photos Noora Yau

can see: In some samples (example in Figure 3a), the iridescence can cause a very “fast” and “dramatic” change from vivid colours to almost transparent, while in some samples the colours are not necessarily as bright. In those latter samples, the colours do not necessarily become completely transparent depending on the viewing angle but can remain faintly visible with slightly greyish and dull colour shades (Figure 3b).

Non-uniform colours, the coffee ring effect, and textures:

It is characteristic of CNC SC coatings to form uneven colour surfaces, because the variables of the sample drying process and the coffee ring effect significantly affect how the coating and colour look after drying. The rainbow-like edge colour caused by the coffee ring effect (Figure 4a) is clearly visible in a large number of samples, and we have discussed its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potential as a visual effect in the context of design (for example Klockars et al., 2019). Figure 4 illustrates the variety of different textures and colour surfaces created with nanocellulose-based structural colour.

As a designer, when working with this CNC SC, attention must be paid not only to the properties of the nanocellulose coating but also to the properties of the base material and how it affects the colour. For example, the organic nature of the wooden surface can vary in properties, such as the ability to absorb water, surface texture, its chemical and structural composition, and mechanical processing. All of these have an effect on the final result and appearance of nanocellulose-based structural colour.

Intensity of the colour (background effects)

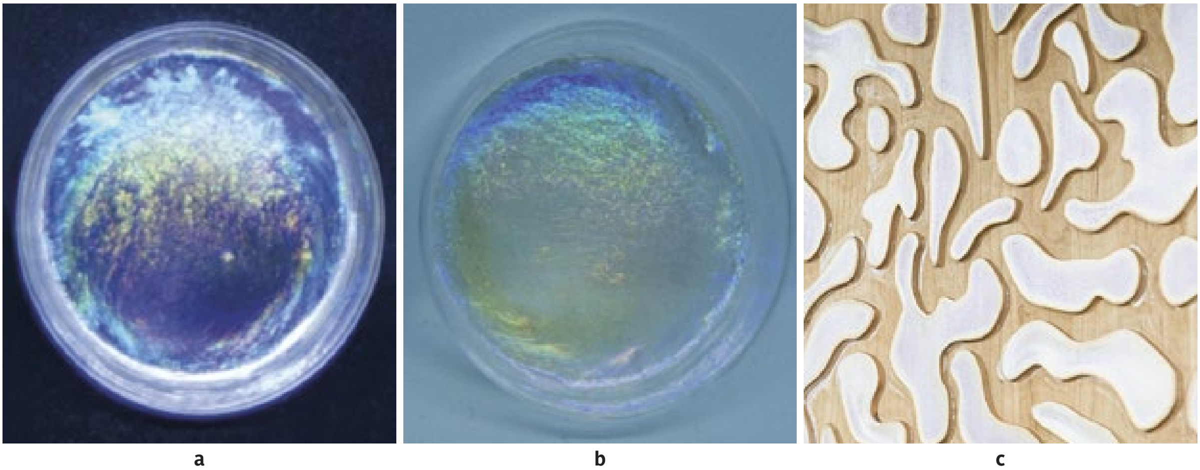
We examined colour coatings on top of light and dark base materials. We compared the appearance of the coatings, and based on the results, the colour on a light surface is not as intense as on a dark surface. On light surfaces, the colour resembled "mother of pearl", in other words, a "pearlescent" colour (Figure 5c), while on a dark surface, the colour is often very intense (Figure 4d).

Hygrochromicity

Figure 6a shows the same glass bubble photographed twice. As the coating (which appears as flakes of colour inside the glass bubble) gets wet, the colour slowly changes towards yellow and red and eventually becomes transparent. This process is completely reversible, and the colour reappears when the coating dries. At the moment, the colour loses a little durability in its wet state, so water resistance is a challenge when using this effect in artistic applications. Figure 6b shows an example of an experiment with a nanocellulose coating whose colours are only visible at a UV frequency. However, the colours become visible by depositing water on the coating.

4 Different textures and colour shades.
a example of coffee ring effect on CNC coated glass,
b–o different colour shades and textures of CNC structural colour coating (b,h: CNC on 3D-printed wood filament, k, l & m: free-standing CNC film, others: CNC on wood).

Photos d and o Esa Naukkarinen, others by authors

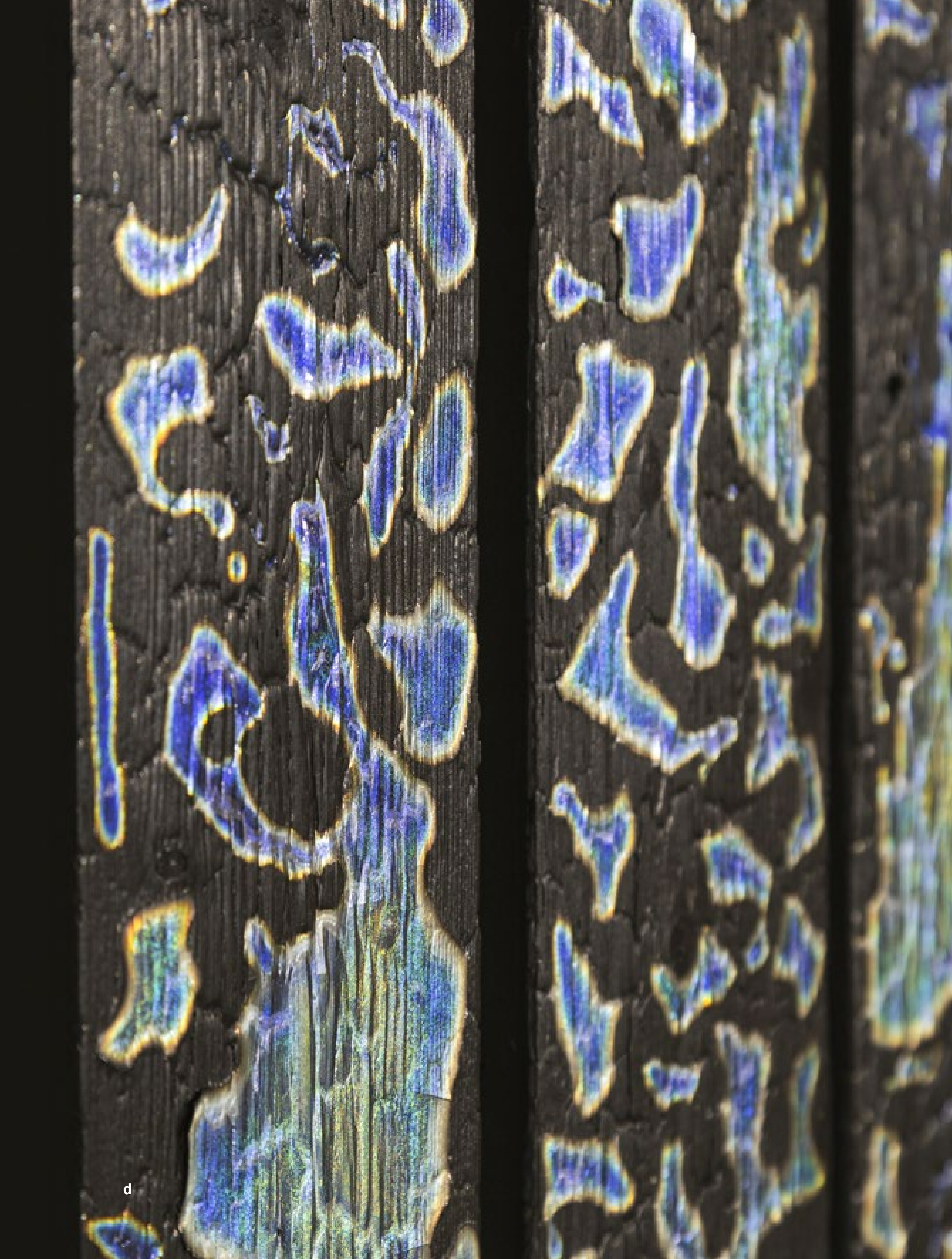


5 **a, b** The same CNC free-standing film on top of a black background and a white background.
c, d The difference in the intensity of the colour is clearly visible in wooden prototypes.
c CNC coating on top of the cherry wood.
d CNC coating on top of torched spruce.
Photos a and b Noora Yau, c and d Esa Naukkarinen

Discussion and conclusion

In this text, we have focused on understanding the visual properties, appearance, and aesthetics of a nanocellulose-based structural colour (CNC SC). We are trying to understand what CNC SC looks like and what visual features are characteristic of it. Unlike the current research around nanocellulose-based structural colour, we approach the colour in the design context as a possible addition to the designer's future colour palette rather than focusing on its technical aspects. We discuss the possible challenges of using CNC SC, especially highlighting the materiality of colour. If designers use self-assembling nanostructures to create colour in the future, an understanding of the relationship between nanostructure and colour formation must be emphasized.

Nanocellulose-based structural colour is a potential future alternative to many current harmful raw materials for structural colours. However, the properties of the colourants still need to be developed, considering their visual and technical characteristics. Sometimes same features that seem like mistakes for materials science can be interesting, characteristic, and even valuable and desired properties from a design point of view. In the case of CNC SC, for example, Droguet et al. (2022) have studied the possibilities of colour in the field of effect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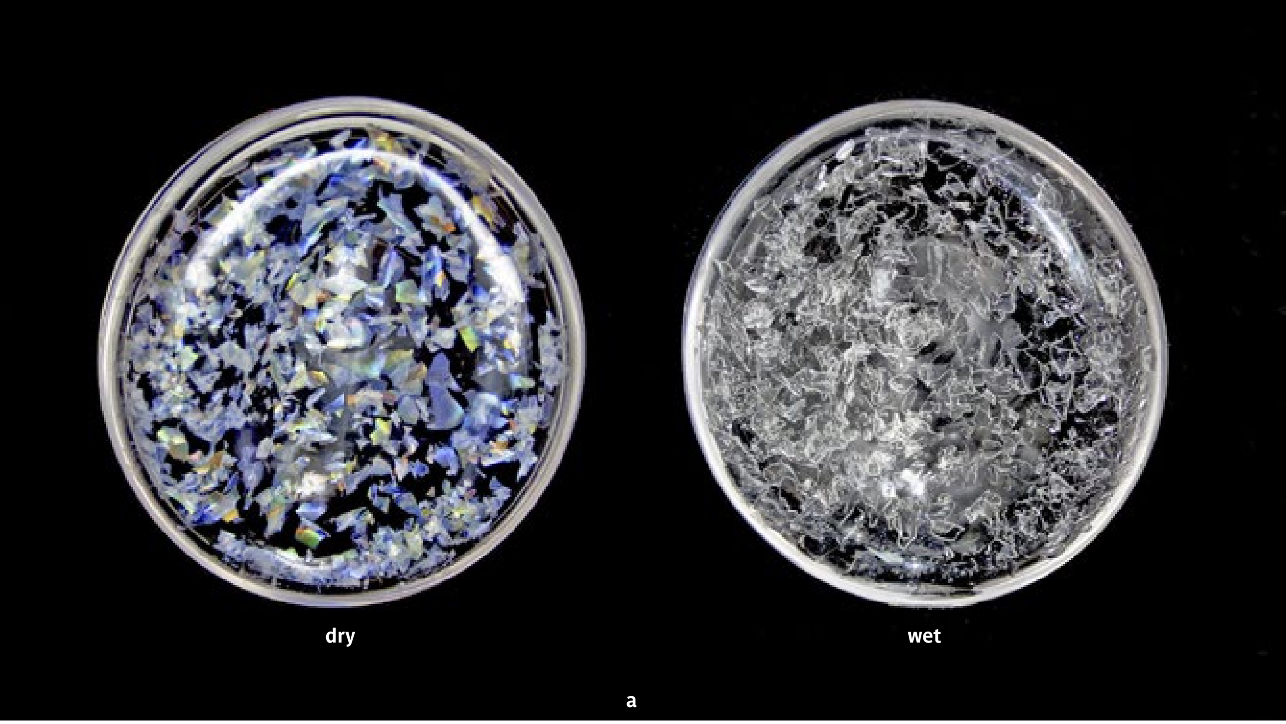

pigments. The development of the colourants has generally aimed to create colour surfaces as smooth and even as possible.

While it is essential to develop CNC SC to replace traditional industrial effect pigments, it can also be meaningful to study and consider the natural unevenness of the CNC SC from a design perspective. The organic textures of CNC coating are reminiscent of glazes created with oxides. The surface colour treated with oxide glazes is usually not supposed to be as even and smooth as the glaze surface coloured with industrial pigments. Different textures and variations in glazes are desirable features that make each glaze unique and speak of quality and artisanship.

In the future, structural colours will likely be considered alongside traditional pigment colours. Wooden products, furniture design, architectural elements, and fashion are all possible areas of applications for CNC SC. Recognizing the unique effects, aesthetics, and appearance of nanocellulose-based structural colours can help make the possibilities of CNC SC more visible and, therefore, more likely to be a part of the conversation about future colourants.

6 Hygrochromicity in CNC samples.
a In the dry state the colour is visible, in the wet state the colour becomes transparent.
b Nanocellulose colour coating whose colours are only visible at a UV frequency. The colours become visible by dropping water on the coating.
Photos Noora Yau

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Woad-coloured seaweed

Photo Julia Lohmann and Bioregion Institute

SUSTAINABILITY AND APPLICATIONS


Photo Tuovi Aalto


Individual woad blossom

Woad (Isatis tinctoria)

Woad is an ancient dyers plant in the mustard family, producing blue colours. In its first year, it grows a rosette of green leaves rich with indigo precursors — the molecules producing the colourant. In the second year, woad grows long flower stalks with an abundance of yellow blossoms, making it a valuable supplier of food for many pollinators.


Woad plant


Woad seed pods

The ancient Egyptians wrapped their mummies in woad-dyed bandages and Julius Caesar reported that the British tribesmen used woad to colour their bodies blue green to appear more frightening in battle.

Woad is also intertwined with culture and language. The German 'blau sein' (being blue) means being drunk and 'blau machen' (making blue) for not showing up for work are linked to the use of drinkers' urine in woad dyeing.


Woad seeds and seed pods

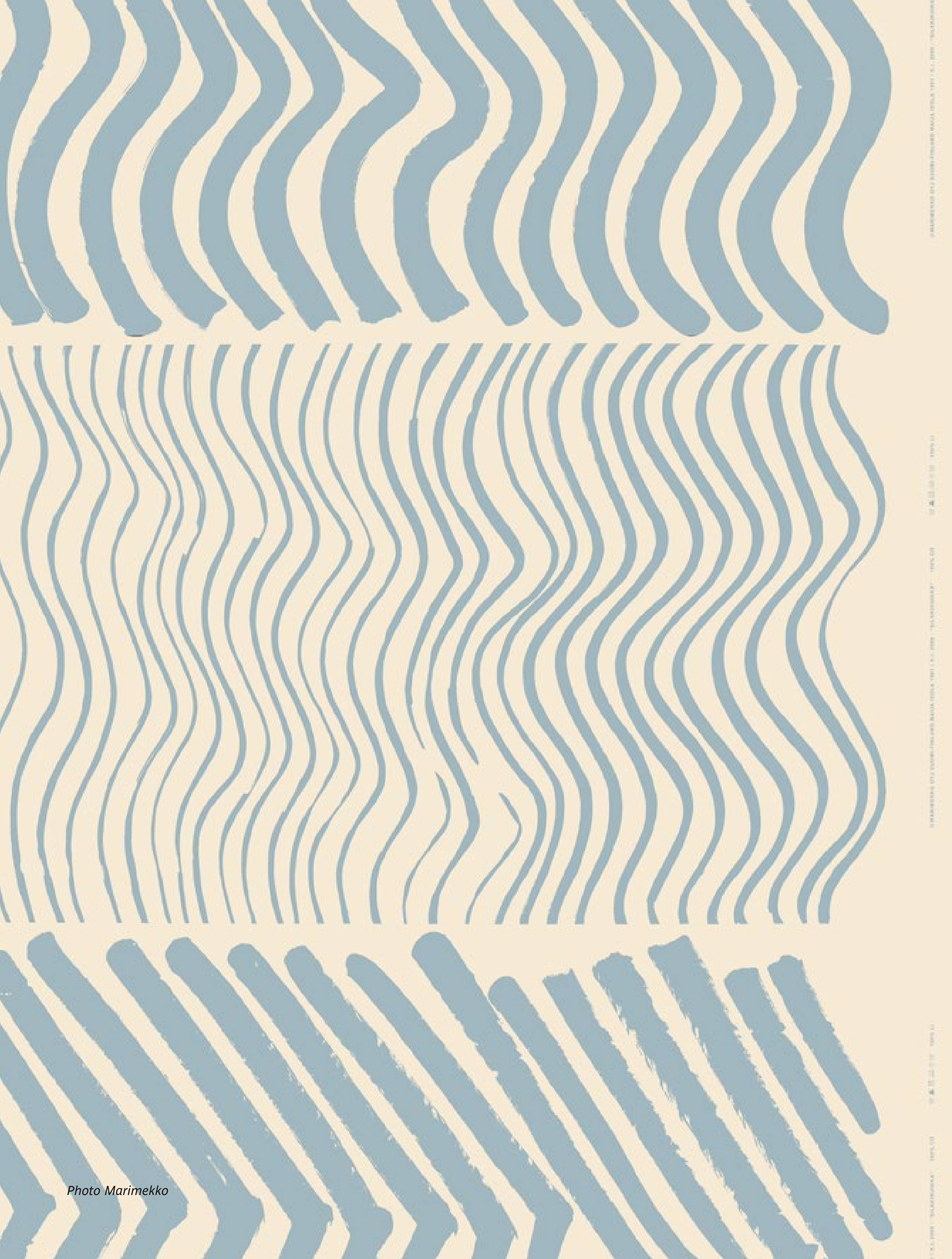

Photo Marimekko

Scarf dyed with woad by Riikka Räisänen.
Photo Julia Lohmann

Kirsi Niinimäki, Leonardo Hidalgo Uribe

Sustainable colour aesthetics

ABSTRACT

The textile and fashion system has huge environmental impacts. The rise of the fast fashion phenomena in particular has increased textile, and garment manufacturing to previously unseen figures. The system is based on mass manufacturing in lower cost countries and on controlling all aspects of design and manufacture. Therefore, synthetic dyes originating from fossil fuels are used in the industry, and this leads not only to an increase in environmental impacts but also to an aesthetic of sameness.

This article conceptually and philosophically discusses natural colours and the acceptance of different kinds of colour aesthetics in the context of sustainability. It argues that by accepting different kinds of colour aesthetics, we would be able to repair some part of the industrial textile and fashion system, leading to a new kind of understanding of imperfection, scale, and temporalities.

Keywords
colour aesthetics, natural dyes, sustainability, imperfect aesthetics, fashion system, textile industry

Heidi Karjalainen's dress is made of woad-dyed viscose material.
Photo Anne Kinnunen / Aalto University

Green leaves, yellow bloom
Like my cheerful friend in tears
Inside you are blue.

Woad haiku by Juha Jordan

Photo Riikka Räisänen and Julia Lohmann

Introduction

In terms of environmental impacts, the textile and fashion system is broken. The rise of the fast fashion phenomena since the mid-1990s in particular has increased fiber, textile, and garment manufacturing to figures that exceed even the global population growth figures (Niinimäki et al., 2020). Fast fashion, which is based on linear economy principles and super effective mass manufacturing in lower cost countries, has greatly influenced the garment and textiles field, as well as its environmental impacts and its aesthetic outcome. This way of designing and manufacturing through super-effective mass production results in an aesthetic of sameness; everything looks the same. Different brands have the same trends and colours. It is not only styles and silhouettes that are the same but blues are the same, reds are the same, and pastels are the same.

The industrial system is currently based on long supply chains, and garments for consumers in the Global North are manufactured in the Global South. This means that brands are taking the easiest way and controlling manufacture, and this has required instructions and systems to guide manufacture from a distance. Current mass manufacturing aims for stability and easiness in manufacturing processes and this means controlling, for example, colour choices by using colour trend forecasting maps and colour trend systems (e.g., Pantone), so that each colour can be defined by a number. In this way, different industrial partners can easily communicate their colour choices to each other. Colour control of all fabrics and other haberdashery coming from different factories means that each garment, including all their details, end up exactly the same shade of colour. This provides stability and control in industrial production.

As Balthazar (2021) points out "[c]olour precision is critical, especially in textiles. In fact, colour is one of the first aspects of apparel products and other textile goods that consumers notice upon entering a store, and it is a key influencer of purchasing decisions, leaving little room for colour mismatches or other errors." The current industrial system sees colour instability, colour imperfection or even slight differences in colour shades as a mistake that hinders sales and leads to second rate quality in mass manufacturing. It also sees colour inconsistency as a negative, unwanted attribute. Durability and stability have been the most relevant bases of colour quality and have both productive and aesthetic consequences in terms of good or bad colour.

> *[A] good colour was also permanent. It did not fade when washed or when exposed to sunlight or heat. Good colour did not become dull as it aged, nor did it peel, rub off or destroy the medium it coloured. Discussions of the stability or solidity of colours were more exacting than deliberations about beauty. Permanence was a more difficult goal to achieve, and its failures were a greater concern.* (Lowengard, 2001, p. 94).

This historical comment by Lowengard shows that concern regarding permanence existed even in the early stages of industrialization, before synthetic dyes were invented. This is also the reason why the textile industry currently uses synthetic dyes that are easily replicated and reproduced, and always produce the same colour. But these colours also have environmental impacts.

Perhaps we could change our colour aesthetics and take the environmental impacts of synthetic colours into account. Perhaps we could cultivate a new paradigm that accepts a new colour aesthetic that is based on the attributes of natural colours and their behavior. “It is time to change the unsustainable fashion culture and build a new paradigm. In the last 20 years we have experienced the emergence of a fast fashion culture, which has succeeded exponentially from a business point of view but has caused ever increasing environmental impacts.” (Niinimäki & Durrani, 2020, p.xv.) Perhaps it is high time to challenge the current textile and fast fashion industrial system and become more critical of it and construct a new paradigm and a sustainable system with new colour aesthetics based on variety. If we could look at our textile and fashion aesthetics from the viewpoint of sustainable colour, we could possibly repair some part of the fashion system.

This article discusses colours, natural colours, and the acceptance of different kind of colour aesthetics in the context of sustainability in a conceptual and philosophical way. It attempts to direct the discussion towards the following: Could we construct a new kind of colour aesthetics in the context of sustainability, and would this new colour aesthetic be able to challenge the current fashion system and industrial mass manufacturing that creates the aesthetic of sameness?

Synthetic and natural dyes

Different kinds of dyes are used to give colour to different fabric types. The textile industry uses over 10 000 different synthetic and pigment dyes, which mostly originate from oil production (Chequer et al., 2013). Most synthetic dyes are carcinogenic and toxic for ecosystems (Aghaie-Khouzani, 2012). They are highly stable and durable, giving a garment a long use time, they do not biodegrade when they end up in wastewater. Most of these dyes "escape conventional wastewater treatment", or wastewater treatment may not even exist in dye factories located in developing countries. These synthetic dyes ending up in water streams have a substantial environmental impact. It is even estimated that the greatest environmental impacts of the textile sector come from dyeing processes, mainly because production rates have increased drastically, synthetic colours do not biodegrade, and many toxic chemicals are used in textile dyeing processes (Chequer et al., 2013, p. 152). However, there is a contradiction here. The Western consumer culture and current commercial logic shortens the use time of garments to increase profits (more sales). Garments are disposed of rapidly, but their colours are made to last, using highly stable, durable synthetic dyes.

"Dyes derived from natural materials such as plant leaves, roots, bark, insect secretions, and minerals were the only dyes available to mankind for the colouring of textiles until the discovery of the first synthetic dye in 1856" (Verma & Gupta, 2017, p. 57). After this, synthetic options conquered the dye markets quickly. Natural dyes have traditionally been used in small-scale craft production but can also be used in industrial dyeing processes. However, as they are not as stable, durable, or easy to use or reproduce as synthetic dyes, they are not largely used in industry. It is estimated that currently only 1% of textiles are dyed with natural dyes (Phan et al., 2021). One property of natural dyes is that their shades can change depending on their origin and even their cultivation year and weather conditions. "As dyes collected from similar plants or natural sources are influenced and subjected to the vagaries of climate, soil, cultivation methods etc." (Verma & Gupta, 2017, p. 57) and while natural dyes have several different colours (co-pigments), they have a natural tendency for the dyeing results to vary each time. *Variety* even be highlighted as their natural quality. From an environmental perspective, natural colours are biodegradable and therefore safer for the environment than synthetic colours. As Verma and Gupta (2017, p. 57) emphasize "if we compared natural dye with synthetic dye then natural dyes are found eco-friendly and they have no carcinogenic or allergic effect for human being especially for dyers." The weak side of natural colours is very often low light fastness and even low wash fastness, which manufacturers have tried to improve by using toxic chemicals as helping agents in the dyeing process (e.g., metallic mordants). Instead of metallic mordants, safe bio-mordants could improve natural dyes' durability (Phan et al., 2021).

From individual and local colours to mass manufacturing for "sameness"

The aim to control colour shades started already before synthetic dyes were invented, but speeded up with the production of synthetic dyes. It can even be said that synthetic dyes were a kind of solution to the lack of colour control in textile production. Lowengard (2001) showed how the dyeing industry in France made considerable efforts to define colour quality criteria that could be institutionalized already during the eighteenth century. There was a need to control the aesthetics as well as the manufacturing qualities of colours, which laid the foundations of the beauty concept in the context of mass production and industrialization and can be seen as being based on efficiency and "economic logic".

Categorizing colour was a challenge in terms of natural dyes, especially when beauty in colours were subject to regional taste and subjective perspectives. Local and regional variables also affected the criteria of quality, making it more difficult to standardize colours. Regional aspects such as local taste, customs and the reputation of the dyer would also complicate the ideal of a universal standard for the colour industry (Lowengard, 2001, p. 102). Different water qualities used during the dyeing process altered the results of the colours and their performance, challenging the idea of a unique, ideal dyeing process for certain sources of colour. "Natural philosophers saw the

capture, definition and ordering of colour as an essential aid to their classification efforts and, simultaneously, as significant to the work of artisans.” (Lowengard, 2001, p. 92).

Change in colour was undesirable and its vulnerability was seen as a determinant of bad quality. Quality tests were performed to assess the capability of a dye to remain unaltered for a long period of time. Chemical and physical tests simulated the “time-based colour change” (Lowengard, 2001, p. 95). Any alteration was seen as decay and loss of beauty. The resilience of a dyeing material was conceived as an indicator of good quality. There was concern about the sensitivity of the colour to its surroundings: “Many colours faded after even minimal contact with light or polluted air. Weavers and inspectors at the Gobelins tapestry works often complained that these colour changes ruined carefully arranged colour combinations.” (Lowengard, 2001, p. 94). Some colours faded easily with continuous washing and wear, but they could also become darker with time.

1 Garments designed by Kirsi Niinimäki and Arttu Åfeldt benefit from the uneven dyeing result and use it as a surface design element. Colour blue origin from Finnish woad plant by Natural Indigo Finland.
Photo Eeva Suorlahti / Aalto university

Additionally, they could drastically change when exposed to substances of different pH, such as splashes of lemon juice or vinegar, as happens with Cochineal scarlet reds (ibid.).

The use of synthetic dyes solved the problem of achieving the desirable brightness and exact hue through cost effective dyeing processes. Additionally, innumerable colour options allowed printers to create variations of their designs without changing the pattern—changing the colour was enough. The idea of colour harmonies became another crucial factor when evaluating the aesthetic qualities of textiles and products in terms of colour, which also involved the practice of colour management.

Colour management and control are linked to an increase in the efficiency of industrial manufacturing and designing for industrial production. Synthetic materials and plastics and their durability and vast colour palette became symbols of human control, as they are controlled aesthetic qualities. Fisher (2013) analyzed the qualities of plastic materials since their development after the Second World War, and found they were able

2 This dress by Sofia Ilmonen is designed to include the fading or changing effects of the colours. The dye used is logwood.

Photo Diana Luganski, photo manipulation Pirita Lauri to transform human control over material existence (ibid., p. 289). Since the 1950s, the smoothness and shine of these materials were equivalents to cleanness and sterile control, whereas their variety and gaiety of colours was promoted as a colourful, delightful, and promising new synthetic era. Another aspect was the promise of permanence and durability, and that the beauty of their shine and hue would last forever (Fisher, 2013). However, the promise of a synthetic paradise was broken in the 1970s, when doubts about the chemical origin of plastics emerged: "By 1968 the relatively innocent curiosity about and enthusiasm for the new materials that characterised their reputation in the 1950s, albeit tinged with a suspicion of them as cheap substitutes, had been joined by doubts about them as simple symbols of a beneficent and delightful control over nature." (Fischer, 2013, p. 295). This forced manufacturers to advertise plastic containing natural materials and to appeal to the ideals of returning to nature (ibid., p. 298). Here, Fisher uses the term "chemophobia", which addresses the negative connotations related to fully man-made materials (ibid., p. 287) and could also apply in the context of synthetic colours.

Concerns arose about the use of chemicals, plastic materials, and synthetic dyes made from fossil sources. Ehrman (2018) points out:

> *The growth of the fashion industry between 1900 and 1990 and its increasing reliance on non-renewable fossil fuels and chemicals to provide energy for transport and machinery, and the raw materials for manufacturing fibres, dyes and other finishing effects, had a corresponding impact on the environment, flora, fauna and human communities.* (ibid., p. 134)

In this way, industrial super-effective mass production broke the harmonious connection with the environment and nature and introduced the logic of artificial, harmful, and abusive. Despite environmental concerns, industrial production grew, and relied on easily produced materials such as polyester and mass manufactured synthetic dyes. The easiness and permanence of colour enable control in the current industrial system, which is based on economic logic only. This aim for control has resulted in the mass manufacturing of the aesthetic of sameness.

3 Sofia Ilmonen's red dress is dyed with durable natural dye carmine which is sourced from the cochineal insect.
Photo Juho Huttunen

New colour aesthetics through natural dyes

Natural colours have a different kind of aesthetic than synthetic ones. Synthetic colours are pure colours, which enables the creation of clear, primary colours. They are easy to use in industrial mass manufacturing. They have the same end result each time so they are easy to reproduce, they are stable, and durable. Natural colours, on the other hand, are not so easy to handle in industrial-level dyeing processes: The final dyeing result might vary, and although each colour contains several co-pigments, the end result might have a slightly different shade each time. In this way, natural colours are much more demanding (from the dyeing process perspective) if the goal is to reach an exact colour each time. Their shade is not so easy to reproduce.

Finlay (2007, p. 383 based on Wittgenstein, L.) pondered the question of colour in the following way: Are "pure colours mere abstractions, never found in reality? What is the relationship between the world of objects and the world of consciousness? Is there such a thing as a natural history of colour?". Here, the philosopher makes a distinction between the abstract and the concrete in colour understanding. Renaissance Naturalism established the need for fixed colour referents for scientific practice, and later Newton's theory of optics contributed to approaching colours from an objective point of view (Finlay, 2007, p. 384). Nevertheless, Goethe's ideas of "physiological colours" maintain the position of a subjective understanding of colours and include environmental factors that affect colour perception, such as culture or the natural world.

In terms of production, synthetic dyes and contemporary colour systems rely on stable colour references, and colours are comprehended in terms of their abstract qualities (hue, brightness, etc.). On the other hand, natural dyeing presents the challenge of unstable colours, which rely on external environmental conditions or the very nature of natural dyes; their *variety, unstableness, harmonious shades, fading, uncontrollability*. The logic behind colour management using synthetic and natural dyes is totally different. "Ambiguity" and "environmental context colours" should be considered as categories for creating colour systems for natural dyes.

“Ambiguity” and “imperfection” of natural colours

In Japanese aesthetics, imperfection and insufficiency refer to the appreciation of “the aged, the obscured, the impoverished and the defective.” (Saito, 1997, p. 377). Imperfection and insufficiency require acceptance of what is beyond our control (ibid.). The craft-making process contains factors that cannot be controlled entirely and which might lead to “unexpected colours, shape and texture” (Ibid). This can also happen during the process of natural dyeing, when variables such as the time when the dyeing material was harvested, soil, and water qualities can affect the resultant colours. Instead of discarding unexpected results, the aesthetics of imperfection and insufficiency advocate the acceptance and submission of the maker or designer to the uncontrolled influence of nature, and as a consequence, accept it as a positive aesthetic endorsement. The aesthetics of imperfection require an attitude of submission to the uncontrollable and to uncertainty, and yet they can be meticulously planned and arranged (Saito, 1997, p. 378). Dyeing with plants and other natural sources often involves the ephemeral, the unexpected, and the uncertain in the resultant colours, but it can also involve appreciation of their perishability and dependence on environmental factors. Designing objects to look impoverished or defective embodies “spontaneity and freedom”, and also involves the acceptance of accidents and processes beyond human control (Saito, 1997).

Natural dyes come from living plants and their behavior is directly affected by environmental changes (temperature variations, erosion, sunlight, meteorological phenomena) (Holt, 1991, p. 48). As Holt (1991) emphasizes, “botanical artifacts” such as natural dyes are characterized by their dynamism, as they are “highly responsive to ecological and cultural changes” (ibid., p. 58) and able to develop an interactive relationship between consumers, the environment, and culture.

“Colour precision” is a critical factor in textiles and garments and it strongly influences consumer interest and purchase decisions, as by learning the accepted colour aesthetics, we have learned the beauty of industrial colours. Continuous colour-correct products are expected of industry and this colour control is an important part of the quality work in companies. (Balthazar, 2021) Talman (2019) in turn questions the idea of quality, in terms of aesthetic features and the standards of durability in the field of textile design. Textile practice has seen the design and production of fabrics as something static, recognizing any sign of change, such as the fading of colours or wear, as loss of value. Quality tests aim to assess the capacity of textiles to resist change. Social norms and the expectations of hygiene also influence how the aging of fabrics is experienced. As a consequence, these types of quality control exclude variation and standardize the homogeneous production of textiles. Talman states that "instead of trying to delay the inevitable signs of wear and tear in textiles, these could be consciously included in the design process, shifting the focus away from the static textile and onto creating evolving textile expressions." (Talman, 2019, p. 204).

The appreciation of counter-aesthetics requires "openness to new objects and forms" which consequently upholds diversity. In this case, Fenner refers to diversity as maximizing the incorporation of different aesthetic elements that are usually discarded because they do not fit the standardized aesthetic qualities dictated by economics and production (Fenner, 2004, p. 75). As Cheyne (2023) highlights, counter or imperfect aesthetics can "lead to different ethoses or cultural atmospheres." Imperfect aesthetics can create a more inclusive approach, the spirit of acceptance and openness (ibid.) and perhaps even openness to a new aesthetic understanding in which environmental values lay the ground for aesthetic evaluation (Niinimäki 2014; 2015).

Imperfect environmental aesthetics

Cultural and social contexts determine how we understand colour and what kind of meanings we give it. Colour preferences and perceptions are tied to cultural practices and are learned (Hine, 1995; Adams, 2006), but they can also be challenged in the light of environmental knowledge. "In other words, colour preferences can also be understood as a form of social and cultural construct that are time and space specific." (Durrani & Niinimäki, 2023) but they also include the underlying value base of society. If we think of colour through current industrial and economic logic, which is connected to their easy

4 Garments by Sofia Ilmonen are coloured with red onion. The shirt print is designed to become more visible slowly as the base colour is exposed to light.
Photo Diana Luganski

production and durability resulting from mass manufacturing, yet on the other hand bases its practices on linear economic realities emphasizing very short use time of garments and easy disposal, we end up with unsustainable colour aesthetics produced with synthetic dyes and environmentally harmful colours and chemicals, which are highly dependent on fossil fuels.

The acceptance of colour variations goes together with the variation of the environment (different geographies–different colours) or appreciation of changes in the same environment (different seasons or life cycles–different colours). Accepting colour variations emphasizes understanding nature and its connection to colour aesthetics. If we accept other kinds of colour aesthetics such as variety, instability, uncontrollability, and even fading or changing colours, we can create a more sustainable colour palette, which is more in harmony with the environment. These kinds of colour aesthetics can be implemented on a smaller scale; with designers and craft artists or by working with more local colour sources; using plants harvested close by, even close to the end user; creating a different kind of relationship with the environment. The designer, the environment, industry, and the end user can have a meaningful connection. We also need to take into account the limits of the environment. This means that textile and fashion production has to decrease drastically if we want to use natural colours. Therefore this approach also challenges the scale (decreasing) and temporalities (slowing) of the textile/fashion system. We need to understand the limits of production caused by the limited resources of nature and the seasonality and temporalities of natural colours.

We need to rethink durability, the aging process, wear and tear, and our understanding of beauty and see these in a new sustainable way, even through a new temporal view. This new colour aesthetic based on imperfection can be seen as a political act which may lead to a better balance in the eco-social approach and a new environmental understanding. This approach can also be seen as a criticism of “the standardized aesthetic qualities dictated by economics and industrial mass production” that results in the aesthetics of *sameness and control.* We conclude that creating imperfect colour aesthetics with natural dyes may correct some part of the currently broken industrial system and create better balance with the environment.

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Arsenic wallpaper sample from *Shadows from the Walls of Death,* 1874

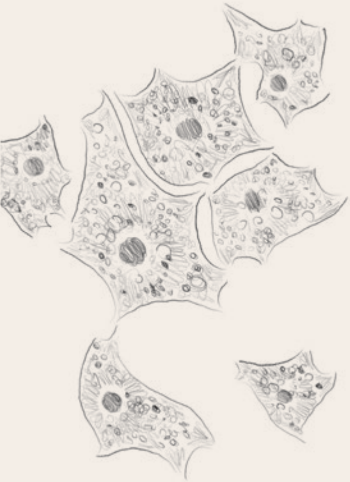
Green

Green fascinates us. It reminds us of the multitudes of organisms that produce and display it. However, when we try to reproduce green, we cannot make it last. We cannot recreate the chlorophyll spike of living colours and fixing artificial green pigments often involves toxic substances. What we are failing to grasp is that our human pursuit of permanence is alien to nature. Green is transient and ephemeral, emerging and degrading in the ever-dynamic web of life.

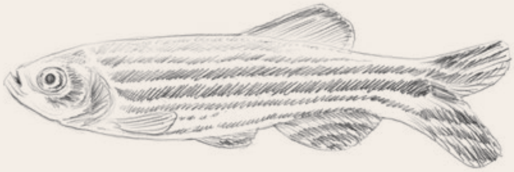
Water flea (Daphnia)

Testing Toxicity

Aquatic organisms, such as water fleas (Daphnia) and zebrafish (Danio rerio), and in vitro cultivated human liver cells help scientists understand the long-term toxicity of colourants – be they synthetic or bio-based.



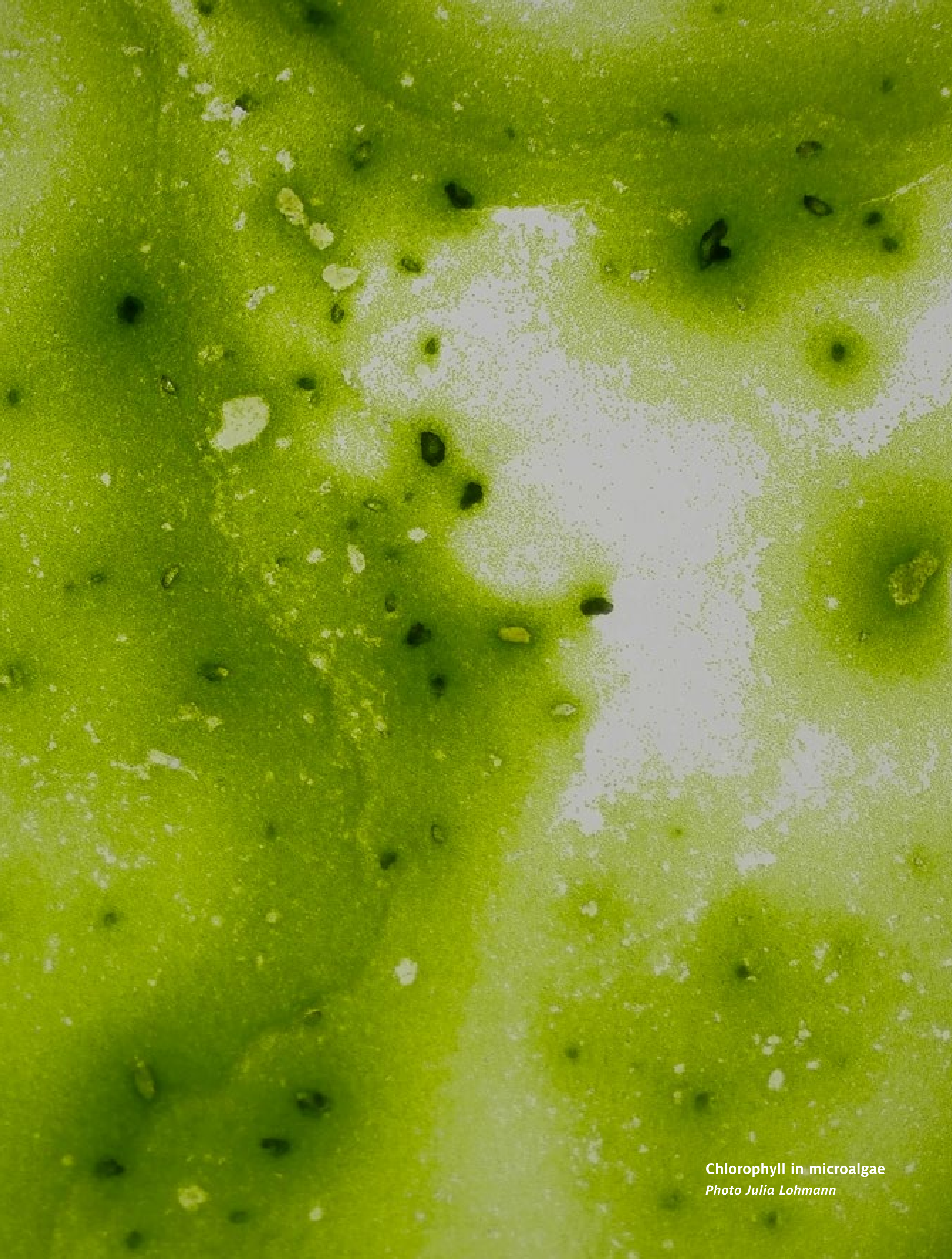
Human liver cells



Zebrafish (Danio rerio)

← A page from a reference book of bound wallpaper samples that was sent to US libraries in 1874, so that citizens might identify whether their own wallpaper was toxic, and if so, remove it.

Photo Leonardo Hidalgo Uribe



Chlorophyll in microalgae
Photo Julia Lohmann

Photo Leonardo Hidalgo Uribe

Harold S. Freeman, Tova N. Williams,
Gisela A. Umbuzeiro, Riikka Räisänen

Colourants and sustainability

ABSTRACT

This article introduces ways of which synthetic colourants are produced and processed. It also looks at colourants' safety and their impacts on environment. Colourants are widely used in the built environment, but the consumer, and user, knows little about their production and characteristics. This article looks at colourants from a sustainability point of view. It discusses what kind of advances in colourants and colouring practices would need to be favoured when reaching toward a more sustainable future. Taking account that the colouration of textiles comprises the major use of dyes with processes that rise severe environmental concerns.

Keywords
colourant, dye, environment, sustainable, aromatic, synthetic

Introduction

Colourants (dyes and pigments) are used everywhere in the global environment (Slama et al., 2021). Yet, the average consumer, and user, knows little about their production and characteristics, and their impact on sustainability, for example environmental and human health. Globally, the market size for synthetic colourants was valued at $38 billion in 2022 and is projected to grow annually at a rate of 5.3% during the period 2023 to 2030. (Market Analysis Report, 2023). Their production relies heavily on petroleum-based raw materials (e.g., aromatic amines and phenols), a major source of pollution and a non-renewable material and energy source. In addition, some dye manufacturing processes involve the consumption of toxic chemicals, as will be expounded upon later. The cost to produce a single colourant depends on a variety of factors, especially the cost of its raw materials. Generally, the most economical dyes produced are of the azo class, as their production typically involves using pair of organic components that react to form the target product. (Christie, 2015, pp. 72–98) Also, the production of the azo dyes is carried out using low temperatures (i.e. energy), water (instead of organic solvents), and without the need for toxic metal catalysts, making the dyes not only more economical but also more sustainable compared to other dyes produced. Sustainability includes not only environmental and ecological issues but also economic, cultural, and societal aspects. For instance, what types of advances in colourants and colouration practices would be favoured when reaching toward a more sustainable future?

Bearing in mind that the colouration of textiles comprises the major use of today's colourants and has been a significant source of environmental concerns, textile colourants will be the point of emphasis in this chapter. This overview of textile colourants will include their molecular nature and design, along with the basis for colour in synthetic and natural colourants. The discovery of natural and synthetic colourants will be briefly presented, their applications to different fabric types (cotton, wool, nylon, polyester,

Sofia Ilmonen's green dress is dyed with chlorophyllin, which lightens quite fast when exposed to light. This colour attribute can be used as a design element.
Photo Juho Huttunen

acetate, and acrylic), and concerns pertaining to their potential impact on human health and the environmental will be discussed. It is envisaged that this will inspire readers engaged in dye development and colouration activities to consider the potential impact of their operations on sustainability issues.

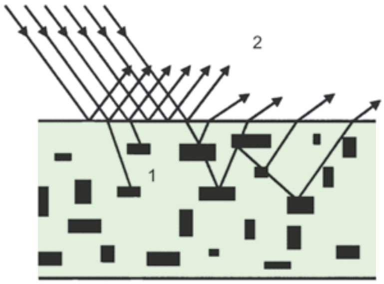
Textile colourants are organic compounds

Textile colourants are chemical organic compounds that have three essential features (Abrahart, 1977, pp. 1–7):

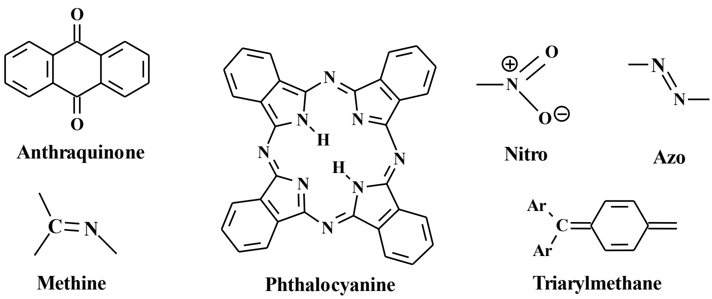
1. *They absorb light in the visible region* (400–700 nm) of the electromagnetic spectrum. Associated with each dyed object is the colour absorbed when light (e.g. sunlight) strikes an object and the reflected colour is seen (Figure 1, Table 1). These two colours are known as complementary colours, as joining them together produces white light again.
2. They have a *chromophoric* (colour bearing) *group* (e.g. azo, anthraquinone, phthalocyanine, methine, nitro, triarylmethane), as shown in Figure 2. These groups are the most effective part of the conjugated system that produces colour. Azo and anthraquinone chromophores are dominant among textile dyes, together covering about 80% of all dye structures.
3. They have *a conjugated system* – a series of alternating single and double bonds. Increasing the length of the conjugated system acilitates colour production, as illustrated in Figure 3 for vitamin A and beta-carotene.

Removing any one of the above three features from the molecular structure of the colourant leads to loss of colour.

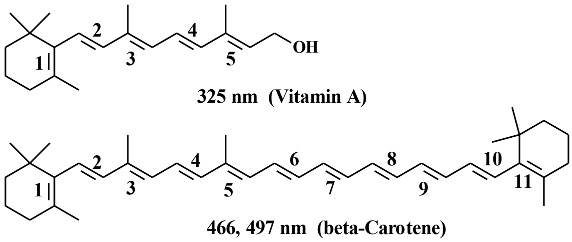
In addition to chromophoric groups, most organic colourants contain groups known as auxochromes (colour aiders), examples of which are carboxylic acid (–COOH), sulfonic acid ($-SO_3H$), amino ($-NH_2$), and hydroxyl groups (–OH). While such groups are not responsible for colour, they can shift the colour of a colourant following their



1 Colourant molecules absorb some of the wavelengths (1) while others are reflected (2). The reflected wavelengths of the visible light are seen as the colour of the object. See also Table 1.



2 Examples of chromophores present in organic colourants. Ar = an aromatic ring



3 Effects of extended conjugation on absorption wavelength and hence colour. Vitamin A is colourless as the absorbed wavelength is in the ultra-violet range, non-visible spectrum, and beta-carotene is yellow as blue wavelengths are absorbed.

addition. They are most often used, though, to influence the solubility of the colourant, a point that will be covered later.

Regarding their solubility properties, organic colourants fall into two classes, namely dyes and pigments (Allen, 1971, pp. 11–13). The key distinction is that dye colourants are soluble in water and/or

Table 1. Colours perceived (seen) following visible light absorption by the colourant.

Wavelengths of Absorbance (nm)	Colour Absorbed	Colour Seen
400–435	Violet	Yellow-Green
435–480	Blue	Yellow
480–490	Green-Blue	Orange
490–500	Blue-Green	Red
500–560	Green	Purple
560–580	Yellow-Green	Violet
580–595	Yellow	Blue
595–605	Orange	Green-Blue
605–700	Red	Blue-Green

4

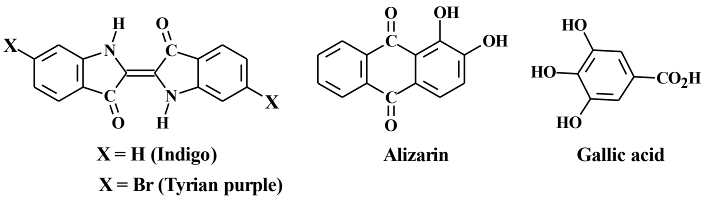
an organic solvent, while pigment colourants are generally *insoluble* in both types of liquid media and are insoluble in the medium in which they are used. Typical structures for colourants that fall into these two groups are described in this chapter. It will be shown that dyes can be incorporated into textile fibers from aqueous media while pigments are restricted to the fiber surface under those conditions.

In what is known as subtractive colour mixing, dyes can be mixed to produce the variety of colours we see in today's textiles. Normally this is achieved using the three primary colours: yellow, magenta, and cyan, as illustrated in Figure 4. where we see a Colour Triangle produced by dyeing polyamide with different combinations of these three primary colour acid dyes.

Natural dyes

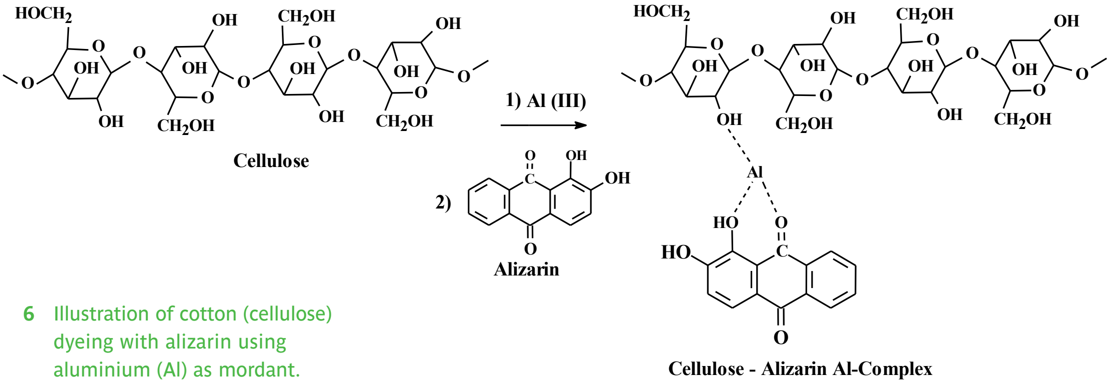
In a world before man-made (i.e. synthetic) dyes, the initial dyes employed for textile colouration were natural dyes, examples of which are indigo and its dibromo derivative (Tyrian purple), the anthraquinone dye alizarin, and tanning agents such as gallic acid and its gallate derivatives (Figure 5). Natural dyes come from plant, fungal and animal sources, with certain animals (e.g. insects and gastropods) containing colourants less than 0.01% of their dry weight and plants/berries containing colourants up to 27% of their dry weight. Dyes of this type had little to no inherent affinity for the fibers available at the time (cotton, wool, and silk), leading

4 Dyeings produced from subtractive colour mixing of an acid dye trichromy (yellow, magenta, cyan) on polyamide fabric. Primary colours are seen at the corners of the triangle.

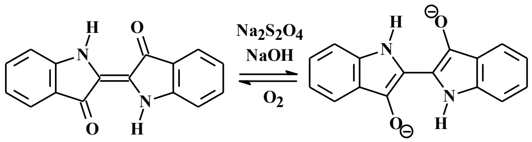


5 Examples of natural dyes used for textile dyeing before synthetic dyes were developed.

to the need for dyeing assistants called mordants which serve as a linking agent between natural dyes and textile fibers (Figure 6) (Püntener & Schlesinger, 2000). The commonly used mordants were metal salts and included metals such as chromium (Cr), copper (Cu), iron (Fe) and aluminium (Al). As Figure 6 suggests, the cotton fabric to be dyed is first placed in a solution of the mordant (e.g. alum, containing Al) and then added to a solution of the natural dye (e.g. madder, containing alizarin as the main colourant), with Al serving as a bridge between cellulose and alizarin. A scarlet fabric colour arises from the Figure 6 dyeing process but the colour changes to dull bordeaux, reddish-brown, yellowish-brown, and orange, when Al is replaced by Cr, Fe, Cu, and Sn, respectively. Similarly, alizarin produced deep red, violet to black, and red shades on wool when Cr, Fe, and Al were used as mordants. While dyes such as alizarin and gallic acid require mordants, indigoid dyes do not. Instead, they are applied to cotton textiles through a vat dyeing process in which the insoluble form of the dye is reduced to the water soluble form, diffused into the fibers and then re-oxidized inside the fibers, as illustrated in Figure 7 (Leube, 2003).



6 Illustration of cotton (cellulose) dyeing with alizarin using aluminium (Al) as mordant.



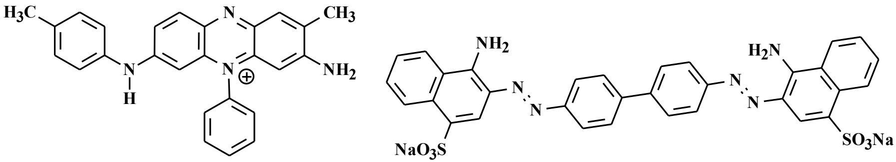
7 Reduction and re-oxidation processes of indigo in vat dyeing.

Regarding sustainability, natural dyes are biodegradable, renewable, and generally non-toxic themselves, as they are often extracted from sources that are also used for food or are known for centuries without hazardous effects. Yet, the use of toxic metals as mordants in dyeing process can be problematic. Some natural dyes are used in food and cosmetic products, having the ability to meet stringent safety and toxicological standards. However, they often exist as mixtures with imprecisely defined composition and dyed fabric shades vary with 1) the part of the plant employed for dyeing, 2) extraction method, 3) soil and cultivation history of the plant, as well as 4) weather and seasons (Glover & Pierce, 1993). About 30% of the world's farm land would be required to meet the current needs for textile dyeing if cultivated plants were used as natural dye sources. Regarding dyeing with indigo, 176 million tons of fresh dye plant requires circa 3 million square kilometres of land for cultivation and generates 170 million tons of waste biomass following dye extraction from plant material. (Glover, 1998.) Cost wise, dyeing 1 kg wool can cost 100 times more with plant dyes versus synthetic dyes and dyeing 1 kg cotton can cost 200 times more with plant dyes than with synthetics. Further, we now know that metals such as Cr and Cu are harmful to human health and the environment, restricting their use in textile dyeing. Therefore, we need research and development to apply bio-based dyes in sustainable and cost-effective ways. And after all, the price of the colourant in the total price of a product is infinitesimal, cost per t-shirt being ca. 15 cents for synthetic dyes.

Synthetic dyes

An overview of the synthetic dye types (classes) in order of discovery is captured in Table 2. This is followed by a description of the individual classes, along with specific examples and how they are used in textile manufacturing, particularly dyeing.

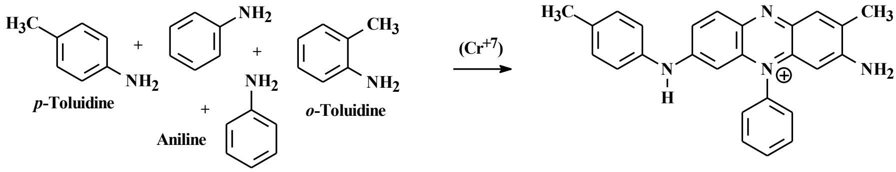
Early synthetic dyes included mauveine and Congo red shown in Figure 8. The first synthetic dye became available in 1856, when



Mauveine

Congo red

8 Examples of early synthetic dyes suitable for textile dyeing without mordants.

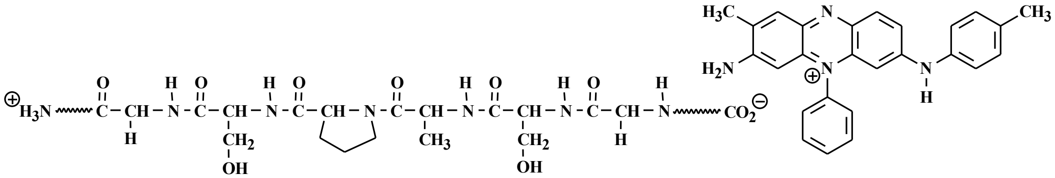


Sir William Perkin discovered that the oxidation of crude aniline using potassium dichromate produced a cationic colourant (mauveine) that duplicated the shade produced by Tyrian purple on silk fabric (Allen, 1971, p. 8). Elucidation of the mauveine structure revealed that the supply of aniline used in Perkin's work was actually aniline containing a mixture of *ortho*- and *para*-toluidine (Figure 9).

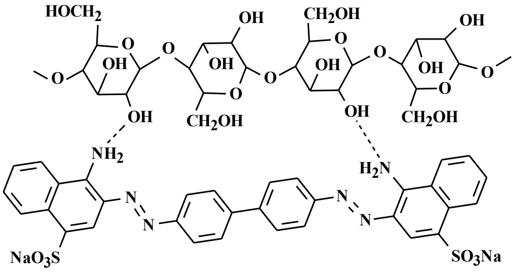
9 Formation of mauveine by oxidative coupling of mixed aniline compounds: two molecules of aniline and one molecule each of ortho and para toluidine (chrome needed as catalyst). In ortho toluidine the attached groups are beside each other while in para form the groups are on the opposite sides of the benzene ring.

Table 2. Synthetic dyes – in order of their discovery.

Dye Class	Dye Name	Inventor	Year
Basic	Mauveine	Perkin	1856
Acid	Alkali blue	Nicholson	1862
Mordant	Alizarin	Grabe & Liebermann	1868
Vat	Indigo	Baeyer	1878
Direct	Congo red	Böttiger	1884
Sulfur	—	Vidal	1893
Azoic	—	Zitscher & Laske	1911
Disperse	(Simple monoazo dye)	—	1920s
Phthalocyanine	(Phthalocyanine blue)	Linstead & Diesbach	1928/29
Reactive	(Reactive red)	ICI	1956

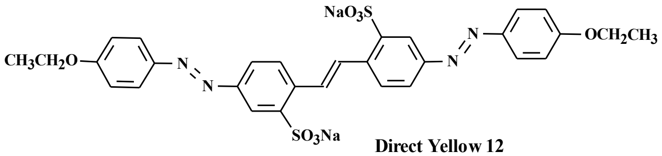


10 Illustration of bonding between the silk structure and mauveine (ionic bonding).

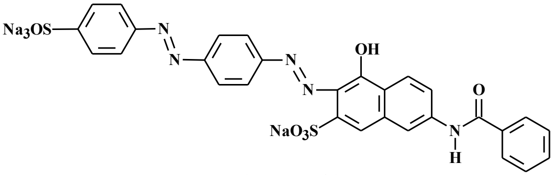


Cellulose - direct dye interactions

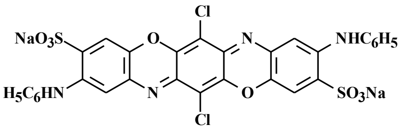
11 H-bonding interactions between Congo red direct dye and a cotton cellulose polymer chain.



Direct Yellow 12



Direct Red 81



Direct Blue 106

12 Examples of yellow, red, and blue direct dyes for cotton fibers.

Mauveine requires 2 molecules of aniline and 1 molecule each of *ortho* and *para* toluidine. The resulting cationic dye forms an ionic bond with anionic groups on the end of the polymer chains of protein fibers (Aspland, 1993a) such as silk, as illustrated in Figure 10.

The development of dyes capable of dyeing cotton without the need for mordants (i.e. direct dyes) (Hunger, 2003b) occurred in 1883 is illustrated in the Congo red dye (Figure 6). These dyes are attracted to cotton through secondary valency forces such as H-bonding, as illustrated in Figure 11 where two interactions are shown between the cellulose repeat unit and the direct dye structure (Trotman, 1964). Direct dye affinity is most effective when the dye molecules are long and linear in form, giving proximity to the cellulose chain. Over time, direct dye structures have expanded to four main chromophores: azo (e.g. Direct Red 81 and Direct Black 22), stilbene (e.g. Direct Yellow 12 and Direct Yellow 11), oxazine (e.g. Direct Blue 106) (Figure 12), and phthalocyanine (e.g. Direct Blue 86 and Direct Blue 199). About 82% of all direct dyes have bisazo or polyazo structures, while stilbene and monoazo structures occupy about 5% each and thiazole, phthalocyanine, and dioxazine structures cover the remaining few percent (Shore, 1990). Suitably substituted direct dyes can be converted to metal complexes. In this regard, Cu is the metal of choice and examples are Direct Blue 218, Direct Red 83, and Direct Brown 95. About 5% of all azo direct dyes are metal complexes and unlike most direct dyes, these dyes have good light fastness, as would be anticipated by the addition of metal ion which stabilizes the dye's structure.

Molecular design

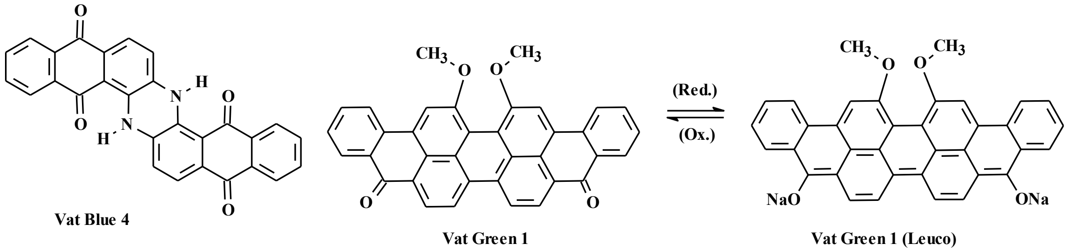
Since the effectiveness of a textile dyeing process often hinges on the affinity between the colourant and substrate, different dyes are designed and developed with the target fiber type in mind. In this regard, colourants used in dyeing are designed such that they have 1) greater affinity for the substrate than the medium (usually water) from which they are applied, 2) a high degree of permanence under end-use conditions (e.g., resistance to fading upon exposures to water and/or sunlight), and 3) safety in the environment in which they are used. Textile dye design as a function of these considerations is summarized below.

Dyes for cellulosic fibers

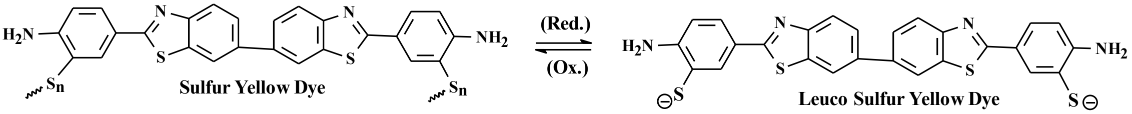
Cellulosic substrates include fibres such as cotton, viscose, and linen, all of which are very hydrophilic and, therefore, need water-soluble dyes for their colouration. While direct dyes have affinity for cotton in the absence of a mordant, many have limited permanence to cellulosic fibers under wet conditions resulting in low wet fastness, as the H-bonds between dyes and cellulose can be disrupted by H_2O molecules, enabling those dyes to be "dissolved" out of the fiber. The ease with which cellulosic substrates such as cotton swell and lose certain colourants during a laundering step has led to the design and development of a more wide variety of dye colourant families for cellulosic fibers than any other substrate.

To enhance dye wet fastness on cotton, non-sulfonated dyes were developed. The idea was to incorporate a water-insoluble colourant into the polymer matrix to prevent colour removal upon exposure of the dyed substrate to water. This led to the development of vat, sulfur, and azoic dyes (Aspland, 1990a,b,c). In their application to textiles, water insoluble vat and sulfur dyes are converted to a water-soluble (leuco) forms that diffuse into cellulose and are converted back to their water-insoluble form after fiber penetration, giving good permanence under wet conditions. Figures 13 and 14 show examples of commercially used vat and sulfur dyes, along with a representative chemical transformation associated with their dyeing of cotton.

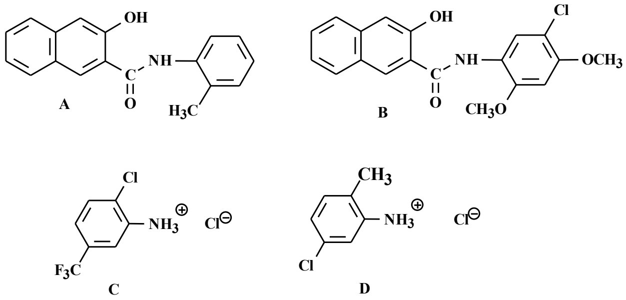
Azoic colourants are also known as naphthol dyes because naphthol compounds are used in their synthesis. These predominantly red colourants do not exist “on the self” *per se*, instead they are generated inside the polymer matrix by applying the required two components (a coupling component and a diazo component) to the substrate separately (Figure 15). In the case of the formation of E and F dyes, during the dyeing process, the coupling component (A or B) employed is dissolved in NaOH solution, the solution is applied to cotton fabric, and the fabric is dried. To prepare the azoic diazo component (C or D) for dye formation, the ammonium (NH_3^+) group is converted to the required diazo (N_2^+) group using nitrous acid. When the naphthol-treated fabric is added to a solution of the diazo compound, the two precursors find each other and combine to form a water insoluble azoic colourant of the type shown in Figure 16. In these examples, precursors A + C produce dye E, while B + D produce dye F (Figures 15 and 16).



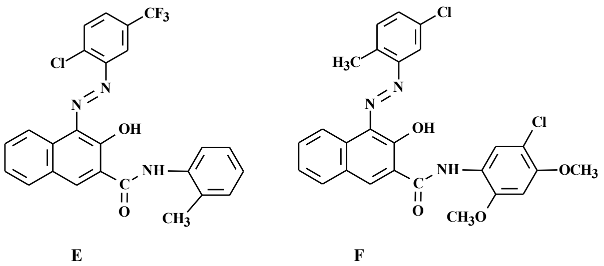
13 Examples of anthraquinone vat dyes and a representative reduction/ oxidation process.



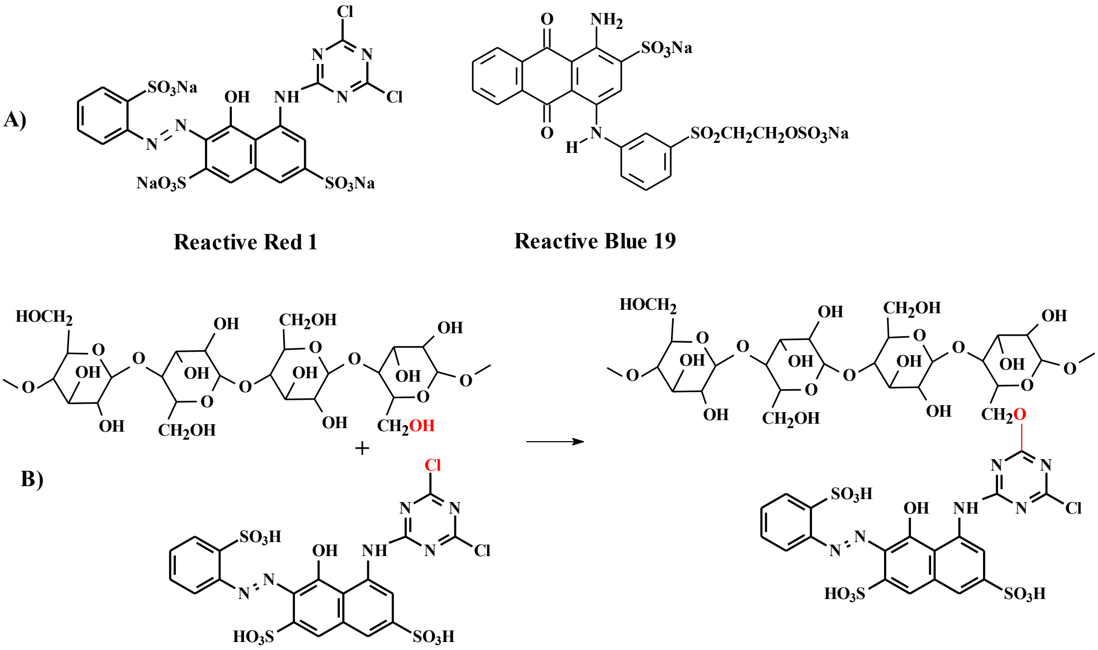
14 Examples of sulfur dye structures and a representative reduction/ oxidation process.



15 Azoic coupling components A and B; and azoic diazo components C and D.



16 Azoic dyes E and F arising from azoic coupling and azoic diazo components.

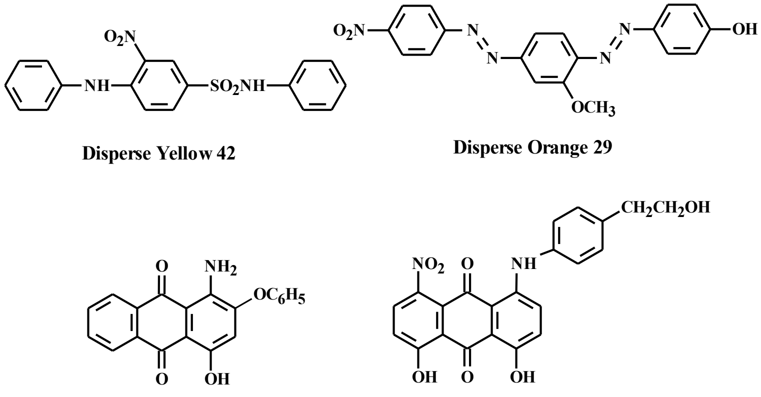


17 Examples of reactive dye structures (A) and the bonding process on cotton cellulose (B).

The final family of suitable colourants for cellulosic fibers is known as reactive dyes (Siegel, 1972) (Figure 17a). They derive their name from the fact that they undergo a chemical reaction with an –OH group of cellulose to form a covalent bond (Figure 17b). Unlike dyeing with other dye classes for cotton, the chemistry shown in Figure 17b can take place at room temperature. These water-soluble colourants opened the door to bright wet fast shades on cellulosic fibers that were not previously attainable, especially when direct dyes were used. Most reactive dyes require salt to promote dye exhaustion from aqueous media and alkali to facilitate bonding to cellulose. Further, reactive dyes are often used for tie-dyeing and constitute the most widely used dyes for cotton (Aspland, 1990d).

Dyes for polyester

Unlike cotton, polyester fibers are hydrophobic which prevents dyeing them with any of the dye classes described previously for cotton. In this case, dyes invented for hydrophobic acetate fibers were found to be good options for polyester. Such colourants are very sparingly soluble in water and have become known as disperse dyes (Weaver, 2003). Their name is derived from the fact that they are dispersed (using a surfactant), rather than dissolved, in water to carry out the colouration process. Examples of the many commercial options are shown in Figure 18. These colourants have no affinity for hydrophilic polymers such as cellulose, which makes them unsuitable for dyeing cotton, cellophane, and paper but quite suitable for dyeing polyester and cellulose acetate. In this case, the mechanism of colouration involves "dissolving" the colourant in a hydrophobic polymer matrix, i.e. forming a solid–solid solution. This is best achieved when the dye particles are converted to the micron level and dyeing is conducted at 130°C in a sealed chamber (Aspland, 1990e). The high temperature softens the fibres and the dyes are able to penetrate into them. When temperature decreases after dyeing fibres solidify and dyes remain trapped inside. This kind of dyeing results very high wet fastness.



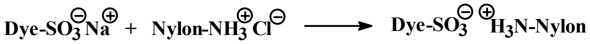
Disperse Yellow 42

Disperse Orange 29

Disperse Red 60

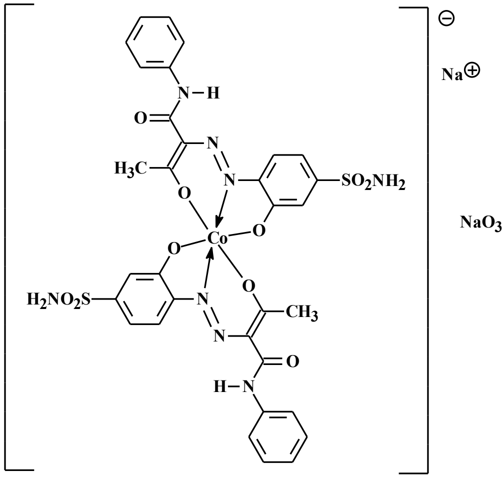
Disperse Blue 27

18 Examples of disperse dye structures used for polyester dyeing.

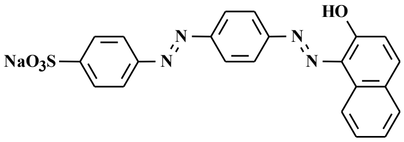


$$\text{Dye-SO}_3^{\ominus}\text{Na}^{\oplus} + \text{Nylon-NH}_3^{\oplus}\text{Cl}^{\ominus} \longrightarrow \text{Dye-SO}_3^{\ominus}\ {}^{\oplus}\text{H}_3\text{N-Nylon}$$

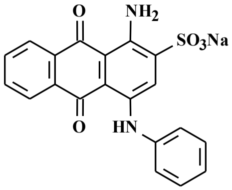
19 Schematic representation of dye–polymer binding via ionic bonding on polyamide (nylon).



Acid Yellow 151



Acid Red 151

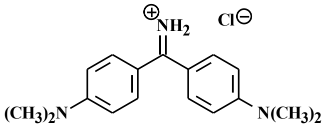


Acid Blue 25

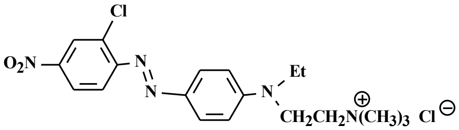
20 Examples of yellow, red, and blue acid dye structures.

Dyes for polyamide and wool

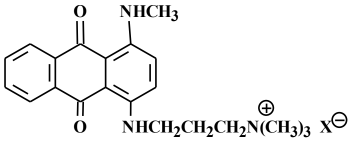
In this case, colourants bearing a negative (anionic) charge are used because textile fibers such as polyamide, wool, and silk possess a positive (cationic) charge – especially during the colouration step (Aspland, 1993b). The presence of NH_3^+ groups on the polymer chains of these fibers opens the door to ionic bond formation (Figure 19) within the polymer matrix. Anionic colourants for polyamide and wool fibers are known as *acid dyes*, azo and anthraquinone examples of which are shown in Figure 20. Their name is derived from the fact that they are typically applied to suitable substrates from a medium containing acid. These colourants have little to no affinity for polyester, cellulosic, or cationic polymers, since such substrates cannot form either an ionic or hydrophobic bond with them.



Basic Yellow 2



Basic Red 18



Basic Blue 22

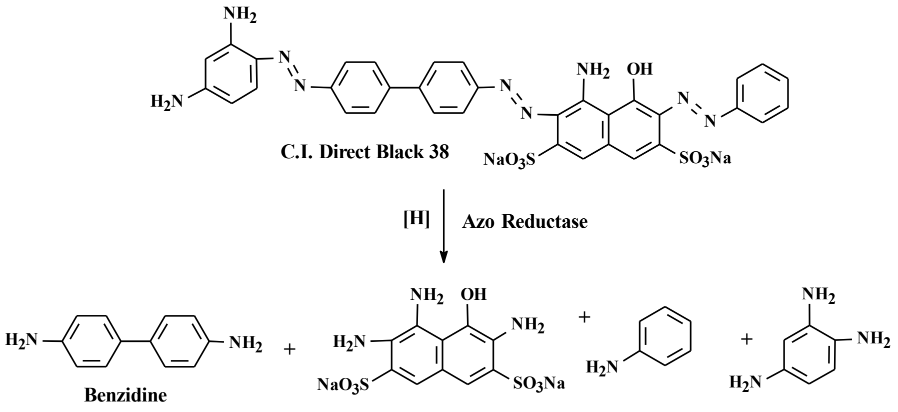
21 Examples of yellow, red, and blue cationic colourants for acrylic and other anionic fibers.

Dyes for acrylic fibers

Dyes for this substrate also form ionic bonds within the polymer matrix. In this case, colourants bearing a positive (cationic) charge are used because polymers such as poly(acrylonitrile) and sulfonated polyester possess a negative (anionic) charge in their backbone (Rivlin, 1992), making the ionic character of the interacting substances the reverse of that described previously in section 3. Cationic colourants for acrylic substrates were initially known as *basic dyes*, because they used to be applied in a basic (or alkaline) medium to dye wool and other protein fibers (Christie, 2015, pp. 168–193). Three examples of these dyes are shown in Figure 21. Today, their name is derived from the fact that they possess a cationic group. These colourants have no affinity for traditional polyester, cellulosic, or polyamide polymers, since such substrates do not form an ionic bond with them.

Dyes and sustainability

Regarding dye sustainability, synthetic dyes do not require mordants for fiber fixation, are more reproducible, more economical, readily available, and typically have much better colour strength than natural dyes. However, they are much less biodegradable, not renewable, and may require metals such as Hg or genotoxic aromatic amines in their synthesis. Their residual presence in dyebath effluents can pose problems for drinking water and aquatic life. Potential sustainability issues as a function of textile dye class are summarized below.



22 Reductive cleavage of C.I. Direct Black 38 to form aromatic amines such as benzidine.

Direct dyes

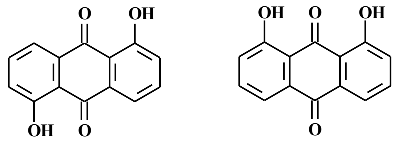
Historically, sustainability concerns pertaining to direct dyes have involved the use of genotoxic aromatic amines in the synthesis of azo dyes in this family. The heart of these concerns was the recognition that the direct dye precursors benzidine and its congeners (3,3'-dimethylbenzidine and 3,3'-dimethoxybenzidine) are carcinogenic compounds. This led to the banning of products containing dyes derived from these diamines along with 20 other aromatic amines (ETAD Information Notice No. 6, 1996) which deemed to pose a cancer risk to humans. The basis for this decision is the awareness that azo dyes can undergo reductive cleavage in mammalian systems to produce the aromatic amines used in their synthesis. This means that dyes such as C.I. Direct Black 38 can form benzidine upon azo reduction, as illustrated in Figure 22. While currently used direct dye manufacturing no longer involves carcinogenic amines, some researchers have continued to use the cancer risk associated with benzidine as a basis for designating all synthetic dyes as toxic. However, this practice is entirely inappropriate, as is the designation of all natural dyes as nontoxic. It should also be taken into consideration that human cancers tend to arise from repeated handling of amines such as benzidine and beta-naphthylamine during dye manufacturing rather than from exposure to the associated dyes.

In addition, some direct dyes employ Cu(II) in their synthesis and salt (NaCl) in their application to textiles. Since both substances can be harmful to the environment, there are regulatory limits regarding their discharge in effluents (The NIOSH pocket guide to chemical hazards, 2007).

Vat dyes and sulfur dyes

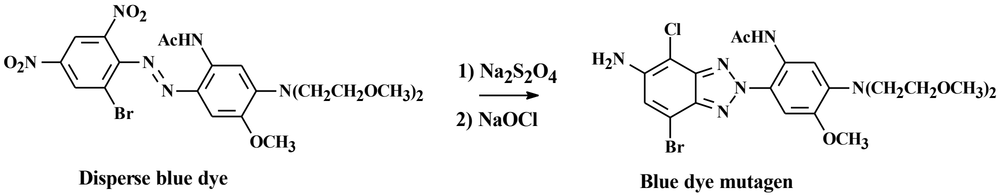
The principal concerns pertaining to vat dyes involve the aquatic toxicity of the reducing agents (e.g. sodium hydrosulfite) when released to the environment in dye wastewater. Thus, alternatives agents such as glucose and NaOH have been developed (Zollinger, 2003).

Disperse dyes



23 Precursors anthrarufin (left) and chrysazin (right) used to synthesize anthraquinone disperse dyes.

Disperse dye sustainability concerns arise from three main areas: 1) the formation of anthraquinone dye intermediates, 2) the use of aromatic amines in their synthesis, and 3) the use of certain plasticizers in their application to polyester fibers. About 30% of commercial disperse dyes are anthraquinones, some of which require precursors such as anthrarufin and chrysazin (Figure 23), and are synthesized using an Hg(II) based reagent (Gordon & Gregory, 1987, pp. 69–72). Residual amounts of this agent may be found in the final dye. About 60% of disperse dyes are azo compounds, which means that they are derived from aromatic amines and are subject to metabolic processes that can regenerate the parent amines. Care must be taken in the choice of aromatic amines for disperse dye synthesis, to avoid mutagenic precursors. Further, it has been found that certain azo disperse dyes can be converted to mutagenic compounds during wastewater treatment steps. An example is shown in Figure 24, where hydrosulfite treatment followed by hypochlorite treatment has produced a phenylbenzotriazole (PBTA) mutagen in a public waterway



24 PBTA formation from disperse blue azo dye treatment in dyeing wastewater.

(Shiozawa et al., 2000). One other toxicity concern pertaining to disperse dyes involves the use of trichlorobenzene as a carrier when dyeing polyester at 100 °C.

Acid dyes

Bearing in mind that nearly 80% of commercial acid dyes have azo structures, hydrophobic precursors that are cancer-suspect agents must be avoided. Unlike disperse dyes, acid dye precursors include sulfonated compounds which are much less likely to be genotoxic. However, this dye family does include many examples of metal complexes derived from Cr and cobalt (Co) ions, and attempts to use less toxic replacements such as Fe and Al have been pursued (Szymczyk et al., 2007).

Basic (cationic) dyes

About 40% of the basic dyes are azo compounds, opening the door to exposures to aromatic amines during dye synthesis. Dyes developed must take into consideration the genotoxic potential of the precursors. While these dyes do not include metal complexes, lead dioxide (PbO_2) has been used in the synthesis of triarylmethane members of this family. Alternatives to Pb(IV) have been pursued and adopted (Zollinger, 2003, p. 106).

Toxicity of dyes and the environment

Several synthetic dyes, but not all, are mutagenic (Morgan et al., 1994; Tsuboy et al., 2007). Some disperse azo dyes were responsible for mutagenic effects in source and drinking water (Umbuzeiro et al., 2005), highlighting the importance of monitoring them in the environment.

In dyeing activities, water is usually used in great quantities. Because dyes are not totally attached to the fibers, they can remain in the wastewaters, and if not properly treated, they can reach the environment as part of the effluent. Dyes as well as their waste treatment products can cause adverse effects on aquatic species (Croce et al., 2017; de Luna et al., 2014; Vendemiatti et al., 2021). For example, Disperse Red 1, an azo dye, was found in receiving waters at concentrations that pose a risk to the aquatic biota (Vacchi et al., 2016).

Natural dyes

Natural compounds have a long history as colourants but only more recently there is growing interest in their use as replacements of synthetic dyes to achieve a more sustainable production of textiles. But the use of natural dyes as a safer alternative has not been properly studied. In fact, the general idea that natural is safer than synthetic does not seem to be always true. There are some examples of natural dyes from the class of the anthraquinones that have mutagenic properties, such as emodin (Masuda & Ueno, 1984), alizarin, and others (Westendorf et al., 1990). Some natural dyes are also toxic to aquatic species, e.g., erythrosominone (Abe et al, 2017 & 2019) and alizarin (Liberman, D. et al, 1982; Babu et al, 2005). Because natural dyes are not designed with textile dyeing in mind, sometimes mordants are used, which are typically metal salts (e.g., copper and chromium salts), adding an additional environmental concern. Also, the concentrations of natural dyes in the wastewater tend to be higher if their affinity to the fiber is not optimized.

Therefore, to achieve sustainable dyeing activities it is mandatory that any dye is evaluated for its toxic and genotoxic properties before being marketed. Biodegradability also needs to be considered when discussing the environmental safety of dyes. Whether natural or synthetic, as chemicals they can persist in the environment and exert adverse effects on humans and biota. Risk assessments must be performed in realistic scenarios to define the safe concentrations of dyes in the aquatic or terrestrial environment.

Conclusions

In summary, it is clear that the choice of dyes (natural vs. synthetic) for dyeing a given textile product is based on the fiber type(s) present, the end use of the product, and human and environmental safety considerations. Thus, when breadth of colours, economy and large volumes are of paramount importance, synthetic dyes are advantageous. However, when biodegradable and fully natural products are sought, natural dyes can be the way to go. It is good to remember that neither type is automatically sustainable nor toxic solely based on class. Interestingly, the ability to bio-manufacture natural dyes in homogeneous form and in large quantities could change this picture significantly, giving natural dyes the advantage.

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willow coppicing

willow pollarding

Willow (Salix spp.) & Lignin

Willow bark is a source for a wide range of phenolic molecules that can be used both as bio-colourants or in materials applications.

The bark is a side stream of the forestry and paper industries and could be used to produce a range of natural colours at scale. Some compounds found in willow also have anti-bacterial and UV-protective qualities. Making more of the materials willow provides and using it more widely might also have eco-systemic benefits. A revival of willow coppicing and pollarding could create plantation habitats sheltering and supporting a wide range of wildlife.

Photos Leonardo Hidalgo Uribe

Yarns dyed with Spruce cones

From early December 2021 to late August 2022, I did a series of walks in the nature reserve of Vanhankaupunginlahti in Helsinki. I searched for dyeing materials that grow from plants and examined their availability according to the seasonal change of the forest. Winter and spring offered mostly tree barks and cones, while in summer, I met with an explosion of leaves, flowers and berries. By walking, I experienced the change in the environment and the materials that grow in it. After each visit, I collected materials from the plants I found in my walks and experimented with the possible colours I could get from them by dyeing different shades of wool combined with alum and iron as mordants and pH variations.

— Leonardo Hidalgo Uribe

Päivi Laaksonen, Monika Österberg, Juha Jordan

Researching biocolour

ABSTRACT

Biocolourants differ from the conventionally utilized synthetic colourants and thus their dyeing processes and performance also differ from the conventional solutions. The need for understanding their interactions with various materials and releasing the full potential of the biocolourants has inspired us to carry out studies on the physicochemical characteristics of biocolourants. In this chapter, these studies are compiled into three cases. Case #1, "Stability of biocolourants", highlights pushing the limits of biocolourant stability and presents two studies on colour fastness of natural indigo pigment on wood coating applications. Case #2, "Textile dyeing with natural colourants and biomordants", introduces metal-free fixation of dyes to textiles and features two studies on textile dyeing with bio-based colourants and mordants. Case #3, "Biocolourants in functional materials", focuses on potential of biocolourants with unique properties and presents a group of studies on camouflaging and antioxidative biocolourants.

Keywords
biocolourants, physicochemical characteristics, stability, fastness, biomordants, functional materials

Fabrics dyed with willow bark.
Photo Valeria Azovskaya

Photo Valeria Azovskaya

Introduction

Colour is one of the most deciding factors when people are choosing materials to surround themselves with. To create lively colour on otherwise dull materials, millions of tons of dyes and pigments is produced every year (DCP, 2022). Many of these colourants are very stable and thus easily accumulate to the environment either during the colouration process or after disposal of the coloured product. When accumulated to the environment, synthetic dyes and pigments may cause severe harm to the ecosystems. (Tkaczyk, 2020.) Due to the sustainability and possibility for biodegradation, biocolourants have been proposed as a replacement for the synthetic colourants and a lot of research is conducted to explore new biocolourants and their application possibilities (Nambela, 2020; Shahid 2013).

The emergence of biocolourants in large scale use has prompted further interest in additional value of colourants. Because of natural origin, these substances may have interesting properties found in nature, such as antioxidative or camouflaging properties. Taking these properties into use, requires research and development of the technology, but also greatly increases the potential value of the biocolourants. For instance, biocolourants' antioxidative nature can be helpful for improving stability of the colourant molecule itself or some other sensitive compounds. So, instead of having just one function, the same dye may have multiple. How to implement these properties into materials and how to make sure that they work in the desired ways are the essential questions that this chapter intends to answer.

This chapter introduces three cases where different aspects of biocolourant research has been investigated. Case #1 considers stability of biocolourants and their fastness properties when exposed to environmental stress. A study and a thesis work about wood coating with case #2 introduces two studies where biomordants have been used to attach biocolourants on textile fibers. Finally, case #3 highlights the potential of biocolourants as functional substances, i.e., substances with additional value besides the colour they provide. In this case, a group of studies about camouflaging and antioxidative colourants will be presented as an example.

Case #1:
Stability of biocolourants

In addition to the actual colour, one of the key properties of colourants is their stability (Jespersen et al., 2005; Poggio et al., 2016; Räisänen, 2009). This is especially important for commercial products, such as garments, furniture, vehicles, kitchenware, and other objects that are exposed to environmental stresses including sunlight, humidity, and different chemical environments in their everyday use (Hinsch & Robinson, 2018). Different product types may have quite different expected lifetimes, but also their exposure to the environment varies greatly (Chakraborty, 2011; Meenaghan & O'Sullivan, 1986). For example, the required stability for a car paint and a dress are vastly different and therefore, it is utterly important to make sure that a suitable colourant, with high enough stability, is selected for a given application or product (Gürses et al., 2016).

One of the key elements of sustainable design is to keep the product in use for as long as possible (Kaddoura et al., 2019). There are several reasons why products are abandoned from use, and aesthetics is one of them (Saito, 2018). For a consumer or company, instability of the colouring of a product may lead to unwanted changes and the product may no longer seem appealing, fashionable enough or it does not fulfill some other criteria, such as the brand specific colour (Chang & Lin, 2010; Tepper, 1993). At the other end of the lifetime scale are consumable products that are expected to have a short lifetime. For disposal, it may not be reasonable to use chemicals, such as dyes or pigments, whose stability exceeds the other components that the product consists of. An example could be a biocompostable paper bag that contains very stable pigments that remain in the compost long after the bag has degraded.

Biocolourants are emerging and hopefully soon they will be in wider use in textiles, coatings, packages, composites etc. products. The exposure to environmental stress depends on the application area of the product and there are different criteria set for each area. This case discusses particularly the stability criteria that are set for coatings. The work aims at understanding the limitations and possibilities for enhancing the stability of biocolourants by collecting data of various experiments carried out in the laboratory. In the following section, we describe our methods for studying the stability of biocolourant-pigmented coatings and some experimental findings related to their stability, as presented in publications of Jordan et al. (2021) and Helander (2020).

Methods

The samples in the study were paints, varnishes and oils meant for coating of wooden facades. The experiments were carried out by pigmenting the studied coating with natural indigo of *Isatis tinctoria*, applying the coating on wooden sample and exposing the coating to accelerated weathering. The studied coatings were linseed oil (Uula Linseed Oil) (Figure 1a), linseed oil-based varnish (Uula Boat Varnish), and titanium white paint (Uula Linseed Oil Paint) (Figure 1d). The oil was applied directly on the wooden surfaces, whereas the varnish and paint were applied on top of white primer coating layer. Four layers of coating were applied on each sample. Unpigmented coatings were studied as control samples. For all coatings, comparison of the results was also done against commercial ultramarine pigment and synthetic indigo. (Sigma-Aldrich; Jordan, 2021; Helander, 2020)

For studying the durability and suitability of the coating for outdoor conditions, accelerated weathering tests were carried out. These experiments simulate the effect of UV light, temperature, and humidity on the coatings. In practice, the coated samples are placed in a chamber equipped with UV lamps and adjustable temperature and humidity. Conditions in the chamber are programmed to vary in a cyclic manner to resemble outdoor conditions, but the conditions in the chamber are typically harsher and thus cause changes in a shorter time span than would naturally occur. The accelerated weathering tests create stress-induced changes in the samples over weeks that would happen in outdoor environment over months or years. The operation of the device is based on alternating cycles of UV radiation and condensation, which simulates natural sunlight, rain, and dew. The continuous exposure cycle chosen for the linseed oil coatings consisted of alternating four-hour long periods of UV radiation at 60 degrees Celsius and condensation humidity at 40 degrees Celsius. For paint and varnish samples, exposure was done according to standard EN 927-6:2018. As described in the standard, one exposure cycle lasted 168 hours and consisted of 24 hours of condensation at 40 degrees Celsius followed by 144 hours of a repeating subcycle.

The subcycle consisted of alternating 2,5 hours of UV-radiation at 60 degrees Celsius and 0,5 hours of water spray on the samples.

The stability of the applied coating was assessed by measuring the changes in its colour before and after the weathering test. Colour measurements were performed by measuring reflection spectra of the coated wood samples before and after each exposure cycle. Determining the colour changes was based on the CIELab system, which defines colours based on coordinates representing opposing colours. The CIELab coordinates include colour brightness (also known as luminance or lightness) L^*, red/green coordinate a^*, and yellow/blue coordinate b^*. The L^* value indicates the brightness of the colour on the scale from 0 to 100, where 0 means completely black and 100 means completely white. The a^* and b^* values together describe the hue and intensity of the colour. The stability of colour is determined as the total colour change during the sample exposure, ΔE, that can be calculated using the following equation:

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

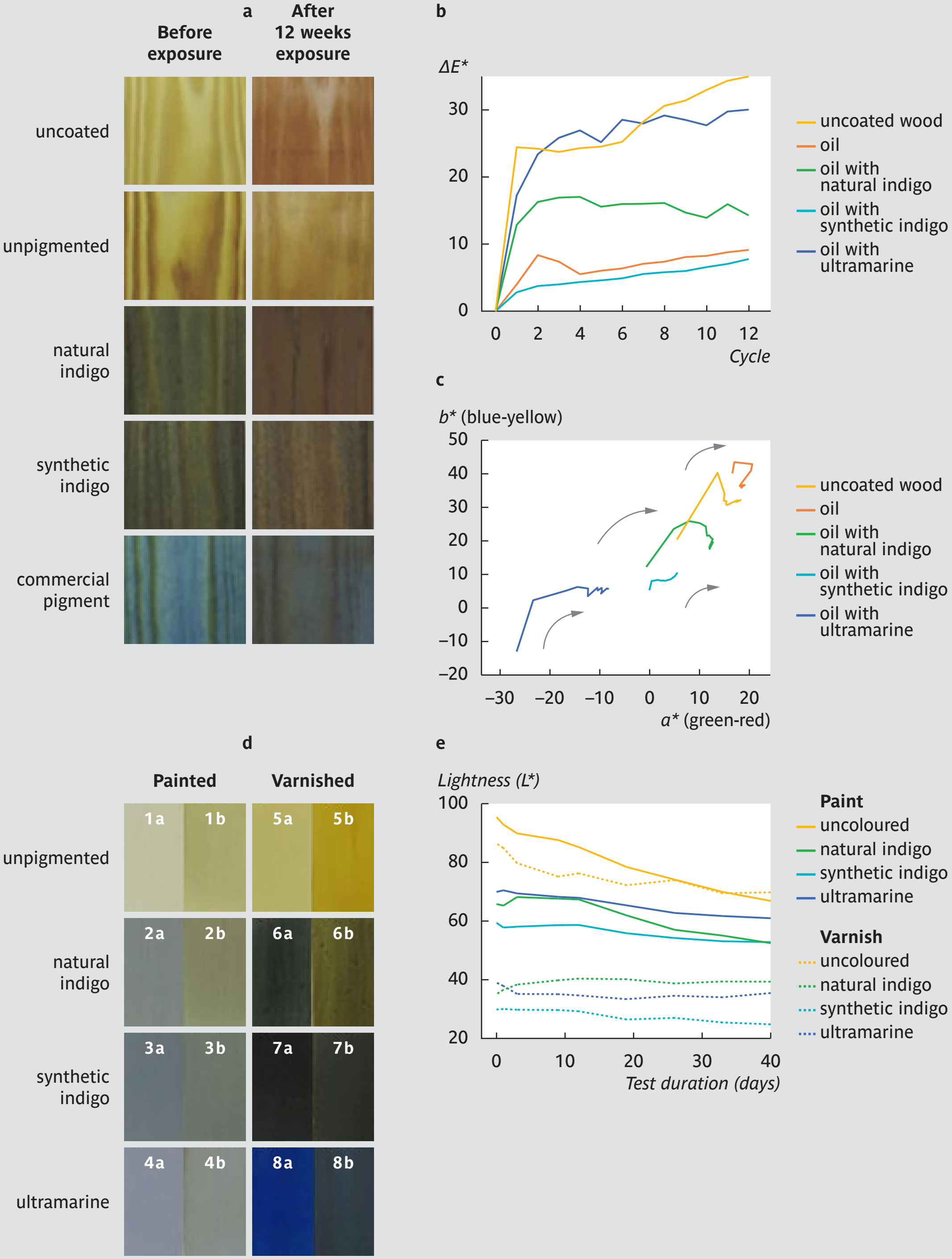
Here ΔL^*, Δa^* and Δb^* indicate the changes of L^*, a^* and b^* during the experiment.

Results and discussion

The appearance of the linseed oil-coated samples before and after exposure to weathering is shown in Figure 1a. For all the samples the major changes in the total colour occurred during the first 2–3 weeks, after which the indigo-pigmented samples a stable colour whereas the unpigmented coatings kept changing in a moderate manner (Figure 1b). The samples pigmented with synthetic indigo went through the least change in the total colour and the samples containing natural indigo fell in between the two extremes. Change of the colour hue during the exposure (Figure 1c) was measured and showed an initial change from blue towards yellow, followed by more pronounced reddening. After a few cycles, many of the samples turned slightly towards blue maintaining the red coordinate. The smallest

1 **a** Wood samples coated with linseed oil before and after 12 weeks of exposure to accelerated weathering
b and their colour change upon exposure.
c Colour parameter b* as a function of a*.
d Painted (1–4) and varnished (5–8) samples before and after the accelerated weathering.
e Lightness upon exposure.

A, b and c Reproduced from Helander (2022). D and e Reproduced from Jordan et al. (2022) with the permission of John Wiley & Sons Ltd.


a
Before exposure
After 12 weeks exposure
uncoated
unpigmented
natural indigo
synthetic indigo
commercial pigment
b
ΔE*
30
20
10
0
0 2 4 6 8 10 12
Cycle
uncoated wood
oil
oil with natural indigo
oil with synthetic indigo
oil with ultramarine
c
b* (blue-yellow)
50
40
30
20
10
0
−10
−20
−30 −20 −10 0 10 20
a* (green-red)
uncoated wood
oil
oil with natural indigo
oil with synthetic indigo
oil with ultramarine
d
Painted
Varnished
unpigmented
natural indigo
synthetic indigo
ultramarine
1a 1b 5a 5b
2a 2b 6a 6b
3a 3b 7a 7b
4a 4b 8a 8b
e
Lightness (L*)
100
80
60
40
20
0 10 20 30 40
Test duration (days)
Paint
uncoloured
natural indigo
synthetic indigo
ultramarine
Varnish
uncoloured
natural indigo
synthetic indigo
ultramarine

changes in the colour occurred to the samples coated with oil containing synthetic indigo. The sample coated with unpigmented oil did not change much during the experiment. According to Teacă et al. (2013), yellowing of the wood surface reflects changes in lignin and hemicellulose molecules. Since the linseed oil coatings are translucent, the obtained colour changes were mostly due to the changing colour of wood rather than the colour changes of the pigment.

The appearance of the painted and varnished samples also changed during the weathering (Figure 1d). The painted samples darkened during the exposure, whereas the varnished samples stayed at constant level of lightness, except for the varnish sample with no colourant, which yellowed visibly. The unpigmented white paint darkened more than the pigmented paint samples. The colour of the samples changed typically towards more yellow and red hues, which could be associated to loss of blue colour of the pigment as well as to yellowing of the coating. The coatings containing synthetic indigo were the most stable ones also showing less aging of the coating matrix.

Case #2: Textile dyeing with natural colourants and biomordants

In addition to dyes, industrial dyeing processes use a variety of substances designed to attach and stabilize the dyes on the desired surface, which increases the environmental load of dyeing. Many of these chemicals, especially metals, often end up in the wastewater streams and accumulate in the environment. Especially in context of natural dyeing, it is imperative to seek alternatives to these auxiliary chemicals to achieve an environmentally friendly dyeing process.

Mordants, which are chemicals designed to attach dye molecules onto fibers, are an important group of auxiliary chemicals used in dyeing. Due to prevalence of direct dyes, mordants are less commonly used than before, but they are still needed, for instance when using biobased dyes. In traditional dyeing using natural colourants, the most common mordants are metallic salts, some of which are harmful if continuously released to the environment. Consequently, biomordants, such as organic acids, have been sought to replace metal mordants. In 2019, Pinheiro et al. successfully biomordanted natural dyes of *Hibiscus sabdariffa*, *Allium cepa* and *Curcuma longa* onto banana fibres with *Acacia mearnsii* sawdust extract. Furthermore, in 2006, Vankar et al. successfully used *Eurya acuminata* extract to biomordant alizarin from *Rubia cordifolia* onto cotton fabric. Even enhanced fastness properties using biomordants over metal mordants have been reported: In 2014, İşmal et al. found that using pomegranate and valonia extracts improved light fastness of almond shell dye compared to alum and chromium mordants.

Colouring cellulosic fibres, such as cotton, with most natural dyes is difficult due to the negative charge of cellulosic fibres, repelling the negatively charged dyes. Thus, using positively charged mordants or complexing the dyes is necessary to attach the colourants onto the cellulosic fibres. One potential positively charged biomordant is chitosan, which originates from crustacean shells. In 2023, Rahman et al. studied biomordanting curcumin dye onto cotton fibres and achieved competitive colour and fastness properties with chitosan mordant compared to metal mordants. Moreover, in 2019, Manisha et al. reported antibacterial behaviour when chitosan natural dyes from madder and turmeric were combined with chitosan mordant. As an alternative to using positively charged mordants, dyes for cellulosic fibre colouration can be complexed with some organic acids. This complexation is done to modify the charge of dye to make it more attractive to the cellulosic surface. One example of such complexing mordant is tannic acid, which has been successfully used by K. Sangamithirai in his 2019 study of biomordanting marigold dye on cotton. Also, Ghaheh et al. (2021) reported good fastness properties when biomordanting natural dye extract from *Hibiscus sabdariffa* L. on cotton fabric with tannic acid.

The following section features two previously published studies about biomordanting. The first study presents biomordanting willow bark dye onto microcrystalline cellulose fibres with tannic acid, oxalic acid, and citric acid. (Lohtander, 2020) The second study explores biomordanting red onion dye onto cotton fibres with chitosan. (Grande et al., 2023) The aim of this case is to highlight the potential of biomordants in natural dyeing and compare the dye uptake of biomordants to some common metal mordants.

Methods

The first dye to be studied was extracted from the bark of four-year-old willow hybrid (*Karin*) using hot water extraction. The extract was filtered and freeze-dried into powder form for storage. The substrate materials for dyeing were a never-dried microcrystalline cellulose (MCC) (Vanhatalo & Dahl, 2014) and regenerated lyocell-type IonCell-F cellulose fibers (IC) (Sixta et al., 2015). The details of the sample preparation can be found in the original study by Lohtander et al. (2020).

The dyeing was done at 80°C for a period of 60 minutes. The fibre-to-liquid ratio was kept at 1:50 and the amounts of the dye and mordant were 20 % and 10 % of the weight of the dyed material. The studied biomordants were citric acid (CI), oxalic acid (OX) and tannic acid (TA). As a control experiment, metallic mordant alum (AL) was used. Experiments without mordant were also carried out for reference.

The method for analyzing the willow dye and its uptake on the cellulose materials were liquid chromatography-mass spectrometry (LC-MS) that could be used both to separate different compounds of the dye and to identify the compounds based on their molar masses. For measuring the colouration properties of the dyed materials, UV-vis spectrophotometry was used. Fourier-Transform Infrared Spectroscopy (FTIR) was used to study the chemical changes on the surface of the materials due to dyeing.

The second study described here utilized the red onion dye (ROD), obtained by hot water extraction of red onion skins (*Allium cepa*). The extraction at 80°C was carried out for 60 minutes, after which the extract was filtered and freeze-dried. The fabric dyed with ROD was a single-knit cotton fabric. Before dyeing with ROD, the cotton samples were pre-treated with alum, iron sulfate or chitosan as described in Grande et al. (2023). The dyeing with ROD extract (0.1 g/L) was carried out in a fabric-to-liquid mass ratio of 1:20 at 50°C for 95 minutes using a small-scale dyeing machine (Linitest).

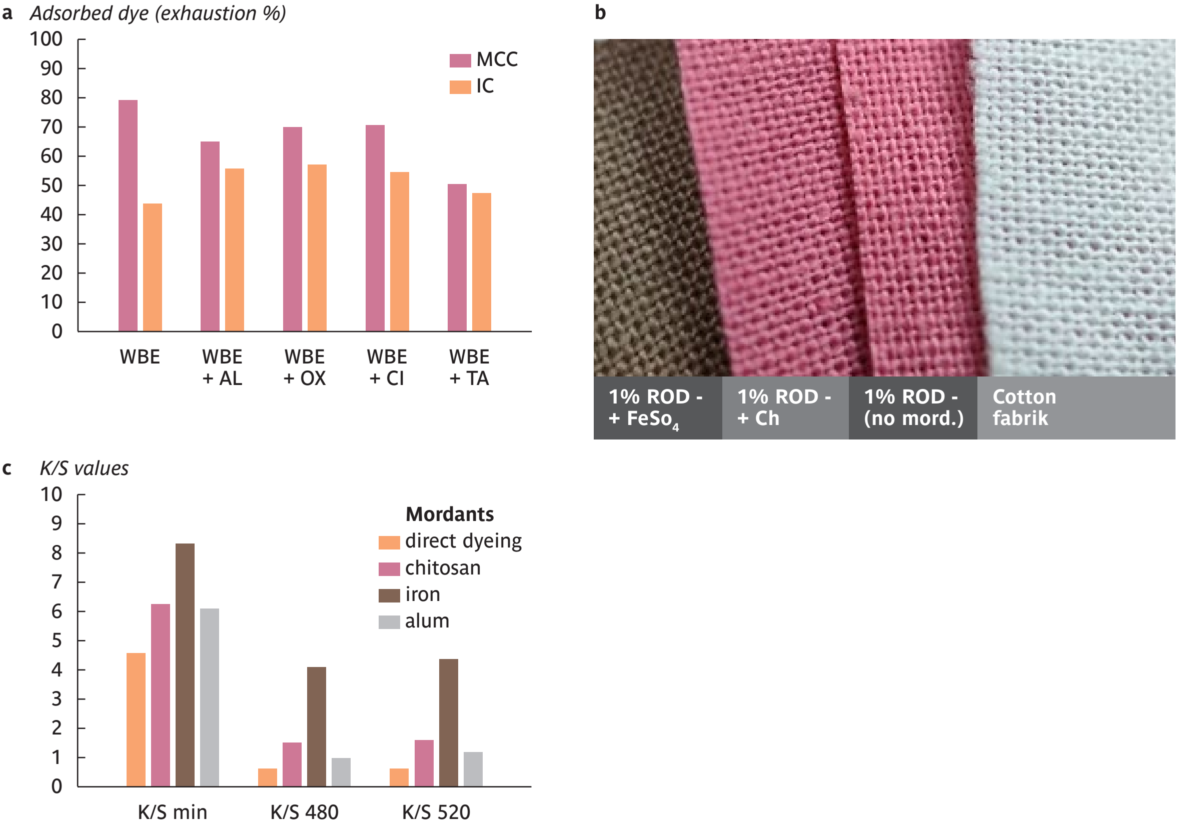
Quartz crystal microbalance with dissipation monitoring (QCM-D) was utilized to investigate the adsorption kinetics, i.e., the attachment of the dye on cellulose and the mordanting mechanism of chitosan as a function of time. A nanocellulose thin film was prepared on the microbalance surface to model the cotton material. In the experiment, the solution containing the mordant or dye was consequently pumped through a chamber accommodating the cellulose surface. The adsorption to the surface was detected as a change in the mass that can be very sensitively measured.

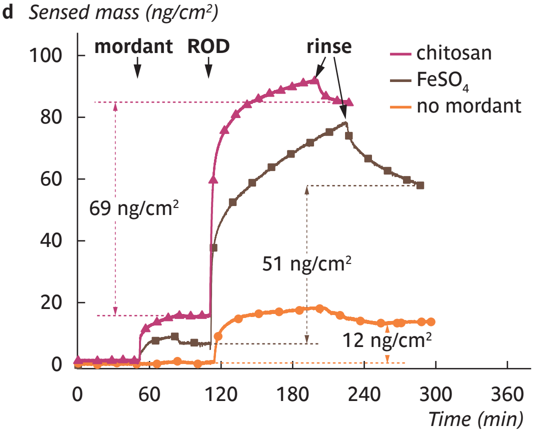
Results and discussion

The efficiency of dyeing microcrystalline cellulose and IonCell-F using willow bark extract was assessed by both measuring the colour properties of the material after dyeing and by inspecting the change in the dye liquor composition before and after dyeing using the LC-MS method. The highest colour depth (K/S) for dyed microcrystalline cellulose was obtained using alum mordant, whereas highest colour strength for IonCell-F was obtained using oxalic acid mordant. The dye uptake on the materials was estimated by quantifying the chemical compounds of the willow bark dye identified with LC-MS analysis, as shown in Figure 2a. In all the cases, the dye uptake was higher for the microcrystalline cellulose than IonCell-F, which was most probably related to different surface area and morphology of the materials. The FTIR measurements showed changes in the chemical structure of the cellulose surface indicating to bonding of the dye to the surface upon dyeing, only for microcrystalline cellulose.

Colour depth K/S was measured for fabrics dyed with ROD using mordants chitosan, iron sulfate and alum at pH 4, which was the optimum condition for the adsorption of the molecules (Figure 2b and c). Chitosan mordanting increased the dye adsorption compared to direct dyeing and worked as well as alum, which is a metallic mordant often utilized in natural dyeing. The colour formed with iron sulfate mordanting was brownish (Figure 2b) and with alum mordanting green (not show). This was due to the strong complexation of the ROD compounds with the metals. In contrast, chitosan retained the purple colour of the ROD due to a different binding mechanism.

Adsorption of the mordants and ROD on the nanocellulose film was detected with the QCM-D method. The curves in Figure 2d show clearly how mordants are adsorbed at the sensor surface, after which the ROD dye could adsorb as a second layer. It is clearly shown that chitosan works efficiently as a mordant under these conditions, where the charge of the cellulose surface is slightly negative, and charge of chitosan is positive (Grande et al., 2023).





2 **a** Dye uptake for each dyed material estimated by comparing sample liquids with the original willow bark extract (WBE). The mordants were oxalic acid (OX), citric acid (CI), tannic acid (TA) and alum (AL).
b Cotton fabrics dyed with ROD using iron sulfate, chitosan or no mordant.
c Colour depth K/S at minimum reflectance values, reflectance at 480 nm and 520 nm of the ROD-dyed cotton fabrics.
d QCM-D measurement of the adsorption of mordants and ROD on cellulose model surface.

A reproduced from Lohtander.
B–d reproduced from Grande et al. (2023).

Case #3:
Biocolourants in functional materials

Biocolourants can bring more than just colour to materials. This section considers the spectral, bioactive, and structural properties of materials and compounds that are regarded as biocolourants. The chosen topic encloses interesting features of plant- and algae-based components as building blocks of functional materials with camouflaging or antioxidative properties.

Biocolourants' spectral properties are special because they typically consist of more than one component and thus the natural spectra have features that deviate from those of single-component synthetic dyes and pigments (Lohtander-Piispa, 2022). In the context of industrial manufacturing, unrepeatable colour of the colourant can be seen as a problem and a severe quality issue (Affat, 2021; Kusumastuti et al., 2022). However, in camouflaging applications varying spectral properties and unpredictable variation can become assets, when the dyed object is meant to appear like a part of natural environment (Forsman et al., 2022; Karpagam et al., 2017). We highlight here some results of the studies where the properties of light-weight camouflage materials were dyed using brown lignin and green algae (Forsman et al. 2022 and Lohtander et al. 2022). The studies focused on hyperspectral and infrared properties of the materials.

Coloured natural plant extracts include a vast range of different bioactive compounds, such as tannins, phenols, and flavonoids, which are often enriched at various parts of the plants, such as the roots, leaves, or flowers (Altemimi et al., 2017). A reliable source of polyphenolic compounds are the wood barks that contain a lot of tannins, protecting the tree from physical and chemical threats such as UV-irradiation and oxidative stress (Raitanen et al., 2020). Similar chemistry acts also in the human skin as a defense against pathogens and sunlight-induced damage (Lu et al., 1996).

Polyphenols and phenols can be used in materials science as structural components due to their ability to form cross-linked polymers (Gao et al., 2021; Li et al., 2022). A potential application area for bioactive and structural biopolymers and natural bioactive phenolic components could be in packaging of food and other sensitive products where dense but thin barrier films are needed to facilitate product preservation by blocking the diffusion of oxygen and moisture

(Biao et al., 2019; Feng et al., 2018; Zhang et al., 2021). Here, we present some findings of the study of utilizing compounds of willow bark as a functional barrier material published earlier by Lohtander et al. (2021). The resulting materials can block UV radiation, are antioxidant and can function as a barrier film. Being able to use wood-based components in the barrier films in packaging applications would also increase the recyclability of the products, as they would only consist of lignocellulosics instead of thermoplastics.

Methods

The camouflage foams were prepared from birch pulp as described in the published papers (Forsman et al., 2022; Lohtander et al., 2022) and dyed using purified UPM BioPiva 100 kraft lignin powder and dried *Chlorella vulgaris* microalgae powder. The dyes were mixed to the foam constituents, resulting in foams that were coloured throughout. The foam stability and appearance were studied by placing the foam into volumetric glass as shown in Figure 3a. The compositions of the foams were optimised with respect to stability and volume of the foam. The optical camouflage properties were characterised by photographing the foams with Specim IQ hyperspectral camera that could capture a spectrum on wavelength range 400–1000 nm at each pixel of the photograph. Some natural materials were photographed as reference materials for assessment of the camouflage ability.

The full description of the willow bark extract experiments can be found in the published paper (Lohtander et al., 2021), and only certain parts are described here. The polyphenols of the willow bark were extracted by hot water extraction of bark of *Karin* willow as described in an earlier study (Dou et al., 2018). The extract was filtered and lyophilised into powder form that could be dissolved into water for further experiments. The main components of the willow bark water extract are phenolic compounds called catechin, picein, and triandrin. The willow bark extract was studied as a component of nanocomposite films prepared together with gel-like TEMPO-oxidized nanocellulose. The cross-linking of the willow bark extract could be carried out by creating linkage between the phenolic groups either by irradiation with UVC radiation (254 nm) or by a reaction catalysed by a laccase enzyme in the solution. Nanocomposite films were prepared by casting the cross-linked gel on a Petri dish and letting water evaporate.

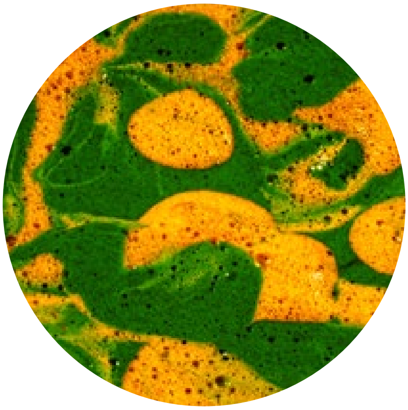
The cast films of the nanocomposite were characterized by measuring the transmittance of visible light and UV radiation through the sample. The radical scavenging ability of the films were measured using ABTS assay method (Re et al., 1999) that characterises the relative ability of an antioxidant to scavenge the ABTS radical formed in the solution. In the experiment, the nanocomposite film was immersed in the testing solution. Tannic acid, which is a well-known antioxidant, was used as a reference. Oxygen transmission rates (OTR) of the cast films were measured according to ASTM standard F1927 using gas permeation tester. The chemical structures of the nanocomposite films were measured using attenuated total reflection Fourier-transform infrared (ATR-FTIR) spectroscopy.

Results and discussion

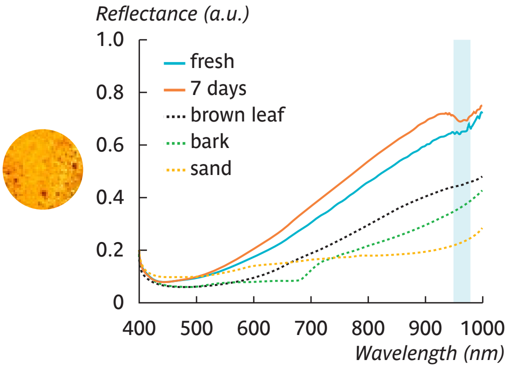
The optimal recipes for stable pulp-based foams resulted in intensely coloured wet material that could be spread on surfaces. The brown colour of the fresh lignin and green colour of the fresh Chlorella microalgae foams are shown in Figure 3a and b. The brown lignin foam was anticipated to provide camouflage in an environment that contains brown natural materials such as the bark of pine and spruce, sand, and brown leaves whereas the green microalgae foam was imitating living plant material. The hyperspectra of the lignin-containing foam had a similar shape as the spectrum of brown leaves (Figure 3c). The microalgae foam however, could not exactly repeat the spectrum of the green leaves that it was compared to. The very steep increase in the spectrum at around 700 nm of living green plants is caused by the intense green colour of chlorophyll, which unstable and difficult to imitate using synthetic colourants (Figure 3d). After cutting, the chlorophyll in plant biomass turns brownish upon drying of the plant, which makes the reflectance spectrum less steep around 700 nm (Clark, 1999). The spectrum of the microalgae in the foam was still quite promising, as there was no substantial shift in the spectrum, i.e., change in the colour, after aging of the foam. The results showed that lignin and *Chlorella* as natural colourants could be used to create camouflage in a boreal forest environment where there are naturally green and brown elements. The raw materials of these stealth materials are scalable, safe, and renewable, and can thus be utilized on a large scale.


a

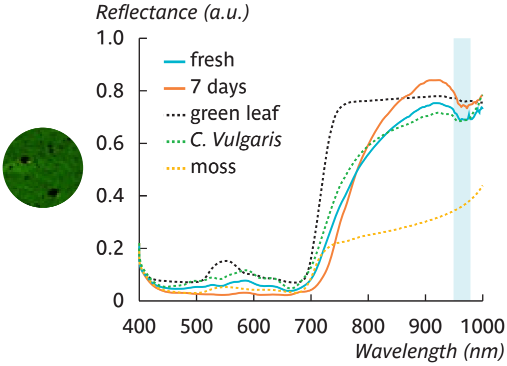
b

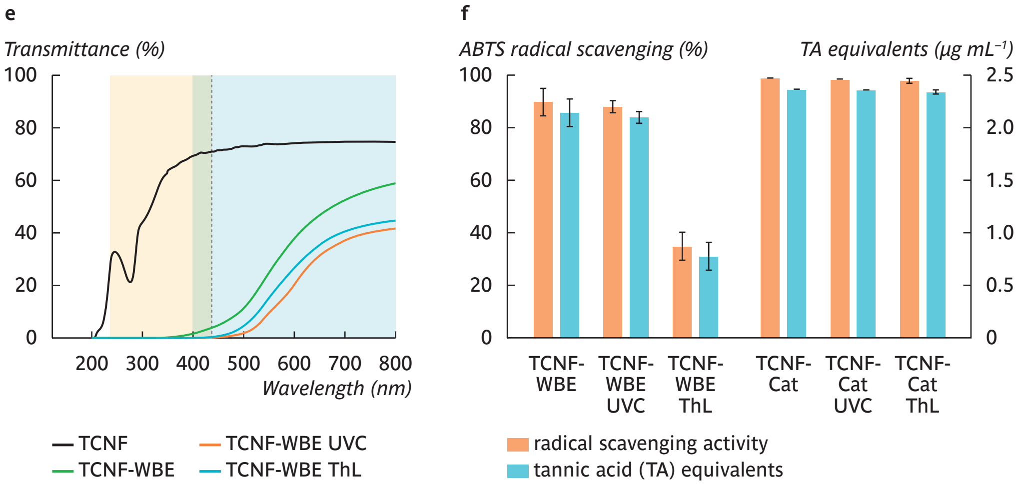


c


Reflectance (a.u.)
1.0
0.8
0.6
0.4
0.2
0
fresh
7 days
brown leaf
bark
sand
400
500
600
700
800
900
1000
Wavelength (nm)

d


Reflectance (a.u.)
1.0
0.8
0.6
0.4
0.2
0
fresh
7 days
green leaf
C. Vulgaris
moss
400
500
600
700
800
900
1000
Wavelength (nm)



The nanocomposite films consisting of willow bark extract and nanocellulose very effectively blocked UV irradiation even without polymerisation of the willow bark extract as the transmission below 400 nm was minimal for all the films containing the willow compounds (Figure 3e). The light blocking effect was enhanced when the films were cross-linked either by UVC or by laccase enzyme, which was also seen visually, as the colour of the material turned darker brown. Similarly, dyeing a cellulose nanofibril film with extract from red onion skin (ROD) also efficiently blocked UV light, showing that UV protection can be gained with a variety of natural dyes with varying colours (Grande et al., 2023). The radical scavenging ability of the uncross-linked nanocomposite films and the nanocomposite cross-linked with UVC radiation were near 90 % whereas material cross-linked with the laccase, had only 40 % radical scavenging ability (Figure 3f). This implies that the laccase is a highly effective cross-linker for the phenolic units and the ability to scavenge radicals has lowered because the number of available, unreacted phenolic groups was simply lower. (Lohtander, 2021)

3 **a** Cellulose foam dyed with microalgae, lignin foam and an undyed cellulose foam.
b Lignin and microalgae dyed foams.
c Hyperspectra of pulp foams stabilized with lignin and
d microalgae as fresh and after 7 days including natural reference materials (dotted lines).
e UV-shielding properties of TEMPO-oxidized cellulose nanofibril nanocomposite containing WBE.
f The radical scavenging activity and tannic acid (TA) equivalents of the nanocomposite films.

A Photograph by Valeria Azovskaya. B, c and d reproduced from Forsman et al. (2022) with permission from the Royal Society of Chemistry. E and f reproduced from Lohtander et al. (2021) with permission from the Frontiers.

Oxygen transmission rate is the volume of oxygen passed through the studied film area in one day ($cm^2/m^2/24h$). Values between 0.9-3.4 $cm^2/m^2/24h$ were measured for the nanocomposite films consisting of nanocellulose and willow bark extracts (Lohtander 2021). The barrier properties were excellent, considering that the film thickness was less than 100 micrometers. For reference, a film can be considered as a high oxygen barrier if the oxygen transmission rate is less than 15.5 $cc/m^2/24h$. Uncoated polymer films have typically OTR in the range of hundreds of $cc/m^2/24h$ (Priolo et al. 2015) and often a thin metallic layer is needed to provide good barrier properties for polymers, even though plastics are common materials for packaging.

According to the FTIR measurements, cross-linking the phenolic compounds of willow bark in the presence of TEMPO-oxidized nanocellulose did not lead to chemical bonding between the nanocellulose and phenolics. The phenolic compounds polymerized into larger entities maintaining their functionality without disturbing the structural properties of the nanocellulose (Lohtander, 2021).

Discussion and conclusions

As discussed in case #1, the accelerated laboratory weathering test provides valuable data because it allows the experiments to be controlled and repeated if necessary. In natural weathering tests, the studied samples are exposed to complex, natural climatic conditions for a long time, which, on one hand, give a more reliable result than the laboratory tests, but on the other hand, last longer, and variation may be large and non-repeatable.

The results of accelerated weathering of coatings pigmented with natural indigo showed that its stability in the given conditions was moderate and all the weathered samples differed from samples coated with non-pigmented coatings. Even though the stability of natural indigo coatings were not as high as the synthetic indigo coatings, they still provided better protection against weathering of wood than the coatings pigmented with commercial ultramarine pigment or non-pigmented coatings. We also learned that other pigments and fillers in the coating matrix may affect the stability of the indigo colourant and the matrix itself and it turned out that aging of the natural indigo in the paint formulations containing titanium dioxide was accelerated. (Jordan, 2021)

In Case #2, the free surface area of cellulose affected the uptake of willow bark dye. Use of the biomordants tannic acid, citric acid, and oxalic acid, appeared to create chemical attachment of the mordant compound on the surface of the microcrystalline cellulose but not on the surface of IonCell. The efficiency of the mordants in terms of dye uptake varied only slightly, and the biomordants showed comparable results with the commonly applied alum. According to the dyeing results, oxalic and citric acid are quite suitable alternatives to alum when mordanting willow bark dye onto cellulosic fibres. This work highlighted that colourants extracted from natural sources are often mixtures of multiple compounds that may have differing spectral properties. Some polyphenolic compounds may only absorb UV light and are thus invisible. While adsorbing on to the fibres they are blocking the adsorption sites of the compounds having visible colouration. (Lohtander, 2020) The findings of this study, however, encourage finding alternatives to synthetic dyes and their mordants from nature, since the acids applied as biomordants are also found as natural compounds from many sources.

The surface sensitive QCM-D method appeared as a good method for modelling the dyeing mechanism of cellulosic materials and a logical result for red onion dye adsorption was observed at different conditions. Understanding the limitation for adsorption due to electrostatic repulsion is important when designing dyeing methodology, especially when new mordants and dyes are proposed. Chitosan mordanting led to a comparable dyeing result with iron sulfate and alum mordanting, however the final colour depended on the mordant and with chitosan, the colour resembled most the pink colour obtained without any mordant. Due to the formation of coordination complexes using metal salts, the iron sulfate and alum mordants led to brownish or green final colour. (Grande et al., 2023)

The biomordanting experiments showed a great potential for lessening the amount of metallic mordants for dyeing cellulosic materials with biocolourants. Also, it is utterly important to understand the physico-chemical behavior and limitations of the biocolourants in the dyeing processes.

In Case #3, wet foams containing natural colourants turned out to be potential camouflage materials for boreal forest environment lasting for at least a few days. After a couple of days, the foams had dried, but their colour remained. Lignin and microalgae *Chlorella* *vulgaris* enhanced the natural appearance of the foam formed of white pulp and surfactants. Lignin also had a structural, stabilizing role in the foam (Lohtander et al., 2022) and due to its low price, it showed a great promise as a functional material in the context of stealth against multispectral imaging by supporting the thermally insulating foam structure and providing natural appearance in the hyperspectral region. The foams are rather easy to form in a scale that is able to cover a vehicle, tent or other equipment. The proof-of-concept study showed that this type of technology basing on bio-based materials and a rather simple approach has potential, but does not provide a long-lasting and weatherproof solution. The foams were however fast to form and contained no harmful components, which supports the possibility for large scale use of these materials in the context of natural surroundings, for instance, military and hunting when a temporary thermal and spectral stealth is required.

Willow bark and onion skin extracts could be used in barrier films from cellulose nanofibrils. Both extracts efficiently blocked UV radiation at low concentrations, and could thus work a UV-protective materials. Cross-linking the willow bark extract in the presence of the nanocellulose appeared to be a successful strategy for creating a nanomaterial with great barrier properties combined with controllable antioxidative and UV blocking abilities. In this form, the willow-based phenolics remained active, but were kept immobilized in the film with no signs of leaching. These non-plastic functional materials can have many uses, for instance in packaging technology of sensitive products. Remarkably high ability to block oxygen transmission through the films was obtained, which indicates that the structure of the cross-linked nanocomposites was very tight and only a thin layer of this material could provide excellent barrier film for packaging applications.

The three cases presented in this chapter provide an insight to the authors' research related to biocolourants. The aim of the presented work has been to understand better the various aspects of biocolourants, including the area of developing greener chemicals for textile dyeing, but also to find new possibilities of utilizing biocolourants' special properties in bringing about functionality to materials. The findings summaries here, encourage us and hopefully also inspires others to continue systematic, yet inventive exploration of the world of biocolourants.

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Onions (Allium cepa)

Onion skins contain phenolic compounds that act as dyes, producing rich yellows, browns and greens.

Worldwide, humans on average consume around seven kilos of onions per year. This means that they are readily available and using the material sidestream of onion skins would be resource-wise whilst enabling us to produce a considerable range of biocolours at scale.

Photo TR-T (left),
Julia Lohmann (right)

VÄRJÄTTY KELTASIPULILLA

Allium cepa

Tämä t-paita on värjätty keltasipulilla Helsingin yliopiston johtamassa BioColour-tutkimushankkeessa.

Hanke tutkii biopohjaisten väriaineiden ominaisuuksia ja sovelluksia sekä pyrkii edistämään niiden laajamittaisempaa käyttöä.

Kirsi Niinimäki, Noora Tommila, Riikka Räisänen

Colour collaboration

ABSTRACT

This chapter studies collaboration as a value-adding element in the textile sector's sustainable development. It focuses on the first industrial encounters with natural dyes and presents five company cases. These companies are forerunners in their industry in Finland, bravely experimenting with the production and use of natural dyes. All the collaborations have some connection to the BioColour research project.

The study was grounded on the theoretical basis of collaboration and innovation. Collaboration and an innovative attitude have driven deep the lessons learnt in industry. The common aim was to bring sustainable value to industrial production through alternative colours and dyestuffs and by using biobased colour sources.

This text takes a future-oriented view of the use of biobased and natural colourants in industrial-level production and presents the main learnings from these first encounters. The discussion further highlights some of the drivers of and the obstacles to using biobased colourants in design and production in the textile industry.

Keywords
collaboration, value adding element, innovation, industrial-level production

T-shirts by Nanso are dyed with natural colours.
Photo Nanso

"The only way we will be able to address the important challenges we face today is to do so collectively. Collective creativity can lead to relevant and sustainable innovation."

(Sanders, 2015, p.298).

"Without the drive of entrepreneurs there is no innovation, and without innovation there is no new business."

(Trott, 1998, p.32).

Introduction

Although sustainability is currently the main driver in industrial development work, especially in the textile and fashion industry (e.g. Niinimäki et al., 2020), companies are looking for new opportunities for collaboration to bring new views and especially new knowledge into their industrial practices. Sustainability is a complex issue and the huge amount of academic research in the area is constantly producing new knowledge. To ease this situation of knowledge overflow (searching for the most relevant information for a company), industry can collaborate with academic partners. Academic research benefits from collaboration with industry, as it can test inventions on an industrial scale and in a commercial reality. Inventions can be pushed towards innovation to determine whether they can be commercially successful. As Gorb (1990) points out, innovation is very often a necessary prerequisite for business and also part of business renewal. Innovation processes and business/industry renewal processes need new knowledge, new ideas and new products in the context of sustainability. Accordingly, collaboration between industry and academia benefits both partners.

This chapter focuses on collaboration as a value-adding element in sustainable development. The study defines value-adding elements through collaboration as new shared knowledge, finding sustainable alternatives and developing new sustainable products. By following and studying the real-life cases of five companies that have had their first encounters with biobased and natural colours, we have gained an understanding of the benefits of collaboration. We have also identified the drivers of and obstacles to using biobased colours in the industrial context.

An onion-dyed dress by
Sofia Ilmonen.
Photo Diana Luganski

Looking to the future through innovation

The environmental impacts of the textile and fashion field are well studied, and each company must take these impacts into account in their future practices. Sustainable alternatives can really offer a company a leading role. Currently, sustainability knowledge gives a strong push towards business transformation in the textile and fashion field, and companies have to take steps towards the future and try out, plan and experience alternatives to their current ways of doing business, designing and manufacturing products (Niinimäki, 2022). The more forward-looking companies collaborate actively with their stakeholders and even with academic research to create new understanding and future perspectives for their business. Sustainability development work can be seen as a stepping stone and learning path towards the future and should be part of the strategy work of companies (e.g. Niinimäki, 2020).

How then, do companies approach the challenges of the future? Business development work simultaneously takes place on three temporal levels:

> *In the traditional level of the past, the transitional phase of the present, and the transformational zone in the future. The traditional way of doing business asks, "What is the business?" The transitional looks forward from the present, asking, "What will the business be like?" Companies with a transformational approach peer yet further into the future and are faced with the most challenging question, "What should the business be like?"* (Niinimäki, 2022; Kathryn, 2006, p. 31)

Kathryn (2006, pp. 30–31) highlights that the more transformational the business strategy is the more visionary thinking it requires.

As Mintzberg et al. (2009) explain, strategy formulation can be understood as a visionary process per se, in which the strategy is constantly evolving and being reconstructed. This could be interpreted as companies collaborating with academic researchers to obtain the newest knowledge as well as to integrate the future vision into the company's strategy and practices, that is, knowledge about the sustainable future. As Mintzberg et al. (2009) point out, companies' visionary strategy work has two temporal stages: seeing ahead and seeing beyond. Seeing ahead is looking at past events and building a vision as a continuous path from these. Seeing beyond in turn involves looking even further into the future and constructing the future.

> *It invents a world that would not otherwise be* (ibid, p. 133). *In here the business strategy is aimed to actively seek new opportunities, i.e. opening the futures views to the company or even creating dramatic leaps forward in uncertainty. In here the main focus is on searching for new opportunities* (Niinimäki et al., 2015).

Product design work aims to improve existing products, and the target audience and markets are well known (Keinonen & Takala, 2006). Concept design for innovation, on the other hand, looks further into the future than product design and can include different temporal goals. Concept design can even start as a research project, offering new angles, new information and new visions, which could lead to totally new opportunities. Concept design often follows the more traditional product design process but aims to help transform an invention into an innovation and then into a business reality (Keinonen & Takala, 2006). Collaboration with academic researchers can really help companies create a more sustainable vision of their future or at least obtain some new insights for their sustainability work. This future vision is needed while sustainable alternatives are being sought.

Innovation work and value capturing

Value can be captured in business and industry by developing new products in well-known markets, by finding new markets for exiting products, or by concepting and testing future possibilities. In innovation work, 'stepping into the future' and looking for new opportunities in more creative and experimental ways might help the company understand what kinds of new products they can offer to markets. The innovation process benefits from two different kinds of processes: "capturing value through creative concepting using qualitative methods (designing) and creating value through product refinements through quantitative methods (engineering)" (Niinimäki et al., 2015, p. 2; Cagan & Vogel, 2002). Here, both the creative product design process and the technological process are needed for all testing. Technical testing means making dyeing or printing processes suitable for a certain type of machine, colourants and fibres including all colour fastness tests. Of course, the dye cultivation, harvesting and processing stages also need many new innovations and technological development.

In the case of biocolours, innovation can be described as adapting the interactive model, which according to Trott (1998), includes the technology-push and market-pull approaches: "It emphasises that innovations occur as the result of the interaction of the marketplace, the science base and the organisation's capabilities" (p. 24). Here, the whole innovation process can be understood as a "complex set of communication paths over which knowledge is transferred. These paths include internal and external linkages" (ibid.). The innovation may be the improvement of a material (and in the case of biocolour, a colourant) or it can lead to a more profound R&D process for a material (or e.g. a technology for using natural dyes). In the interactive innovation model, R&D, engineering, design, manufacturing, marketing, and sales are all active (ibid.). All the actors involved are important for value capture.

Methods for studying experiences with biobased and natural colours

The study was based on two different types of data. First, the authors were involved in the project activities (e.g. in company workshops) throughout the BioColour project (which began in autumn 2019), and especially closely followed the companies' industrial activities in this project. In some cases writers acted as researchers developing the dyeing recipes together with the industry partners. In this, participant observation method was used to collect the data as fieldnotes and memos. Participant observation (PO) is a tool for collecting data on people, processes and cultures and it follows the logic of qualitative research (Kawulich, 2005). The approach of using "participant observation as a method is to develop a holistic understanding of the phenomena under study that is as objective and accurate as possible given the limitations of the method" (DeWalt & DeWalt, 2011).

The second part of the data was company interviews, conducted in spring 2023. These interviews were free-format discussions, based on semi-structured questions linked to the company's motivation and experiences of using biobased colourants in their testing, prototyping or production. Data analysis was descriptive and based on a qualitative content analysis (Flick, 2009). The interviews were transcribed and texts were analysed on the basis of the emerging themes. The following text first presents the findings through the company cases and then through an interpretative discussion, highlights the research findings by reflecting on previously presented theories about collaboration and innovation.

From stepping stones and deep learning to commercial possibilities: Natural Indigo Finland

Natural Indigo Finland produces natural dyes on an industrial scale. The company was founded by Pasi Ainasoja in 2019.

Ainasoja has a family farm in Nivala, Finland. He was looking for new ways in which to develop his farm. He was interested in finding and cultivating some special plant, and contacted a researcher at Natural Resources Institute Finland (Luke) to find options suitable for test cultivation. The researcher proposed the woad plant (*Isatis tinctoria*) (in 2013). Ainasoja realised that green development and ideas linked to sustainability were strongly emerging phenomena that were worth following. He believed these aspects presented a commercial opportunity. He was encouraged to try and in 2016 he tested 20-year-old woad seeds. He decided "that now everything will be done exactly correctly. Everything went wrong. And then I understood that this is such a big challenge that I can't do it by myself. And then I started to construct a network and started to collaborate and learn step by step" (Ainasoja, 21.2.2023). He further pointed out that learning how to cultivate the woad plant had been a difficult journey, as each year the summer seasons varied and cultivation circumstances and weather conditions were quite different and challenging. He received a great deal of support in cultivating woad from an English pioneer, Ian Howard, and this help and knowledge have been essential for success. Ainasoja has been actively involved in the BioColour project and has established connections with many companies with the help of the BioColour project researchers.

In addition to cultivating woad, Ainasoja has tested and developed ways to use different kinds of side streams as colour sources. He has tested side streams from agriculture and the forest and food industry. Currently, onion skins (yellow and red onions) (*Allium cepa*) and willow bark (*Salix* spp.) dyes are under production. Ainasoja also reveals that they have developed quite a special production line to handle these plants and to produce extracts from them.

The whole development process has required several experiments, investments and financial support from external sources (different kinds of development support). Ainasoja says that "when you have a big picture in mind, and you have a passion to go step by step onwards, it gives you power. One of the most important things a couple of years ago was that Marimekko was the first company who believed in us…It gave us faith that we were on the right track. (Ainasoja, 21.2.2023).

The greatest challenge has been handling the value chain. The process began by Natural Indigo Finland producing the colourants, but the next steps were problematic as Finland only has three or four dye houses, and these have no experience with natural dyes. Thus, Natural Indigo Finland has had to make the basic recipes for these colourants and to show dye houses material examples to raise their interest, and to convince them that this really is *future business.* On the more positive side, Ainasoja describes how "we've had real, continuous collaboration and dialogue with Marimekko. We do development work, aim for better colour durability and different shades and so on."

Ainasoja states that there is an interest and resources to cultivate special plants, which creates great new economic and business opportunities in the countryside.

> *But we need to aim to help them, so that there will be value chains from the raw materials to commercialization…One produces raw materials and another commercializes, but there are many actors in between. We should get research and business onto the same track, then we could create commercial products as results. If there are only researchers, it won't fly. Or if there are only producers in the value chain, they have no data, which they need from the researchers. So we should build stronger networks and have more collaboration.* (Ainasoja, 21.2.2023.)

Sustainability as a company strategy: Marimekko

Marimekko is a well-known Finnish design house and lifestyle brand, characterised by its original prints and colours. It started production in 1951 and still has its printing factory in Helsinki, even though most of its production is now outsourced.

The interest in testing and using natural colours in Marimekko production is connected to the strategic sustainability work in the company.

> *Our ambition is not to leave burden for the future generations. We believe that, in the future, timeless and long-lasting products will be produced in balance with the environment, in line with the principles of circular economy. We are committed to drive innovations in technologies, materials and business models to push the industry forward and reach ambitious vision that futures products do not leave trace.* (Ahonen and Berglund, 16.3.2023.)

Marimekko began testing the natural dyes in 2019 in collaboration with Natural Indigo Finland and Aalto University. Their factory in Helsinki also functions as a creative innovation hub and test lab for sustainable innovation. The fact that they have their own production factory enables them to test new innovations and sustainable materials and to develop industrial practices. Marimekko has been testing and using woad, willow bark and onion skin dyes as a liquid foam in textile printing. Now they are also starting to test dyes extracted from coffee waste. Different natural colourants demand different kind of processes and this requires learning new kinds of industrial practices. Impurities in the colourants create their own challenges. The use of natural colourants on an industrial scale requires an innovative approach to print design, and natural colours often behave differently with textiles than traditional colours (synthetic colours). Colour is more ”vibrant” and products might have small

1 Marimekko has been printing their fabrics with woad dye.
Photo Marimekko

shade differences. Moreover, natural colours tend to change slightly over time and from the effect of washing and light.

The commercial use of natural colourants demands high durability, uniform quality, and continuous availability. Marimekko representatives believe that these colourants have future potential and that they have already shown that these colourants can be brought to industrial-level production and that more sustainable alternatives can be found in textile production.

Local sustainable production and reliable colours: Lapuan Kankurit

Lapuan Kankurit is a family-owned weaving house that started production in 1917 and is well known for linen products. Today it is run by the fourth generation of weavers and its production is located in Lapua, Finland.

“We have been interested in reviving the use of Finnish wool in industrial production for a long time” (Hjelt, 13.3.2023). Sheep are mainly reared in Finland for meat production and their wool has not been widely collected and has been treated as waste. Since Finnish wool yarn is not available, the company has begun to construct their own yarn production line and to collaborate with local sheep farmers. The idea arose of also using natural colourants in this process, as did the idea to test not only yarn dyeing but also dyeing in the wool fibre phase (the phase before wool is spun into yarn). This would offer completely new colour design opportunities. Moreover, using the natural colours of wool (natural white, brown, black) and mixing them together to create a mélange yarn and a mottled colour inspired Lapuan Kankurit. Jaana Hjelt explains that they considered it quite a natural continuation from this development to use natural dyes in these Finnish wool yarns. She further points out that craft artists have been using natural dyes for a long time but that industrial knowledge is mostly lacking, and that here collaboration really helped. They have joined the events arranged by the BioColour project and have also collaborated with Natural Indigo Finland and Lappajärven Värjäämö.

In industrial production, the end results have to be the same each time, so the aesthetics are very different to those in craft products, which are mostly unique and based on small-scale production.

“We might go to some international fair in the autumn to present our new collection and then the production happens in spring or in a year’s time, so that means that we have to deliver the same colours every time”. (Hjelt, 13.3.2023). Industrial production requires continuation and secure results in large-scale processes, and this in turn requires good recipes and reliable colours.

Colour testing and developing is very slow compared to the use of synthetic dyes in which all aspects have been standardized and optimized when the colour enters the market. Testing natural colourants requires development steps and an iterative process in which learning needs to constantly take place with the collaborative partners (academia, the dye house and the colour producer). Lapuan Kankurit has been dyeing wool and linen with woad: the wool results have been good and products will be on sale in autumn 2023. The linen end result has not been sufficiently even. They have also tested willow bark dye, but getting the same shade with that dye has been problematic. With willow, the colour shade can differ depending on the willow type and where it has grown. All these are still pilot products that will be tested in the market. Hjelt highlights that products going to, for example, Japanese markets must be perfect:

> *They are very picky about what they have ordered and whether it is exactly the same colour. Customers do understand that as it has been dyed with natural colourants there can be some shade differences, if they’ve been informed. But it has to be on the same scale [not too different from the original colour sample]. For example, if the customer buys beige it has to be beige, not grey. In this way, the recipes and colours need to be of a good level when they are brought to the collection* (Hjelt, 13.3.2023).

Sustainability is an important value for the company and they are interested in advancing this development. “Perhaps we could use only natural dyes in the future, but we are still quite far away from this. But if we never start taking these steps forward, we’ll never progress” (Hjelt, 13.3.2023).

Natural dyes, even in the test phase, have also presented an innovative promise of commercial success and the renewal of the whole sector. Twenty years ago, the company Lapuan Kankurit was passed down a generation (new leaders of the company), and at the same time the textile sector was in a recession. Many companies had to stop production and the future did not look too good. Now the textile sector has a completely new spirit. “So many good things are happening currently and there’s huge development [in the context of sustainability]. Natural dyes are part of this beautiful development and it’s great to work in this field” (Hjelt, 13.3.2023).

Looking into future possibilities: Nanso

The clothing company Nanso was established in 1921. It is a well-known casual-wear brand which makes garments from tricot fabrics with cheerful prints. Their printing and dyeing facilities and clothing assembly processes have been located in Finland for a long time. Nowadays their clothing collections have expanded and include types of fabric other than tricot. They have also outsourced production.

Nanso celebrated their 100-year jubilee in 2021, and wanted to show the history of the company, the development in fashion, and also Nanso’s future aspirations in an exhibition in Helsinki’s Design Museum. This motivated the collaboration with the BioColour project to test and show how biocolourants could be used in Nanso’s materials and products. Fabric series were dyed and exhibited in the jubilee exhibition. A small capsulate collection of natural dyed T-shirts were also produced and sold in the Design Museum and in Nanso’s shops. The dyes used in the T-shirts were bloodred webcab mushroom (*Cortinarius sanguineus*) and tancy (*Tanacetum vulgare*). Designer Noora Niinikoski (7.3.2023) explains how she is fascinated by the fine colour palette of natural dyes but sees obstacles to using them in industrial-level production. Nanso’s production is outsourced to other countries (mainly Portugal and Turkey) and this makes trying out biobased colourants in manufacturing challenging. Testing biocolourants depends on the factory’s knowledge of using these types of dyes and on their capability and courage to test new colourants that are not yet at the level of mass-manufactured industrial dyes. “This biocolour thing is profoundly connected to how manufacturing take these as part of their own production processes and how the development work is carried out in these factories” (Niinikoski 7.3.2023). She explains that these colourants have not been studied or developed enough yet for industrial manufacturing, and that

research and development work is still needed to be able to achieve industrial reality. On the other hand, Niinikoski believes that natural dyes will be an alternative, not a substitute, for synthetic dyes. “They will be like any other colour source and will exist side by side with synthetic dyes”. She believes that they will become part of the colour palette that industry uses in the future (Niinikoski, 17.3.2023).

She highlights that durability aspects are quite challenging as products, also sustainable products, need to last: “It’s important that the product is good and that consumers want to use it for a long

2 T-shirts by Nanso are dyed with natural colours.
Photo Nanso

time". Consumers are not ready to accept changes in a product (e.g. colour fading), as Niinikoski says,

> *but we might just have to accept these products dyed with natural dyes. Or then colours need to be developed and their durability attributes need to be good enough. Nanso has existed for a hundred years and is well known for its high quality and durability, so it's not easy to bring natural dyes to consumers. Expectations of product durability and long-lasting colours are so high.* (Niinikoski, 7.3.2023)

Niinikoski also tells us that Nanso has been discussing this issue with their supplier in Turkey and the factory has been testing local plant dyes for dyeing, e.g. acorn, bark from the mimosa tree and the *Rubia tinctorum* plant. In general, the discussion on where these plants originate from and where they are processed or finally used might need more attention and consideration from the logistic point of view, says Niinikoski (7.3.2023).

Towards sustainable success: Lappajärven Värjäämö

Lappajärven Värjäämö began in 1979 as a dye house in Lappajärvi, Finland. It carries out contract dyeing for other companies but also sells its own different types of yarns, paper yarn being one of their key products.

> *We became interested when Pasi Ainasoja from Natural Indigo Finland contacted us and asked if we would be interested in trying out and dyeing yarns with natural colourants. In principle, we're always interested and we're also eager to help in development work as there are so few dye houses in Finland.* (Puro, 6.3.2023)

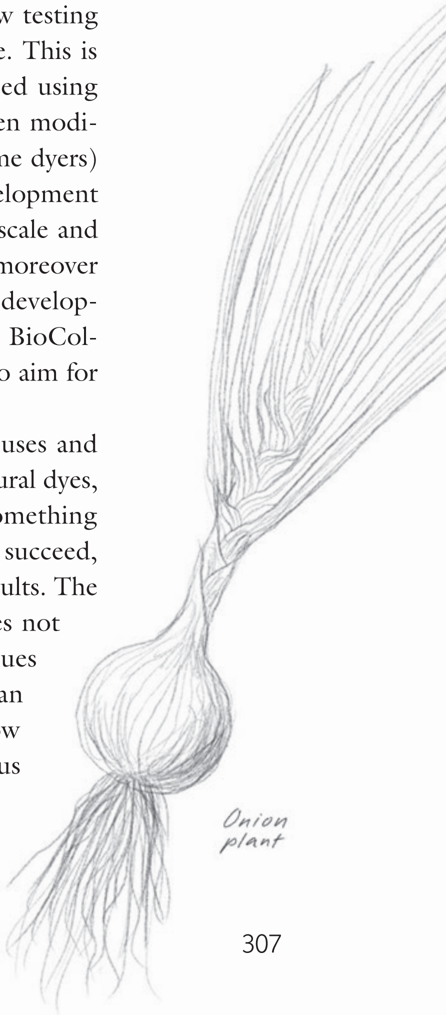
Lappajärven Värjäämö has tested several natural dyes in their dyeing processes. Sometimes they have done so with customer orders (contract dyeing), but they have also dyed yarns that they sell themselves. They have one small dyeing instrument, which makes it easy to also test small samples. They have used it to dye wool yarn, for example.

The small sample size lowers the economic risks and several test rounds can be conducted to adjust the recipes. As paper yarn is one of their key products, they also wanted to immediately test natural dyes in larger-scale dyeing processes with paper yarn.

Natural dyes have been something completely new for Lappajärven Värjäämö. Collaborating with Natural Indigo Finland has been an important initiative to start testing these colourants. Aalto University and University of Helsinki have helped adjust the dyeing recipes and processes. The motivation to try out natural dyes comes from the company's interest in more sustainable dyes and more sustainable processes. The company also wants to strengthen its present locality strategy (e.g. Made in Finland label) and feel that natural dyes are suitable for this. The fact that the colourant is made in Finland also reinforces this strategy.

In the first round they tested woad, and after this, onion skins (yellow and red onion) and willow bark dyes. They are now testing dye from coffee beans' waste, which are also industry waste. This is very promising, and several different shades can be produced using different mordanting agents. The greatest challenge has been modifying the knowledge from the craft sector (hobbyist and home dyers) which has not been tested at all. A great deal of basic development work is needed to expand this information to an industrial scale and to test, for example, which auxiliary agents are suitable and moreover the durability of each colour. As this kind of research and development work is slow, support and help from projects such as BioColour has been essential. The collaboration has enabled them to aim for commercial end products.

Puro highlights that all the actors, both the dye houses and the companies who have tried dyeing their products with natural dyes, have taken a risk with this endeavour, wanting to create something new. There was no guarantee that these experiments would succeed, therefore they have been very happy with the positive end results. The cost is slightly higher than that of other dyes but Puro does not see this as a problem: For some customers sustainability issues are so important that a slightly higher price will not be an obstacle. He also noted that for some customers however, low price is the most important aspect in their choices, and thus price may also be an issue in the use of natural dyes.



This is an expanding phenomenon, and the success of some of their clients in colouring products using natural dyes will help spread the word and interest to other clients. Puro says their company is very interested in working further with natural dyes and that they believe there are many possibilities to develop the use of these colourants in industrial production.

> *Time will tell, but I do believe that in ten years' time a considerable part of textiles will be dyed using these methods and natural dyes. These things have changed so drastically and quickly in the last years that I believe in ten years' time it will be reality. The will to change things is currently so strong that changes may happen quite quickly... The use of side streams especially makes this so much easier [side streams from food industry]…The dyeing process itself is pretty simple… Also the fact that we have achieved good colour durability and washing- and light-fastness makes us believe that colours have futures possibility.* (Puro, 6.3.2023)

He further points out that good colour durability is the key to success because it is not very sustainable if the product or colour only lasts for a short time.

> *A product dyed with natural dyes can't be put the trash bin in the summer [if it was dyed in the winter], as it has taken a lot of resources to make the product…and if the colour has disappeared by the summer, the product will be disposed of…The colour has to last as long as the product... Without this aspect it is wasted work.* (Puro, 6.3.2023.)

Discussion and conclusions

From the company interviews it is obvious that the will to collaborate to bring new knowledge into company practices is strong. Academic partners have contributed with their research knowledge, which is not always easy to digest. As Niinikoski (17.3.2023) describes, collaborating with academic researchers from the BioColour project is quite challenging, yet interesting. Trying to understand all the scientific details, such as the chemical information related to biocolourants is quite challenging for industrial partners but applying research knowledge to industrial reality (e.g. in the form of dyeing recipes) has benefited the industry considerably (e.g. Lappajärven Värjäämö, Natural Indigo Finland, Marimekko). The openness of the collaboration has also made it possible to benefit from each other's knowledge, and iterative testing using industrial processes has constructed a shared learning process not only between the partners but also between academia and industry. Testing biocolourants with industrial machines and in an industrial setting adds the industry and business reality to the process (not always obvious to academic research).

Their curious and experimental attitude has motivated the partners not only to collaborate with each other but also to take brave steps towards more sustainable practices in industry. This can be interpreted as a transitional position or even a transformational approach towards a new kind of business understanding; sustainability is essential and will require great changes in industrial production. Positioning towards the future is especially strong when sustainability is connected to company's strategy work and leads the company's development actions and decision-making, as in the case of Marimekko. This attitude means constant learning, constant envisioning and constantly looking for new innovation opportunities in the sustainability context.

Value has been captured on two different levels, as described previously in the background text: through creative thinking (visionary work in BioColour workshops, design experimentations, prototyping, capsulate collections) and through product and process refinement (developing recipes, test dyeing, durability testing). The innovative approach has required a visionary attitude, brave collaboration, combining different knowledges, and emerging interest from the market side. It can be interpreted that the interactive innovation model, which includes the consumers' interest, the scientific knowledge and industry's capabilities (Trott, 1998) has been successful in the BioColour project, creating value in industry and business with the support of academic knowledge. Furthermore, we can see that the innovation process has required open interaction and communication paths that link the companies' internal work (communication between design, production and marketing) as well as many external linkages (among the companies, and between the companies and academia). Through this kind of collaboration, a biobased colours knowledge network of different stakeholders has been constructed in Finland (e.g. Phelps, Heidl & Wahdwa, 2012).

The use of biocolourants in industry still faces challenges and obstacles. It requires new knowledge, understanding and even different kinds of industrial processes. Biobased colourants are not as easy to use in larger scale industrial processes as synthetic colourants. At present, industry is built on easy processes and the use of synthetic dyes and chemicals, which enables easy mass production. The use of biocolourants needs more time, more testing and different knowledge than synthetic ones. As the companies pointed out in the current study, biocolourants should be easy to handle, they should be in powder form so that international business is easier (easy logistics), they should be stable and durable, and end up in the same shade every time, as well as durable and long-lasting in the consumer use phase.

Industry wants to get these colourants ready; it has no time or resources to do development work with new types of colourants. Industry wants to see these colours as the most suitable for current industrial logic, yet the logic behind these colours might also build a new understanding of time and sustainability; a slow and local or even a new kind of colour aesthetics. We conclude that biobased, natural colourants need further research, and this can lead to two different paths: a) developing them to make them suitable for the same kind of use as that of synthetic colourants today in industrial-scale production, and/or b) challenging current industrial and business practices and offering these colourants with a different kind of logic. Even that these two paths seem contradictory, they do not exclude each other. These paths can be optional and both are needed.

At the end of this chapter we'd like to return to the quotes at the beginning (page 294). We truly need collaboration, collective courage and creativity to think differently in the sustainability context. Open collaboration between industry and academia can enhance innovation. And we also need driving forces to push the development further to reach the commercial reality. The drive of companies and entrepreneurs can really enhance sustainable innovations and the use and understanding of biobased colourants and colour palette they create.

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Interviews

Anna-Kaisa Ahonen and Jukka Berglund, Marimekko, 16.3.2023 (personal communication, Kirsi Niinimäki)

Pasi Ainasoja, Natural Indigo Finland, 21.2.2023 (Interviewed by Noora Tommila)

Jaana Hjelt, Lapuan Kankurit, 13.3.2023 (Interviewed by Noora Tommila)

Noora Niinikoski, Nanso, 7.3.2023 (Interviewed by Noora Tommila) and 17.3.2023 (interviewed by Kirsi Niinimäki)

Mikko Puro, Lappajärven värjäämö, 6.3.2023 (Interviewed by Noora Tommila)

Websites

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https://www.lappajarvenvarjaamo.fi/

Lapuan kankurit
https://www.lapuankankurit.fi/en

Marimekko
https://www.marimekko.com/fi_fi/marimekon-maailma/filosofiamme

Nanso
https://nanso.com/

Natural Indigo Finland
https://www.naturalindigo.fi/

Mordants

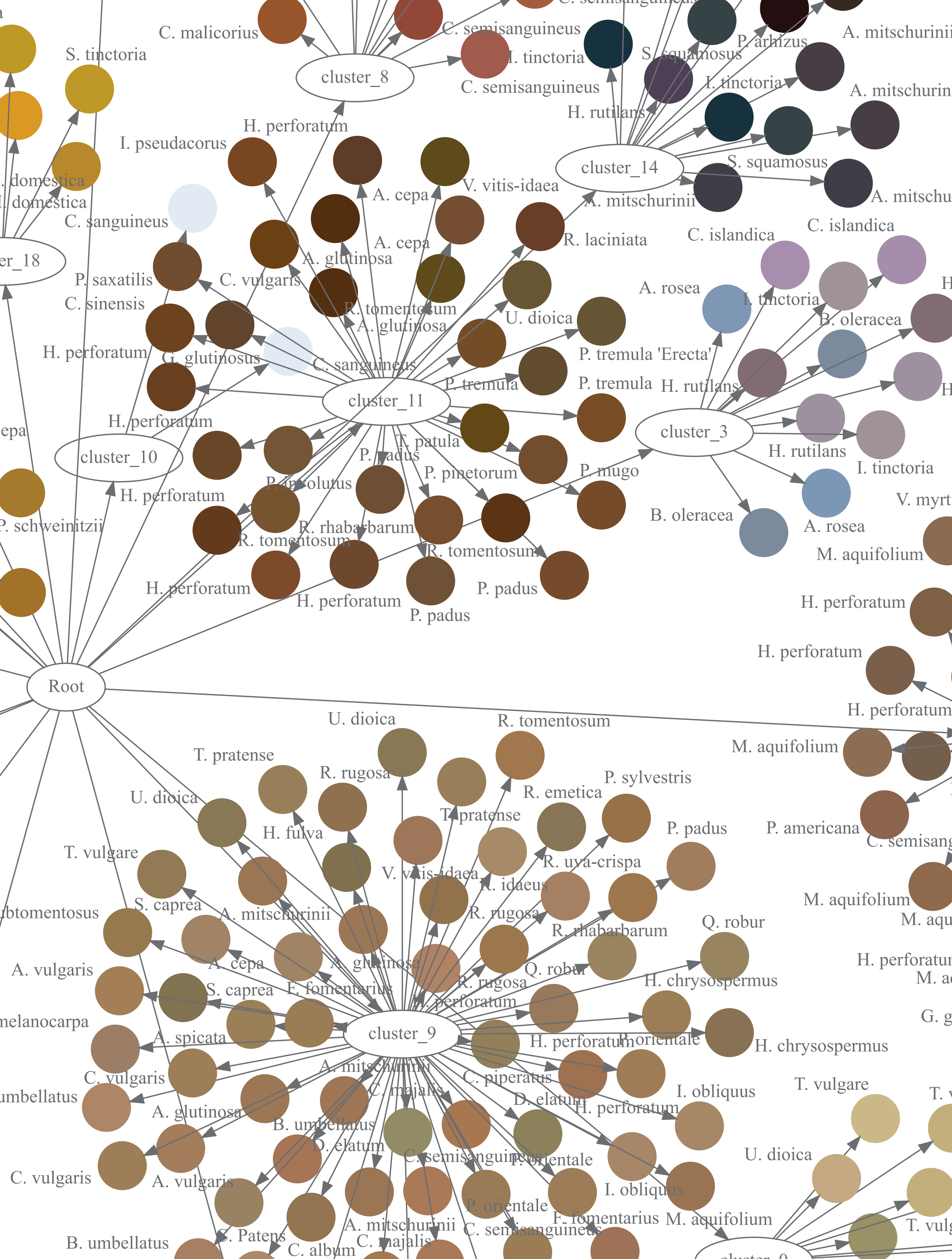
Over millennia, dyers have explored a wide range of organic and metallic substances to improve the lightfastness, washfastness and intensity of colours. These substances are called mordants and support the bonding between colourant and the fibre that is being dyed. Some mordants can be toxic to the environment and the human body. Metal mordants, such as copper, cause harm to our ecosystems through the invasive processes involved in their mining and refinement.

The BioColour research consortium explores how more responsible and sustainable mordanting practices can be developed, for example by utilizing the bark of willow, a fast-growing crop typically used for energy production, and chitosan, a material derived from food industry biomass such as crustacean shells from crabs and shrimps.

The impact of mordants: samples dyed with various biocolours by Pirita Lauri.
Photo Pirita Lauri and Julia Lohmann

Endpapers: Taxonomic circle and Northern colour palette. The taxonomic circle and created colour palette is based on reflectance spectra and CIE Lab colour codes measured from natural dyed samples donated for the BioColour research consortium by Finnish craft enthusiasts.
Research is carried out in University of Helsinki and University of Eastern Finland School of Computing.

Photo Leonardo Hidalgo Uribe


C. semisanguineus
C. malicorius
C. semisanguineus
I. tinctoria
C. semisanguineus
cluster_8
S. tinctoria
S. squamosus
P. arhizus
A. mitschurinii
I. tinctoria
A. mitschurin
H. rutilans
cluster_14
S. squamosus
A. mitschurinii
A. mitschu
H. perforatum
I. pseudacorus
. domestica
I. domestica
C. sanguineus
er_18
A. cepa
V. vitis-idaea
A. cepa
R. laciniata
C. islandica
C. islandica
A. glutinosa
P. saxatilis
C. vulgaris
C. sinensis
A. rosea
I. tinctoria
R. tomentosum
A. glutinosa
U. dioica
B. oleracea
H
H. perforatum
G. glutinosus
C. sanguineus
P. tremula 'Erecta'
P. tremula
P. tremula
H. rutilans
H
cluster_11
H. perforatum
epa
cluster_10
T. patula
P. padus
P. pinetorum
P. mugo
cluster_3
H. rutilans
I. tinctoria
P. involutus
H. perforatum
P. schweinitzii
R. rhabarbarum
R. tomentosum
R. tomentosum
B. oleracea
A. rosea
V. myrt
M. aquifolium
H. perforatum
H. perforatum
P. padus
P. padus
H. perforatum
H. perforatum
Root
H. perforatum
U. dioica
R. tomentosum
T. pratense
R. rugosa
P. sylvestris
M. aquifolium
U. dioica
R. emetica
T. pratense
H. fulva
P. padus
P. americana
C. semisang
T. vulgare
V. vitis-idaea
R. uva-crispa
R. idaeus
ubtomentosus
S. caprea
A. mitschurinii
R. rugosa
M. aquifolium
M. aqu
R. rhabarbarum
Q. robur
A. vulgaris
A. cepa
A. glutinosa
H. perforatu
Q. robur
R. rugosa
M. ac
S. caprea
F. fomentarius
H. chrysospermus
melanocarpa
H. perforatum
G. g
A. spicata
cluster_9
H. perforatum
P. orientale
H. chrysospermus
A. mitschurinii
C. vulgaris
C. piperatus
I. obliquus
T. vulgare
T. v
umbellatus
C. majalis
D. elatum
A. glutinosa
H. perforatum
B. umbellatus
U. dioica
D. elatum
C. semisanguineus
P. orientale
C. vulgaris
A. vulgaris
I. obliquus
P. orientale
F. fomentarius
M. aquifolium
T. vulg
A. mitschurinii
C. Patens
C. majalis
C. semisanguineus
B. umbellatus
C. album
cluster_0

BIO colours

SUSTAINABLE STORIES FROM NATURE, LAB AND INDUSTRY

Sustainability is essential because of the Earth's limited capacity and its limited resources. Promoting it requires the introduction of new products and production methods. We can foster the safety of many products by switching to bio-based dyes, which are safe for both humans and the environment.

Biocolours – Sustainable stories from nature, lab and industry presents the latest bio-based dyes, how to produce them, the use of plants and mushrooms, and the relationship between humans and nature in general. The editors of the book are Professor Kirsi Niinimäki and Professor Julia Lohmann from Aalto University. Professor Kirsi Niinimäki was awarded the State Design Award of Finland in 2022 for her work on advancing sustainability in the textile and fashion sector. Professor Julia Lohmann won the Dezeen Sustainable Design of the Year Award in 2020 for her pioneering work on seaweed and critical design.

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