Future Fashion III: sustainability of synthetic and natural textile dyes

Introduction

The two previous articles in the Future Fashion series focused on the most used textiles and fabrics within the fashion industry. The articles explored the range of raw materials used for the manufacture of both natural and synthetic products, putting the sustainability of such materials into context and into perspective. Throughout those articles we mentioned the chemical side of clothes manufacturing on a few occasions – in particular in the second article which dealt with leather and leather tanning – however we have not yet delved into the textile colouring process.

The first textile dyes are thought to have originated during the Neolithic Era (circa 10,000 BC). Evidence of textile dyeing was also found in China and Egypt, dating back 5,000 years. The dyes had been manufactured from natural raw materials such as plants, bark, algae and insects (e.g. Cochineal insect for red; octopus for sepia brown; pomegranate rind for yellow; and lichens for a range of colours). Nowadays, natural dyes are the exception rather than the rule, with 80% of all dyes in circulation being manufactured from petroleum-derived synthetic compounds.

The recent history of colour dyes, and the discovery of synthetic dyes, is strongly entangled with European colonialism during the 19th and 20th centuries. As European countries colonised other nations around the world, natural resources for the production of natural colour dyes were overexploited for the benefits of European fashion trends. Colonialism also sparked the discovery of the first synthetic dye, when Sir William Henry Perkin was commissioned to synthesise the first artificial quinine from a coal tar-derived aromatic oil, with a view to fight malaria more efficiently and strengthen the colonial hold of the British in Asia[i]. In 1856, through his experiments, Sir William accidentally discovered "mauveine", the first ever man-made colour dye. This discovery sparked a surge in dye manufacturing, with new dyes being synthesised rapidly, and in organic chemistry in general. Following these discoveries, multiple chemists also noticed that some of these new synthetic dyes had medicinal properties. Mauveine in particular is known to have applications in immunology and chemotherapy.

Nowadays, contemporary synthetic textile dyes are mostly known for the toxic compounds that they contain and which tend to make their way in the environment when strict regulations are not applied. Toxic and harmful chemicals are released into water streams at all stages of clothes manufacturing, however dyeing is undoubtedly the process during which most of the chemical pollution occurs. The fashion industry estimated to be responsible for 20% of global water pollution, with around 17% being directly caused by textile dyeing[ii,iii]. Synthetic dyes have become a very controversial aspect of modern fashion and of fast fashion in particular. Water pollution is a catastrophic collateral damage of dyes, and is mainly impacting developing countries in which most of the manufacturing industry is located. The extend of the water pollution is such that critics even say that "you can tell fashion's next season's hues by the colour of the rivers of China."

In this article, we will first cover conventional synthetic dyes, their compositions, variety and environmental impacts. Subsequently, we will explore natural alternatives, reviewing their potential and limitations. Finally, we will review the impact that textile colour dyeing is having on water around the world.

Conventional synthetic textile dyes

A dye is a colored substance that chemically bonds to the substrate to which it is being applied. This distinguishes dyes from pigments which do not chemically bind to the material they color. Dyes predominantly produced from combinations of organic molecules produced from fossil fuels such as oil and coal. Chemically, dyes are comprised of chromophore and auxochrome groups, the chomophore is responsible for dye colour and the auxochrome group for the dye fibre reaction. Dyes are generally applied textiles in an aqueous solution and may require the use of a mordant to improve the fastness of the dye on the fiber.

Synthetic dyes are classified according to a set of parameters: their chemical composition, the type of fibres that they can be used on, their hue, and by the method through which they are applied. The most common method of classification is through chemical composition as it provides information on the type of fibre the dye can be applied to as well. There is a multitude of types of synthetic dyes, way too many for us to all cover in this article, however we will provide a quick overview by summarising a few, highlighting the key aspects that can vary across the range of products available.

Acid dyes are soluble in water and are applied in a low pH dyebath. Those dyes are typically applied to a wide range of protein and synthetic fabrics such as wool, silk, nylon and polyester, however, their acidic nature damages cellulosic fabrics such as cotton and linen. Acid dyes typically provide bright colours. Sulfur dyes are the most common dyes for the colouring of cotton, usually in dark colours such as black, dark blue and brown. Those dyes are insoluble in water and require sodium polysulfide as solvent instead. Their popularity is also due to their cheap costs and the simplicity of the dyeing process that they involve. Vat dyes are another example of synthetic dyes which are insoluble in water. In this case, the dye becomes soluble once it is reduced in the presence of an alkali. The redox reaction taking place allows the dye to change colour during the dyeing process, from yellow in the hypoxic dyebath to green and blue once it enters in contact with oxygen on the fabric fibres. The main colour associated with vat dyes is indigo. Finally, azoic dyes differ quite significantly from other types of dyes as the fabric or garment is not bathed in a solution of the finished dyeing product directly. Here, the dyeing process is done within the fibres themselves, while the fabric is bathed in two colourless solutions consecutively. Once these two compounds come into contact within the fibres, the dyeing occurs. The resulting colour is insoluble in water. There are many more types of synthetic dyes available on the market, with varying chemical compositions and properties matching a range of aesthetic, technical and financial requirements. These include direct dyes, disperse dyes and chrome dyes, to only name a few.

Colour fading under light or through rubbing against other materials is referred to as colorfastness, and is a crucial parameter to consider during clothes manufacturing, especially as dyes can vary greatly in their colorfastness properties. Vat dyes for example have a high colorfastness under sunlight (i.e. the colour does not fade when exposed to UV light), however depending on how the dye is applied, vat dyes can have a low rubbing colorfastness (i.e. the colour can be transferred to other materials, especially clothes). Acid dyes on the other end, tend to have a low wash colorfastness (i.e. the colour tends to fade after several washes), but has a relatively good light colorfastness. Preventing colour fading remains a crucial challenge for the colour dye industry which is unfortunately often solved through the addition of harmful chemical compounds into the dyebaths.

Some of the undeniable advantages of conventional dyes are their low costs, availability and reliability. Industrial conventional dyes are produced consistently, meaning that customers know exactly what to expect from the finished product, which in turn leads to less additional costs overall. This is ideal for fast-fashion in particular. The main disadvantage of synthetic dyes is the efficiency of the colouring (or exhaustion stage), which is referred to as the “fixation rate”, and which varies widely across all types of dye available on the market. Currently, the fixation rate of most conventional dyes is 80%, meaning that the remaining 20% of dye left in the solution is discarded. As many dyes are highly soluble in water, the water bodies themselves become coloured. This leads to light not reaching below the surface which in turn leads to low photosynthetic rates by algae and an overall decreases in oxygen levels affecting the entire aquatic ecosystem. Most synthetic dyes also contain highly toxic compounds such as lead, chromium, copper and sodium chloride (e.g. increases salination in water bodies), which can be very harmful to living organisms on all trophic levels (including humans). As farmers from developing countries are forced to use contaminated water for irrigation (for lack of a better option), the toxic nature of synthetic dyes also affects soil microbial communities and plant growth. The extensive research having been done on the subject highlights the scope of the issue, showing that the environmental impact of synthetic dyes is far reaching, affecting a wide range of habitats and organisms all along the food chain.

Mitigation strategies are being explored to limit the harmful consequences of intensive synthetic dyeing and water pollution. On the front line, regulatory frameworks are being put in place to limit the use of certain dyes and protect public health. The EU has for instance limited to use of azo dyes which are used for colouring by a range of industrial sectors. Some of the azo dyes currently available on the market have the potential to break down into carcinogenic aromatic amines, making them a major risk to public health. Similarly, sulfur dyes have catastrophic environmental impacts due to the toxic and hazardous nature of the sodium polysulfide solvent used during the process, and are therefore disappearing from western manufacturing lines. Eastern countries on the other hand, China in particular, still use sulfur dyes extensively. The trend seen here is reminiscent of the observations made in the previous 'Future Fashion' article in the section dealing with leather tanning. It appears once more that Western countries, which hold economic power and decentralise most of their industrial activities, are more likely to apply regulations on hazardous processes compared to developing countries, in which most industrial activity occurs. Although regulatory frameworks exist, their reach remains limited, in particular as they do not extend to the areas most affected by the issues.

In addition to stricter regulations, the direct treatment of water effluents is a promising mitigation strategy currently being practiced and extensively researched. Physical, chemical and biological processes exist, allowing treatment of a range of types of dyes. Physical treatments include processes such as coagulation, filtration and absorption and are often used in association with chemical methods such as reduction, oxidation, neutralisation and ion exchange. Coagulation is effective on sulfur and disperse dyes and has been shown to produce good results. In this case, the dye particles are made to group together through the addition of positive ions and are then filtered out of the water. Filtration (nanofiltration and ultrafiltration in particular) can also be applied to wastewater on its own. Promising results have been obtained for a range of dyes, however the technique so far remains very expensive and energy intensive. The absorption method involves the chemical dissolution of the dye molecules which then become attached to an absorbent surface. The result obtained through this method have been highly encouraging for a wide range of dyes, however its use remains very limited due to its high cost. Research is now focusing on developing cheaper absorbent surfaces.

Biological treatments include phytoremediation and phytoaccumulation by plants able to metabolise and/or store toxic compounds, and microbial treatments which involve bacteria and fungi able to metabolise and mineralise toxic compounds. The field of phytoremediation is a fairly new one but already shows promise[iv,v]. A range of plants and grasses have been identified as being able to "decolourise" wastewater containing azo dyes, with studies having already isolated the enzymatic pathways involved in the process. There are however many limitations to phytoremediation becoming a widespread method at the moment. First, the process would require a lot of space (i.e. wastewater treatment "fields"). More, replicating lab-controlled experiments can often be difficult, as a many biotic and abiotic factors may affect the metabolism and physiology of plants. Finally, there still remains a lot of unknown side effects, which could prove damaging to the environment. For example, it is not known whether plants would release toxic volatile compounds back into the environment through transpiration. Research is ongoing and time will tell how efficient phytoremediation could become in this context.

The bioremediation of toxic compounds through microbial communities is at a more advanced stage[vi]. It relies on organisms becoming adapted to toxic environments via the production of enzymes capable of breaking toxic compounds down into non-toxic (or less harmful) ones. Such microorganisms already thrive in wastewater environments and have been shown to efficiently breakdown toxic compounds thanks to a range of enzymes. So far, trials have proven this process to be efficient, low cost and safe, however the difficulty in this case lies on being able to scale this treatment up to an industrial level, ensuring that only "desirable" efficient microorganisms are present in the water being treated. The field of metabolic engineering has seen a rise in research projects focusing on isolating the enzymatic pathways responsible for the breakdown of toxic compounds and attempting to engineer microbial strains capable of producing the required enzymes in higher amounts.

Water effluent treatment is a broad and complex field of research that is showing promise and could become an instrumental part of the global effort to transition towards a greener industry, and a greener fashion industry in particular. However, it will not be able to "fix" the dye pollution problem on its own and will need to be used in association with stricter and further reaching legislations and regulations.

Natural textile dyes

As the world attempts its transition towards a "greener" industry, an increasing number of fossil-based products have come under scrutiny and biobased alternatives to commonly petroleum-derived products are being developed at a rapidly growing rate. Colour dyes have not escaped that trend and natural dyes are becoming more popular with leading fashion brands and customers. The toxic nature of a lot of synthetic dyes is also motivating a rapid transition towards biobased natural alternatives.

As mentioned earlier in this article, natural dyes are nothing new. Millennia ago, civilisations across the world used flowers, roots, leaves, bark, fruits, fungi, insects, algae and minerals to produce colours and dye clothes. The main advantage of natural dyes is that they are produced from renewable materials and therefore do not rely on fossil resources (i.e. petroleum and coal). In addition, unlike synthetic dyes, the natural raw materials used here do not usually contain compounds susceptible of harming humans or the environment (two exceptions have to be made for logwood and bloodroot, however, as those can cause negative side effects when inhaled, ingested or absorbed through the skin).

Natural dyes are mainly used to dye natural fibres, both cellulose (e.g. cotton, linen and hemp) and protein (e.g. wool, leather and silk) fibres. The main technical disadvantage of natural dyes is that they do not become fixed to fibres as efficiently as synthetic dyes do. Therefore, the dyeing of both cellulosic and protein-based fibres requires the addition of "mordants". From the Latin *mordere*, meaning "to bite", mordants bind to both the fibres and the colour compounds in the dye, hence linking and holding the two together. Mordants have been used for as long as natural dyes have existed, the most popular mordants used throughout history being alum (aluminum sulfate), iron and tannin. Those are still currently regarded as the safest options as they do not typically have harmful impacts on human health and the environment (although as with any compound on Earth, adverse effects can occur in environments containing high concentrations of these). Other more modern mordant options include tin, and chrome, the latter being regarded as the least safe option as chromium can lead to water and soil contamination, and eventually cause health conditions in humans (cf. leather tanning section in Future Fashion II). As well as allowing the colour to be retained by the fibres, mordants also affect the shade of colour being fixed onto the fabric, they are therefore an instrumental part of colour creation. Natural dyes can also be used to colour synthetic fibres like polyester, nylon and acrylic. The dyeing process is similar to the one required for the dyeing of cellulosic and protein-based fabrics, with mordant treatments being required to improve colour fixation and colourfastness. A range of protocols have been proposed over the last few years, but things seem to remain at an experimental stage for now. Dyeing synthetic fabrics with natural dyes can be done, but the processes have not yet been perfected and standard guidelines for the production of colours have not yet been made available to industrial stakeholders.

The demand for natural dyes is on the increase, showing that they may soon become an integral part of the fashion industry for the dyeing of both natural and synthetic fabrics. To that effect, there has been a recent surge in research aiming to optimise and standardise the processes for the natural dyeing of a range of fabrics. Natural dyes are known for not producing colours as reliably and consistently as synthetic dyes, which could be an issue for clothes manufacturers and designers in an industrial context. Such standardisation would provide a solution to that issue by ensuring consistency of dyeing methods, dyeing process variables and dyeing kinetics.

Although natural dyes are manufactured from renewable feedstocks, sustainability may remain an issue if the exploitation of natural resources is not closely monitored. This is especially relevant in the current context of fast-fashion in which a lot of dye is required. Furthermore, more natural dye is required to colour a given quantity of fabric compared to synthetic dye. For instance, one pound of cotton can be dyed using only 5 grams of synthetic dye, while a total of 230 grams of natural dye would be required to colour the same amount of fabric[vii]. As things stands, if all synthetic dye were to be replaced by natural alternatives, there would need to be a several-fold increase in dye availability compared to today, more specifically in the case of cotton, there would need to be a 46-fold increase in dye availability. Although this is a hypothetical scenario, it shows that a shift in dyeing practices would surely put a strain on natural resources and put the sustainability of natural dyes to the test. This is another issue that optimised standardised guidelines could potentially mitigate if more efficient dyeing methods were to be developed.

Natural dyes offer a viable alternative to petroleum-derived synthetic dyes, however, there remain environmental disadvantages which show that natural dyes are not the “sustainability silver bullet” it is often marketed to be. Regulations are needed in order to both limit the release of potentially harmful compounds in the environment, and to ensure that natural dye production does not lead to deforestation, habitat deterioration and loss of biodiversity. Currently there are no specific regulations for the manufacture and use of natural dyes, which is most likely due to the fact that they remain fairly marginal and at a developmental stage. However, health and safety regulations applied to the synthetic dyeing process, along with regulations dealing with the disposal of contaminated water, already extend to natural dyeing as both types of dyes are used in the same factories. Unfortunately, just like in the case of synthetic dyeing (and even in the case of leather tanning as seen in the previous article), these regulations may not yet be applied in the countries in which most of the textile dyeing industry is located, and where the most damage is being done.

The water problem

In the previous Future Fashion articles we touched upon some of the impacts that the fashion industry has on water, whether through extensive water consumption or intense water pollution. These issues were mainly seen in the context of cotton production and leather tanning, however colour dyeing is responsible for most of the water consumed (and polluted) by the fashion industry.

Water being the main solvent used for the dissolution of colour dyes, water use associated with textile dyeing is extremely high. According to statistics from the U.S. Environmental Protection Agency, between 20 to 160 litres of water are needed to colour one pound of fabric (roughly equivalent to the amount of fabric required to cover one sofa)[viii]. According to the Ellen McArthur Foundation, the fashion industry uses up to 93 million m^3 of water every year, and although this value includes other stages of the clothes manufacturing process, colour dyeing is the most water intensive one.

Not only are enormous quantities of water being used, they are often released back into the environment as contaminated wastewater containing hazardous substances such as heavy metals. About 72 toxic compounds have so far been identified in dyeing wastewater effluents, of which 30 cannot be removed through water treatment and therefore freely making their way into the environment[ix,viii]. It is estimated that around 17% of all industrial water pollution globally is due to clothes dyeing[iii]. Those issues are mainly due to a lack of regulations and enforcement, especially in countries where most of the industry is taking place. This is leading to catastrophic environmental and human damages, which is exacerbated by the often difficult economic and social context in those countries.

The issues raised here are of particular importance in the current global water shortage context. Nowadays, 1.1 billion people on the planet lack access to water, with 2.7 billion reporting that they find water to be scarce for at least one month per year. This trend is expected to reach such heights that two thirds of the world population will experience water shortages by 2025[x].

In 2012, WRAP UK commissioned a "Review of data on embodied water in clothing" which aimed to summarise the UK's global water footprint resulting from the country's fashion industry and clothing consumption. As part of the report's introduction, a global water footprint map is presented, showing that China and India are the countries using the highest amounts of freshwater across the fashion industry as a whole[xi]. China and India are the top 2 textile dyeing industries[xii], and also happen to both be facing extreme water scarcity issues[xiii,xiv]. In India, water pollution is also a big concern, with corruption and lack of protective policies and regulations being blamed for improper disposal and treatment of contaminated wastewater[xv]. If the fashion industry were to reduce its water consumption and the irreversible water pollution it creates as a result of its activities, it seems justified to believe that more water would then become available for direct consumption, hygiene practices, crop irrigation and farming.

There are reasons to hope as the textile dye industry is rising to the challenge and starting to develop strategies and technologies that would reduce both water and energy consumption. Water savings and water re-use protocols are already being implemented, with companies reporting water savings between 20 to 50% when compared to previous practices. "Air Dyeing Technology" is also slowly being introduced. This method uses 95% less water compared to conventional methods, along with requiring 87% less energy and emitting 84% less greenhouse gases[xvi].

Conclusions

The Future Fashion article series has covered several aspects of the clothes manufacturing industry, reviewing conventional widely used fabrics and animal-derived materials, and providing a summary of biobased alternatives to those. The article series also provided an overview of physical and chemical treatments that are applied to those materials, putting them in an environmental context and outlining the "natural" and more sustainable alternatives that are currently available or in development.

Through those articles, we have seen that the debate between conventional and sustainable fashion cannot be a straightforward "black and white" one. The need for change is undeniable. Fossil-derived materials and toxic chemicals must be either replaced or more strictly regulated to prevent environmental damages and protect workers' health in particular. Biobased and so-called "natural" alternatives are often marketed by big brands as the ultimate solutions which will fix all the issues created by the fashion industry, however, although those alternatives are a giant step in the right direction, their sustainability needs to be constantly re-assessed and assured with full transparency. As we enter a new era of sustainable practices and decarbonised industries, errors from the past need to be avoided. Approaches need to be nuanced, marketing needs to be more transparent and honest and the social aspect of sustainability cannot be ignored any longer.

To conclude this series, it appears important to point out that overconsumption remains at the centre of most of the controversial (and not-so controversial) issues raised. Biobased materials provide a great alternative to petroleum-derived products, but overconsumption of renewable resources is unsustainable by definition. There has been a lot of effort put towards raising awareness on the effects of the fashion industry on the environment. Science and technology are moving fast and a wide range of great alternatives have been developed, and are constantly being improved on. However, behaviours will have to change for all these efforts to truly pay off. Consumers will have to buy less, fast-fashion will need to slow down, and policies will have to become stricter while extending to every single country in the world, not just the richest ones.

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