Review

Disruptive Science and Sustainable Leadership for the Future of Colorants

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Abstract: Many pigments and dyes are not only valuable molecules in manufacturing, but also pollutants. Science has certainly been producing sustainable alternatives to counter the issue of dyes, but this is not enough. There is also a need for change in the business attitude and leadership approach of the organizations that operate in the industry. Only through the successful combination of new technologies and forward-looking decision making, it will be possible to alter the status quo and deal with the multiple environmental and supply chain challenges that these businesses are and will be facing. With a focus on colorants, this critical review article will reflect on the importance of both a biotechnological approaches and sustainable leadership to achieve a sustainable, forward-looking fashion industry.

Keywords: Sustainability; textile industry; biotechnological solutions; leadership; sustainable leadership; start-up

1. Introduction

Colours play a key role in our lives: our clothes, our cars and the furniture in our houses come with a wide range of choices when it comes to hues, inks, and paints. Since the accidental synthesis of the first synthetic aniline dye Mauveine by William Perkin in 1856 (Huebner, 2006), the range of dye molecules available has widened and entered not only the textile, food, and cosmetic fields, but also the pharmaceutical, plastics, ink, and packaging industries. As consumers, we mainly see them as a way of expressing our personal taste, mood or personality and usually pay little attention to their origin and production process. As scientists we are fascinated by the chemical processes behind them and, at the same time, mindful of the hazard they pose to the environment. The colorants market has been steadily growing for decades and it was estimated at 31.2 billion USD in 2020; it is now expected to reach 86.9 billion USD by 2030 (Allied Market Research, 2022).

In March 2020, the European Commission launched a new circular economy action plan that is affecting multiple sectors dealing with materials use, such as textiles (European Commission, 2015). If we consider the fashion industry, finishing processes such as dyeing are energy-intensive steps requiring large amounts of energy and water, namely up to 150 L/Kg of fabric, and take a high toll on the environment (Sajn, 2019). The dyeing of textiles is the second largest polluter of water at a global level and a single pair of jeans can require up to 9000 L of water for its production (UN, 2018). It might also be worth remembering that the textile industry is only one of the many sectors that rely heavily on colored molecules. On the other hand, their use is highly restricted in the production of cosmetics, where colored natural ingredients usually provide a valid alternative (Cosing, 2018).

Our relationship with clothes has been, and still is, full of contradictions and colours have certainly fueled many controversial debates. The industry relied on only natural colorants until the middle of the IXX Century and this sometimes posed considerable risks. One striking example is that consumers wore arsenic dresses, mercury hats, and

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flammable clothing (Little, 2016). Arsenic was widespread during the Victorian time because it represented a cheap way to colour in bright green many everyday objects like candles, curtains and wallpaper as well as dresses, hair decorations and shoes. Thanks to the introduction of synthetic dyes, it was eventually possible to find less-risk-posing alternatives for producers and wearers. Discovered by accident, the synthesis of the first green dye was patented by Cherpin in 1862. Biotechnology has also now identified the synthesis of green pigments in many microorganisms (an early example is Caple 1978). This is just one of many examples of how technological advances and scientific innovation have improved the nature and production processes of colorants in sectors like fashion, which has also resulted in higher safety for end consumers, manufacturers, as well as for the surrounding environment.

Many studies indicate how sustainability that entails an environmental, social and economic dimension, provide a competitive advantage for companies by contributing a positive reputation, improved customer satisfaction and organizational commitment (Gupta et al., 2012; Flint et al., 2009). Future-conscious leaders of all organizations should see sustainability as an opportunity to develop a competitive advantage and be at the forefront of their industry by combining their experience and influence with a typical start-up mindset.

This critical review article we will reflect on the importance of not only biotechnological approaches but also of a sustainable leadership to achieve a future-proof fashion industry. Science is actively providing technical solutions but adopting a suitable leadership style is crucial for an effective implementation of sustainable strategies and to continue to foster innovation (Figure 1).

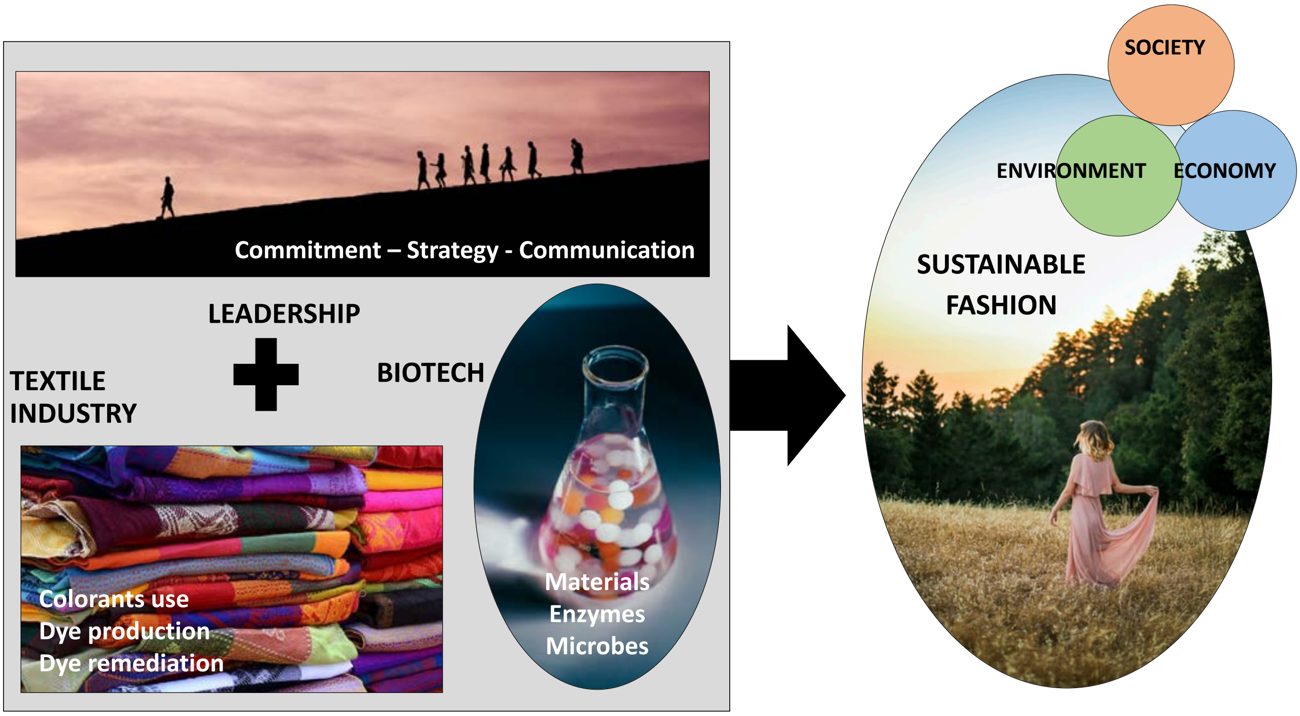

Figure 1. The journey towards a sustainable future requires the combination of multiple aspects with biotechnology and leadership playing an equally key role for the implementation of change to textile industry and its environmentally hazardous use of synthetic colorants.

2. Traditional knowledge and modern biotechnologies

Since ancient times, the fascination with colors has led to explore natural sources from plants, lichens, and animals to be later used for personal decoration and eventually textile dyeing. Colorants were extracted and processed from lichens such as *Letharia vulpina* or Wolf Lichen, mushrooms, plant such as common madder (*Rubia tinctorum*) or henna (*Lawsonia inermis*), and insects such as from the Kermes family (*Coccus ilicis*),

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(Agbahoungbata, 2019). While our ancestors proceeded by trial and error, our efforts are nowadays supported by modern technologies in the form of analytics, *in vitro* cultivation, and genetic engineering.

Plant-based dyeing systems are based on a big amount of traditional knowledge that provides insights on optimal processing conditions (Adeel et al., 2019). Multiple ethnological studies report that the use of plants for dyeing is rooted in the context of the territory and the tribal population in which the knowledge has developed (Example: Hu et al., 2022; Teron et al., 2012). However, this knowledge and application of the process are currently under threat due to the easy accessibility of synthetic dyes and issues related to acculturation (Teron et al., 2012). While these traditional processes might be in danger in developing countries, scientists are focusing on improving the sustainability of industrial processes. Traditional knowledge and vegetal materials are gaining more attention and new sources of dyes are being investigated. For example, the inflorescence of munj sweet cane (*Saccharum bengalense* Retz.) has proven effective in various processes including the creation of mordants and as high temperature and natural agents such as moringa and turmeric (Raza et al., 2018).

Modern analytics based on chromatography can nowadays assist us in identifying and separating all the colored molecules present in an extract, for example from plants. In addition, surface-enhanced Raman spectroscopy (SERS) and high-pressure liquid chromatography (HPLC) have allowed the separation and identification of the colorful molecules present in the extracts of plants that are main players in the Chinese tradition such as Chinese mulberry (*Cudrania tricuspidata*), gromwell (*Lithospermum erythrorhizon*), Chinese rhubarb (*Rheum palmatum*), tangerine (Citrus reticulata) and Morinda (De Luca 2018). In a more comprehensive separation, the use of supercritical CO_2 has proven very valuable and a sustainable alternative to organic solvents, in an attempt to discriminate dyes with different chemical properties based on polarity to size and chirality (Lesellier and West, 2021). At the same time, non-invasive techniques such as UV-Vis-NIR reflectance spectroscopy has been explored as a useful tool to rediscover natural dyes from ancient textiles and rugs (Angelini et al., 2013).

Taking one step forward while leveraging current practices and building on existing knowledge, upcycling provides a great strategy. Already applied to food waste, upcycling has also been explored for both textiles and colors. In general, this does not require novel processing methodologies and even just wet spinning can be applied (Ma et al., 2020). For example, wood waste such sawdust of the *Pterocarpus indicus* tree has been successfully applied to color cotton and silk fabrics (Kandasamy et al., 2021). Plants of current low economical value can also provide hidden valuable molecules. As a study reports, the use of Prickly Pear Peels of *Opuntia ficus*-indica (L. Miller) can be a source of colored molecules suitable for the dying of vegetal and animal fibers (Scarano et al. 2020). Color fixation can often proceed successfully through physical treatment such as drying and heating, or by using natural mordants such as lemon juice, gallnut, pomegranate rind and gooseberry that can compete with metallic alternatives (Kandasamy et al., 2021). It is therefore reasonable to think that, in order to respond to the different manufacturing needs while adapting to local environments and resources, it will be necessary to identify multiple solutions.

3. Colorants and biotech-assisted sustainability

The diversity in chemical structure and origin of colorants (Figure 2) is one of the reasons why making them sustainable across both phases of production and later remediation presents multiple difficulties. Studies have addressed the issue looking at both the single-molecule level and by using complex microbial communities and wastewaters (Figure 2). Production processes with a reduced environmental impact have also been reported to use continuous reaction conditions to decrease the water requirement by some 40% and the footprint by even a 4-fold (Shukla et al, 2021).

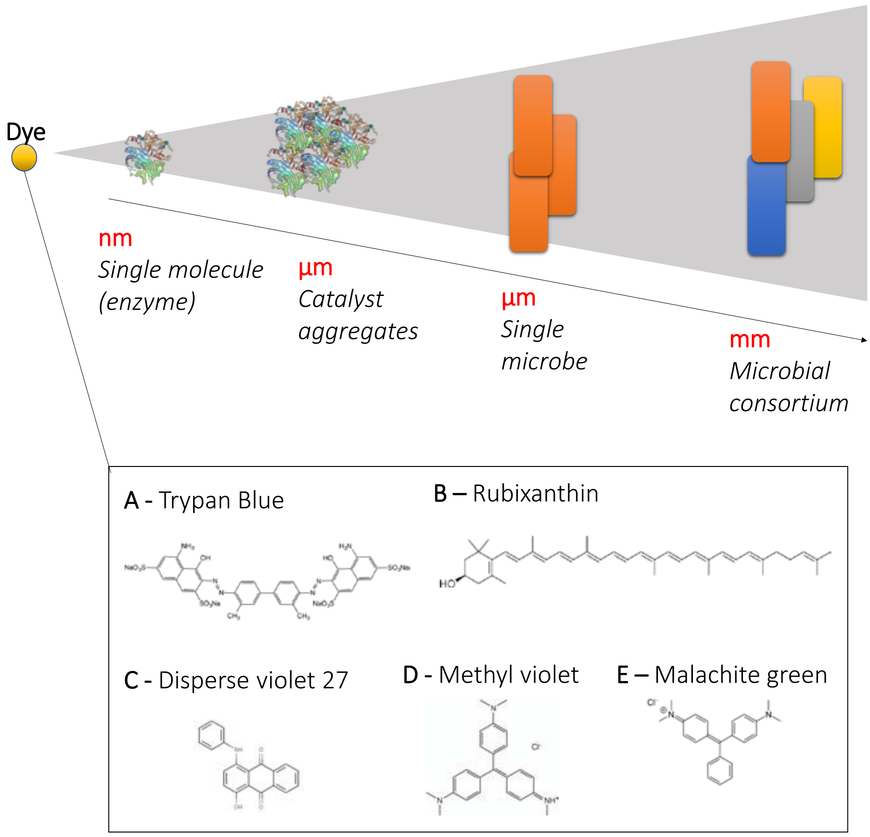

Figure 2. Biotechnological solutions presented to the environmental hazard posed by synthetic dyes encompass a wide range of dimensions from the nanometer-scale of single proteins, e.g laccase (PDB ID: 1KYA, laccase from Trametes versicolor as an example), to the millimeter-size that biofilms of complex microbial communities providing a complex enzymatic toolbox for bioremediation can reach. Enzymes. (Lower panel) Representative colorants used on the industrial scale and whose removal and detoxification has been investigated with biotechnological means. (A) Trypan Blue is an example of azo dyes, organic molecules characterized by the functional group R−N=N−R′, currently applied to cotton coloration on a large scale but also applied to laboratory analytics. (B) Rubixanthin or (3R)-beta-4-Caroten-3-ol is a carotenoid used in food and cosmetics and carotenoids from waste of tomato processing are being tested for dyeing of silk, wool and polyamid (Baaka et al., 2016) to provide a yellow coloration. (C) Disperse violet 27 or 1-Anilino-4-hydroxyanthraquinone belongs to the aniline group of colorants and has been tested with polylactide fabrics (Motegi et al., 2001) and it is used in cosmetics but not allowed for products in contact with mucous membranes (https://echa.europa.eu/cosmetics-colorant).(D) Methyl violet is a family of dyes that has been the subject of extensive studies focusing on adsorption and bioremediation (Parshetti et al., 2009).(E) Malachite green has a shade reminding of the mineral and is chemically a triarylmethane dye that is recognized by the enzyme laccase.

Microorganisms such as fungi and bacteria have proven very valuable for the degradation of colorants of synthetic nature. Their intracellular and extracellular enzymes are produced in response to the environment of growth and, upon growth in polluted settings, the enzymatic activity can be tuned to recognize the contaminants. At the molecular level, multiple enzymes have been explored to catalytically convert dye molecules into less toxic compounds of less color. Major enzymes with potential in this respect, are derived from laccase (benzenediol–oxygen oxidoreductase, EC 1.10.3.2), high redox potential peroxidases (EC 1.11.1.X), polyphenol oxidases (EC 1.14.18.1), and azoreductases (azobenzene reductases, EC 1.7.1.6) classes (Morsy et al., 2020; Bello-Gil, 2018). Catalases are versatile enzymes catalyzing an oxidative reaction using hydrogen peroxide or an organic peroxide. As example sourced by the food industry, waste products (soybean and potato), peroxidases in an immobilized or free form led to a biodegradation of an anthraquinone dye with efficiency levels above 70% (Svetozarevića et al. 2022). This is a great illustrative example of up-cycling for bioremediation.

Fungi, bacteria, even algae and plants have proven effective in dye degradation. Microbial bioremediation has been tested with positive results in the removal of various colorants that are currently posing an environmental hazard (Jamee et al, 2019). Used mainly for wool, tartrazine is a synthetic yellow azo dye used in printing and food coloring (E102) and has been degraded using bacteria *Pseudomonas aeruginosa* reaching 72.65% removal in 5 hours (Kamarudin et al., 2022). Similarly, Pseudomonas strains isolated from industrial water streams have delivered positive results in the remediation of methyl violet (Sarnaik et al., 1995). The multi-purpose azo colorant trypan blue has proven useful in the industrial production of garments, cosmetics, laboratory analytics and materials but poses however an environmental concern for both the product and its degradation (Shukla et al., 2021; Gudelj et al, 2011). Immobilized bacterial consortia (Lade et al., 2015) that achieved decolorization of wastewater in 24 hours, i.e. 50 mg·L−1 dye concentration, produce fewer toxic derivatives. This reduced toxicity is however not an automatic outcome, and a case-by-case assessment is needed, e.g. Congo red in-vitro degradation products by peroxidase fungal enzymes led to an increased *in vitro* toxicity whereas an equal treatment of methyl green reduced toxicity (Sosa-Martínez et al., 2020).

Removal of dyes from wastewater can also be achieved via physical methods, such as adsorption. This physical approach not always requires specialized active materials but can be performed with a sustainable perspective in mind by using waste-products from other industries such as Indian Rosewood sawdust, a timber industry waste for the adsorption of methylene blue (Garg et al., 2004) or sunflower (*Helianthus annuus* L.) seed hull for methyl violet removal (Hameed 2004). Remediation can additionally be obtained using a microbial approaches based on single-bacterial or fungal strains with adapted metabolism (Vijayalakshmi et al., 2014); similarly consortia can also be applied (Jamee et al., 2019; Roy et al., 2018).

4. Entrepreneurial future

In view of a circular economy, the use of waste products or by-products is advisable. The ecological impact of the dyes and chemicals used by the textile industry is critical, and international organizations are responding with limitations and bans giving companies only a few years to adapt (Mowbray 2018). Several publicly funded projects have tackled the production of dyes in a biotech-based manner without relying on fossil sources. As an example, the BioNaD project ended in 2016 (D'Ulivo, 2016) that addressed both new biosynthetic dyes and their biodegradation to create an environmentally friendly leather dyeing. To reduce the land-use of the textile industry, even bacterial fibers such as bacterial nanocellulose has been suggested as textile material that can be dyed with natural extracts of natural dyes based on Eucalyptus (*Eucalyptus globulus* L.) and Onion (*Allium cepa* L.) (Galino et al., 2021). At the end of the supply chain, bioremediation is crucial to repair the danger posed by the disposal of colorants in the environment. Biotechnology and an increased attention to sustainability can positively affect most of the supply chain for colorants (Table 1).

Natural dyes provide a sustainable renewable source with high-biodegradability and low-toxicity for people and the environment as they are produced following the green chemistry principles. The use of natural sources such as plant extracts offer the advantage of providing a complex mixture with possible additional bioactivities to the mere colorant action, e.g. antioxidant, antimicrobial, flavor, and medicinal action, due to the presence of metabolites such as flavonoids, carotenoids, tannins, and even alkaloids (ul-Islam et al., 2015, Faccio, 2020). Plants have certainly a long history of use but require however considerable time to grow and they heavily depend on the surrounding environment and climate. Bacteria and fungi, on the other hand, allow easier and faster growth *in vitro* (Rao et al, 2017). Biotechnology has targeted the biosynthesis of more sustainable dyes using the tools of genetic engineering or by exploiting the enzymatic machinery already present in organisms such as fungi (Rao et al, 2017, Polak et al., 2010). Fungal species are specifically rich in oxidative enzymes such as laccase. Laccases have a wide substrate range and can thus accept different molecules as substrates to produce a plethora of colored products; moreover, results can be obtained only after a few days of cultivation. Fungal species are also a natural source of pigments; these are often produced as a mixture whose composition, and resulting color, can be tuned by tailoring the cultivation conditions (Venil et al. 2020).

Table 1. Examples of the impact of biotechnology on the sustainability of the extended supply chain of the textile industry.

Supply chain part	Example	Reference
RAW MATERIAL	Colorants from plants such as Sweet Cane and Hibiscus	Raza et al., 2018 Prabowo et al., 2022
	Colorants from microbial sources	Santos-Ebinuma, 2013
	Colorants from genetically engineered microbes	Dabai et al., 2021 Cassani et al., 2022
	Colorants from waste products and by products such as food or forestry, even treated wastewater.	Shahid-ul-Islam e al., 2016 Wathon et al., 2019 Montero et al., 2022 Hladnik et al., 2022
MANUFACTURING	Dyeing with water-based colorant solutions	Batool et al., 2018
	Natural mordents	Azeem et al., 2015
	Enzymatic technologies	Smith, 2015
DISPOSAL	Use of renewable materials for adsorption of colorant molecules from effluents	Bhattacharya et al., 2021 Nachiyar et al., 2014
	Biotechnolgical removal of colorants using microrganisms such as mesophilic bacterial, fungi, algae, and others	Prabhakar et al., 2022 Liang et al, 2021 Rani et al., 2014

5. The leadership perspective

Today more than ever organisations and sectors are interconnected and exercise a reciprocal influence in a constant process of exchange and cross-pollination. The advances in biotech and science are therefore only one of many factors that should be considered when addressing sustainability issues. Novel technological solutions and processes cannot be effective without the engagement of all the people involved and an overarching change in strategy that is consistent and supported by all stakeholders. Over the last few decades many industries like the fashion and furniture sectors have pursued growth strategies aimed at achieving high financial returns by producing significant volumes of products and attracting a wider customer base. Unfortunately, this often resulted in high-volume, low-quality products that also have a significant negative impact on the environment (UN, 2018).

The ongoing Covid pandemic and conflict in the Ukraine have also exacerbated a few of the already-existing issues related to supply chain and raw materials sourcing, highlighting the importance of developing reliable and efficient relationships with all parties involved in the production process (KPMG, 2022; Kilpatrick, 2022). This is also an increasingly important factor in the ability to attract new customers and retain existing ones. Consumers, especially those from newer generations, are often much more aware than in the past, when it comes to choosing a product based on factors like carbon footprint, use of natural products and compliance to environmental protection regulations (Lee, 2008, Vătămănescu et al., 2021).

Thanks to documentaries like the River Blue movie in 2017 that draw our attention to phenomena such as the disposal of chemical waste, the consumers' mindset has been shifting towards a focus on quality rather than quantity (Riverblue, 2017). In other words, organisations are under a significantly higher level of scrutiny and need to respond to a demand for change and the adoption of an ethical approach throughout the manufacturing process (Vătămănescu et al., 2021). The alternative is losing part of the consumer base and damaging, often irreversibly, a brand's reputation.

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6. A paradigm shift: sustainable leadership

This also puts additional pressure on organisations to show that they are genuinely adapting their strategies to the changing times and requirements of their consumers and the wider society. This is made even more difficult by phenomena like greenwashing in the fashion industry, which indicates the tendency of certain brands to make misleading claims on the environmentally-friendly nature of their products and production methods and results in consumers being particularly careful when choosing to buy a specific product (Edie Newsroom, 2021). To build a trust-based relationship with these savvy customers, it is not enough for organisations to invest in biotech to find new, better solutions but it is also necessary to show how the whole business supports the change and has a forward-looking strategy. In other words, it is essential that they find a balance between science and leadership. So, when it comes to leaders, how can they make sure that they do that? A successful approach can be summarized in three key points:

1. ***Full commitment.*** Even though Environmental, Social, and Governance (ESG) criteria have been increasingly part of companies' agendas, policies and strategies are often fragmented and only focus on limited aspects of an organisation. In order to adopt processes and techniques that are less harmful for the environment, the consumer and the wider society, it is essential for leaders to encourage a full commitment of financial, human and cultural resources across all business units and functions from procurement and production to finance and reporting.
2. ***A clear strategy and actionable plans.*** It is equally important that there is clarity on short- and long-term objectives as well as action plans necessary to implement it successfully within an organisation. This requires the engagement of employees at all company levels and leaders play a key role in fostering the right mindset and level of commitment to combine the change process with a culture shift.
3. ***Communication.*** Both within and outside an organization, it is critical to devise an effective communication strategy. Employees and customers demand high transparency levels when it comes to the nature of the raw materials used as well as their sourcing and manufacturing. It is therefore key for leaders to manage expectations and provide a consistent, clear message on the strategy adopted and how it will impact customers and the products.

When discussing this topic, many experts speak about sustainable leadership, a concept that refers to an approach that focuses on creating benefits for all stakeholders in both the long- and short-term but also aims at improving the lives of those affected by, or involved in, its work as well as the product end users (Hallinger et al., 2018; Iqbal, 2020). An often-cited example is that of Swedish organisations that make sustainability a central point in the way they operate across all business units, including, for example, procurement, marketing and communication. As a result, they enjoy high levels of trust both within the domestic market and worldwide, which often encourage the creation of a stronger brand image and higher levels of customers' brand loyalty.

7. Conclusion: Can a start-up mindset offer an effective alternative?

Regardless of the type of innovation developed, it is important for businesses to adopt a new mindset and way to operate, in order to survive and stand out from the competition. This radical change is often difficult to be achieved because it entails a significant disruption in traditional business operations, something that proves to be particularly challenging for big corporates. On the other hand, publicly funded investigations have now reached the entrepreneurial scene and many start-ups have emerged. A few notable examples are start-ups such as the French PILI that received a €3.6M funding to use microbes and renewable nutrient sources to produce dyed molecules in 2019 (https://www.pili.bio/). Similarly, French Synovance (https://synovance.com/) has 5 colors ranging from blue to pink in the pipeline and has gathered 50K euros through crowd-funding in 2022. UK-based Colorifix targets agricultural waste products as a source of energy for the conversion of dyes using microbes and as at today has developed 11 different tones (https://colorifix.com/). Furthermore, the startup Allonia (https://allonnia.com/) aims at extracting valuable compounds from wastewaters and has received a $20-million investment in 2021 (Walsh, 2021). It could therefore be argued that sustainability-focused start-ups, play a key role in making the colorants industry greener and encourage a shift towards sustainable practices and production methods.

In conclusion, what can bigger organizations learn from start-ups? Start-ups work as powerful ideas incubators. Free from a few of the constraints typical of big corporates, they not only foster learning and knowledge sharing but they also address issues from a different perspective and encourage the generation of disruptive solutions that often break existing knowledge boundaries. In addition, the agile business model typical of start-ups facilitates lean decision-making and enables this type of organisations to adapt quickly to the changing needs of the market and identify multidisciplinary approaches. On the other hand, what bigger business entities have is accumulated knowledge and experience as well as high levels of investment, power, and influence. In particular, this last point is key. Established businesses could play an instrumental role in leading institutional change and collaborative initiatives across sectors by teaming up with other companies, governments, suppliers and stakeholders from the wider society.

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