DYES FROM DISCARD

UPCYCLING TEA WASTE FOR SUSTAINABLE FABRIC DYEING

Editor:
Vinitha Moolchand Thadhani

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Dyes from Discard: Upcycling Tea Waste for Sustainable Fabric Dyeing

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FOREWORD

Over the past few decades, the textile industry has stood at a crossroads. On one side lies the convenience and low cost of synthetic dyes; on the other, the urgent need to address their environmental and health burdens. Textile dyeing is widely recognized as one of the major contributors to global water pollution, and yet synthetic dyes still dominate commercial practice. Natural dyes, despite their rich heritage, represent only a small share of the market and are often perceived as difficult to scale, inconsistent in shade, or less durable in performance.

The reasons for this imbalance are well known to both researchers and industry professionals: challenges in sustainable sourcing, cost, limited availability, and, crucially, issues of reproducibility and fastness. These very challenges, however, have sparked some of the most creative and impactful research in sustainable colorants. This book, focused on the valorization of tea waste as a fabric dye, is an excellent example of such innovation in action.

Tea is among the most widely consumed beverages worldwide, and tea processing generates large quantities of by-products and waste. While tea (*Camellia sinensis*) has been explored as a natural dye in academic studies, much of this work has remained at the laboratory scale, with limited translation to industrial application. The authors of this volume address precisely this gap. They demonstrate how waste fractions from Ready-to-Drink (RTD) tea manufacturing can be transformed into a robust, scalable, and commercially viable natural dyeing system.

One of the strengths of this book is its clear and logical structure. The opening chapters situate the work within a broader context, tracing the history and rise of synthetic dyes and outlining their impacts on human health and the environment. This is complemented by an accessible overview of contemporary textile dyeing technologies. Together, these chapters provide the reader with a solid foundation for understanding why alternative dyeing approaches are urgently needed.

The book then guides the reader from why to how. It presents a balanced discussion of natural versus synthetic dyes, outlining their respective advantages and limitations, and exploring the role of bio-based textile materials and green chemistry strategies in the fashion and textile sectors. This framing reinforces the idea that dye innovation cannot be isolated from wider efforts to build circular, low-impact textile systems.

At the heart of the volume lies its central contribution: the use of tea waste for sustainable textile coloration. The authors describe in detail how black, oolong, white, and green tea waste streams can be converted into stable dye extracts, explaining the optimization of extraction conditions, application methods, and fastness properties. Importantly, the work does not stop at bench-scale experiments. The narrative follows the process from laboratory studies to pilot trials and then to bulk-scale implementation, offering a rare and valuable roadmap for practitioners interested in moving from concept to practice.

Equally compelling is the way this book embodies the principles of circular economy and industrial symbiosis. By viewing discarded tea fractions from RTD manufacturing as a resource rather than a waste, the authors demonstrate how one industry's by-product can become another's raw material. The fact that the approach has already attracted interest and implementation from reputed brands underscores both its technical soundness and its commercial relevance.

This volume will be of great interest to a wide audience. Researchers and students will appreciate its scientific rigor and clear explanation of process parameters. Textile and fashion professionals will find practical guidance on integrating natural dyes into existing production systems without compromising performance. Sustainability practitioners and circular economy specialists will recognize in this work a concrete example of how waste valorization can be successfully embedded in real industrial contexts.

Ultimately, this book is more than a technical guide; it is a testament to what can be achieved when thoughtful science, meticulous experimentation, and a genuine commitment to sustainability come together. By addressing long-standing barriers such as reproducibility, consistency, and scalability, the authors bring natural dyeing one step closer to mainstream industrial reality.

I am pleased to commend this book to readers and to support its contribution to the advancement of sustainable textile coloration and circular resource use.

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PREFACE

Although textile dyeing is the second-largest polluter of water globally, the market for natural dyes in textiles is growing, driven by increasing consumer demand, environmental and health concerns, and increasingly stringent government regulations associated with synthetic dyes.

Still, the market share of natural dyes is only 5% of that of synthetic dyes. The annual global consumption of synthetic dyes in the textile industry exceeded 650,000 metric tons, while global natural dye consumption annually is only 32,000 metric tons.

Sustainable sourcing, limited availability, and cost, reproducibility of the natural dyeing process, and durability of natural dyes are the primary reasons why the synthetic dye markets still dominate.

Currently, natural indigo, turmeric, and madder are the most frequently used natural dyes in textiles, food, and cosmeceuticals industries. For example, the dry madder stems cost around Rs. 4-7/Kg, but they have only 5-10 % of the active ingredients (pure dye). Incorporating the extraction process cost, the effective cost of madder dye goes up to Rs. 40-140/Kg. Thus, it is challenging to replace the synthetic dyes, which mostly cost under two figures USD per Kg. Considering these factors, natural dyes from waste or industrial by-products are being focused on.

There are ample reports on tea (*Camellia sinensis*) as a natural fabric dye, and few reports on textile dyes from waste tea. However, most of these studies are specialized studies conducted on a laboratory scale, which may not be sufficient for industrial applications. Thus, tea dye has not paved its way to industrial application, even after being the most consumed beverage after water.

Herein, we discuss how tea dye can be obtained from upscaling waste products of the RTD tea manufacturing process, its chemical composition, and the method of application as an effective fabric dye. We also establish its required fastness properties as a fabric dye. Further methods of obtaining different colours using tea dye and minute amounts of synthetic dyes are also discussed. The lab scale results were upscaled to the sample scale and then finally to the bulk scale in the textile industry.

The idea of using waste from one factory as a raw material for another is a win-win scenario, promoting resource efficiency and circular economy principles. The findings of this research have been implemented by various reputable brands worldwide.

The following is a chapter-by-chapter synopsis of the eight chapters of the book.

Chapter 1: History of Natural Dyes and Their Recent Advances

This chapter examines the history of natural dyes from antiquity to the present. The chapter also discusses how contemporary science has improved the natural dye extraction process and its wide application, and how natural dyes are now a vital element of science, sustainability, and creativity.

Chapter 2: Sources of Natural Dyes

This chapter provides a comprehensive overview of natural dyes, demonstrating how their diverse sources, structures, and applications make them valuable for textiles and a wide range of other applications.

Chapter 3: Natural dyes vs Synthetic dyes: Pros, Cons, and Sustainability

This chapter explains how both types of dyes work, how to use them, and how their color strength, consistency, fastness, and ease of use differ. It also highlights the environmental impact and carbon footprint of both types of dyes. Understanding their benefits and drawbacks can assist us in selecting dyeing methods that are more sustainable and efficient.

Chapter 4: Bio-based textile materials towards Green Chemistry in the Fashion Industry

This chapter highlights how more eco-friendly manufacturing procedures can be developed utilizing green chemistry, bioengineering, new dyeing, and recycling approaches for cost-effective production and for limiting greenhouse gas emissions.

Chapter 5: Valorization of Tea Waste for Sustainable Fabric Dye

This chapter presents a comprehensive study of the innovative process of transforming the tea waste of black, oolong, white, and green leaves into a sustainable fabric dye. Furthermore, the parameters for optimizing the tea extraction process are discussed.

Chapter 6: Method of Application of Waste Tea Dye

The chapter presents a refined approach that integrates the functional properties of tea with traditional dyeing techniques, covering substrate pretreatment, different dyeing methods, and post-treatment.

Chapter 7: A success story of Transforming Ready-to-Drink Tea waste into fabric dye

This study establishes the discarded phenolic fraction of the Ready to Drink (RTD) tea manufacturing process as a fabric dye with the required fastness properties, offering insights for researchers, circular engineers, and industries, and presenting a sustainable alternative method for using waste tea as a dye in the textile sector.

Further, the main challenges of commercial application of natural dyes, namely, supply chain, cost, reproducibility, and consistency, have been overcome by utilizing the waste of the RTD manufacturing plant.

This book is the culmination of all the know-how of using tea waste as a sustainable fabric dye. We hope it will help our readers immensely by disseminating scientific knowledge to them step by step.

We wish to sincerely thank Bentham Publications for providing a platform for the dissemination of the information published in this book to a broad audience. We are also very thankful to every author for their essential contributions that have made our journey worthwhile.

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CHAPTER 1

History of Natural Dyes and Their Recent Advances

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Abstract: This chapter explores the historical journey of natural dyes from ancient times to modern times. The use of natural dyes dates back to ancient societies, especially those in the Mediterranean, North Africa, Nigeria, South America, and Europe. Colorful fabrics for clothing, rituals, and commerce were created by people in these areas using plants, minerals, and insects. Various methods for extracting dyes and extending the life of colors were developed over time, utilizing compounds known as mordants. The chapter also discusses how contemporary science has utilized these dyes to enhance the process of extracting and utilizing them. Techniques such as microwave-assisted and supercritical fluid extraction enable us to extract more dye in less time and with fewer chemicals. These innovative methods are safer for both humans and the environment. Natural dyes are now utilized in various industries, including textiles, pharmaceuticals, solar technology, and food production. They find applications in cancer therapies, UV-protective materials, sensors, and solar cells. This chapter demonstrates how natural dyes, with their long and rich history, are now a vital element of science, sustainability, and creativity.

Keywords: Cochineal, Deodorizing finishing, Mordants, Moth resistant, Natural dyes.

INTRODUCTION

Natural dyes are colorants derived from natural ingredients, including leaves, roots, bark, flowers, fruits, minerals, and even insects. Long before the development of synthetic dyes, people around the globe utilized natural dyes to

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color their clothing, paint items, and represent their culture and beliefs. Natural dyeing was a traditional art practiced by generations in North Africa, Nigeria, South America, and Europe.

Historically, manufacturing and utilizing these dyes requires a significant amount of time and effort. To remove the color, they had to boil or soak the plants for several days. They employed mordants to keep the color on the fabric. These allowed the dye to adhere to the textile, increasing the color's brilliance and longevity. Mordants used in different regions ranged from metal salts to plant-based solutions.

As time passed, researchers began to seek more effective techniques to simplify and enhance the natural dyeing efficiency. They developed new extraction techniques, such as solid-phase microextraction and microwave-assisted extraction, which save time and reduce the use of hazardous chemicals. These approaches also make the dyeing process more environmentally friendly.

Today, natural colors are utilized for more than simply garments. They are being utilized in various exciting new applications, including natural colorants in food, medical imaging, antibacterial materials, and solar panels. This chapter discusses the rich history, scientific advancements, and many present applications of natural dyes.

HISTORY OF NATURAL DYES

Natural dyes have had a significant impact on shaping and rewriting history around the world. They bear an important historical witness that broadens the horizon, allowing us to look back at the wonderful past and forward to an optimistic future [1]. For thousands of years, natural dyes have been a popular choice for coloring textiles, food, and various products due to their eco-friendliness, accessibility, cost-effectiveness, and safety [2].

From the dawn of humanity, nature has consistently prevailed over synthetic materials, as those were the sole options available. Now that naturally created materials outperform synthetics, they are prioritized. Color has consistently influenced the evolution of diverse human cultures across the globe. It influences all aspects of our lives, greatly shaping the clothing we choose and the furnishings in our homes. In the past, artists have traditionally used natural dyes derived from minerals, mollusks, insects, and plants in their works [3]. A brief history of natural dyes is depicted in Fig. (**1**).

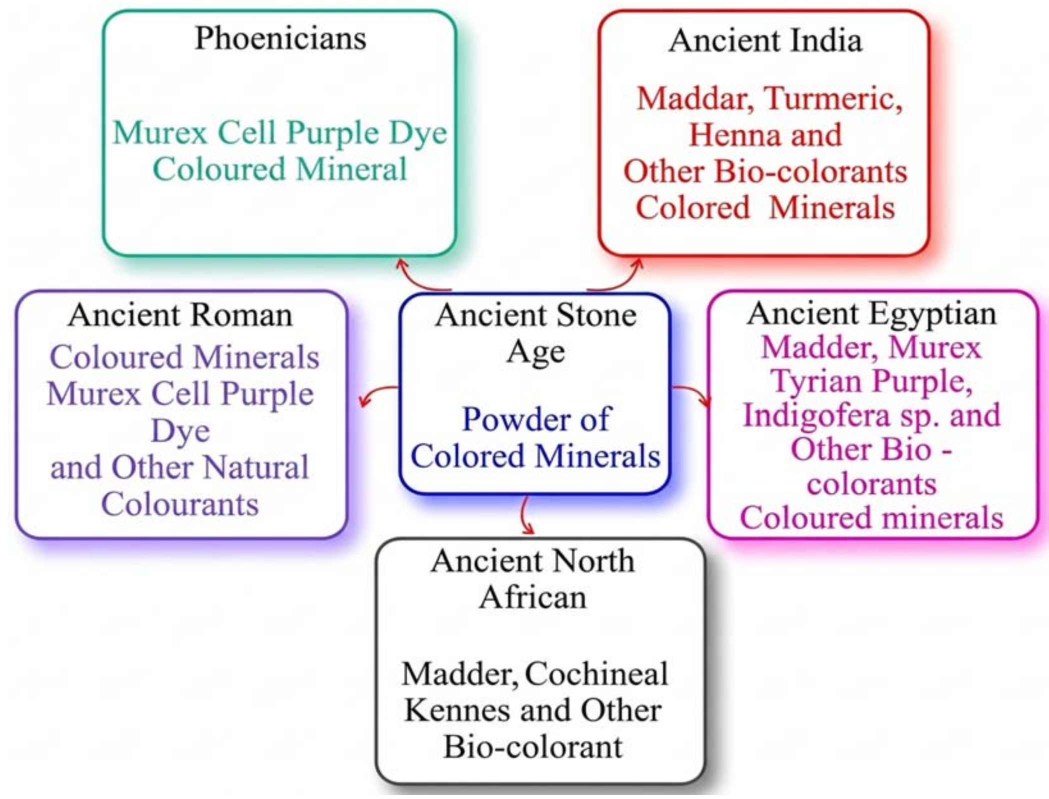

Fig. (1). A brief history of natural dyes.

History of Natural Dyes in the Ancient Mediterranean World

Ancient Mediterranean iconography gives a wealth of information about the intricate and colorful world of textiles. The 'Ancient Mediterranean', a broad term referring to a period from the Bronze Age to the late Roman Empire (1500 BCE-500 CE), indicates a time of substantial cultural and political interaction between Southern Europe, Western Asia, and North Africa [4]. Plant roots, insects, and sea snails provided a wide range of natural hues to ancient Mediterranean civilizations. Expertise and understanding are required for dye extraction and application. The colorants were used as both dyes and dye pigments, with the majority being dye lakes. Important groups of ancient dyes were anthraquinone reds (*Kermes vermilio*, *Rubia tinctorum*), redwoods (*Caesalpinia sappan*), and flavylium/anthocyanin reds (*e.g.*, *Dracaena draco*); indigo (*e.g.*, *Indigofera tinctoria*) and anthocyanins (*Commelina communis*) for blue; Tyrian purple (*e.g.*, *Purpura*, *Murex brandaris*), orchil (*e.g.*, *Roccella* sp.), and folium purple (*Chrozophora tinctoria*); and flavonoid (*e.g.*, *Reseda luteola*), carotenoid (*Crocus sativus*), and chalcone/aurone (*Coreopsis* sp.) yellows [5].

CHAPTER 2

Sources of Natural Dyes

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Abstract: This chapter describes the origins of natural dyes, their diverse varieties, and the mechanisms by which they act. Minerals, plants, animals, and even microscopic living things like fungi and bacteria can be used to make natural dyes. Every source has its benefits and drawbacks, offering a range of perspectives.

This chapter categorizes various natural dyes—including flavonoids, tannins, carotenoids, and anthraquinones—by their chemical composition, explaining how these structures determine the resulting color's hue and intensity. Another approach to categorizing dyes is by application method; some require specific fixing agents or mordants, while others can be applied straight.

A straightforward explanation of the science underlying dyes' ability to adhere to textiles and how their molecules impart color is provided. This chapter provides a comprehensive overview of natural dyes, demonstrating how their diverse sources, structures, and applications make them valuable for textiles and a wide range of other applications.

Keywords: Disperse Dye, Henna, Indigoid, Lichens, Tyrian purple, Tannins.

INTRODUCTION

For millennia, people have used natural dyes to color textiles, food, and other objects. They come from naturally existing sources, such as microorganisms, minerals, plants, and animals. These dyes are more environmentally friendly than synthetic ones, and their popularity is rising as consumers want more sustainable

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and eco-friendly products. The most prevalent source of natural dyes is plants. Their colors are obtained from leaves, roots, flowers, fruits, seeds, and bark. For instance, turmeric imparts a yellow hue, and indigo is derived from indigo plants. Depending on the growth environment, their color may fade more quickly, and the dye production may change. They are generally accessible, biodegradable, and renewable.

Natural dyes are also produced by certain insects and marine life. Carmine is a vivid red dye produced by cochineal insects. Sea snails are the source of Tyrian purple. Although these colors are rich and durable, some users may have ethical questions about them. These are derived from soil and rocks with natural colors. Examples are blue from azurite, yellow from ochre, and red from cinnabar. They are less colorful than plant or animal dyes, but they are more stable and long-lasting. Some fungi and bacteria have the ability to create colors spontaneously. These can be cultivated in laboratories and utilized for textiles and other purposes in the future; however, research is currently ongoing. Flavonoids, tannins, and carotenoids are examples of natural colors that can be categorized based on their chemical structures. These structures determine each dye's color and fabric-retention properties. Lastly, dyes can be categorized based on their intended function. Some can be used straight away, while others require a mordant to fix the color. Selecting the appropriate dye for each material is made easier by being aware of these variations.

SOURCES OF NATURAL DYES

Dyeing is as ancient as human culture. Natural dyes were exclusively employed to color fabrics from antiquity until the eighteenth century. Natural resources are the source of natural dyes, as the name implies. To color a variety of textile fabrics, coloring agents derived from natural resources of plant, animal, mineral, and microbiological origin were employed. Traditional methods of natural dyeing were practiced in several parts of the world, utilizing local natural resources [1, 2].

Types of Natural Dyes

Natural dyes have been categorized according to their chemical structure, application techniques, and sources of production or origin [3]. The classification chart for natural colorants is shown in Fig. (**1**).

Based on Origin Sources

Even though plants are the primary source of natural dyes, these substances can be roughly categorized as plant, animal, mineral, or microbial colors depending on where they come from. Many researchers documented and compiled traditional dyeing techniques in many countries, as well as gathered knowledge from ancient texts, as interest in natural dyes rose. Below is a brief summary of the possible dye resources arranged by their place of origin [4]. Fig. (**2**) shows the classification of natural dyes based on their origin sources.

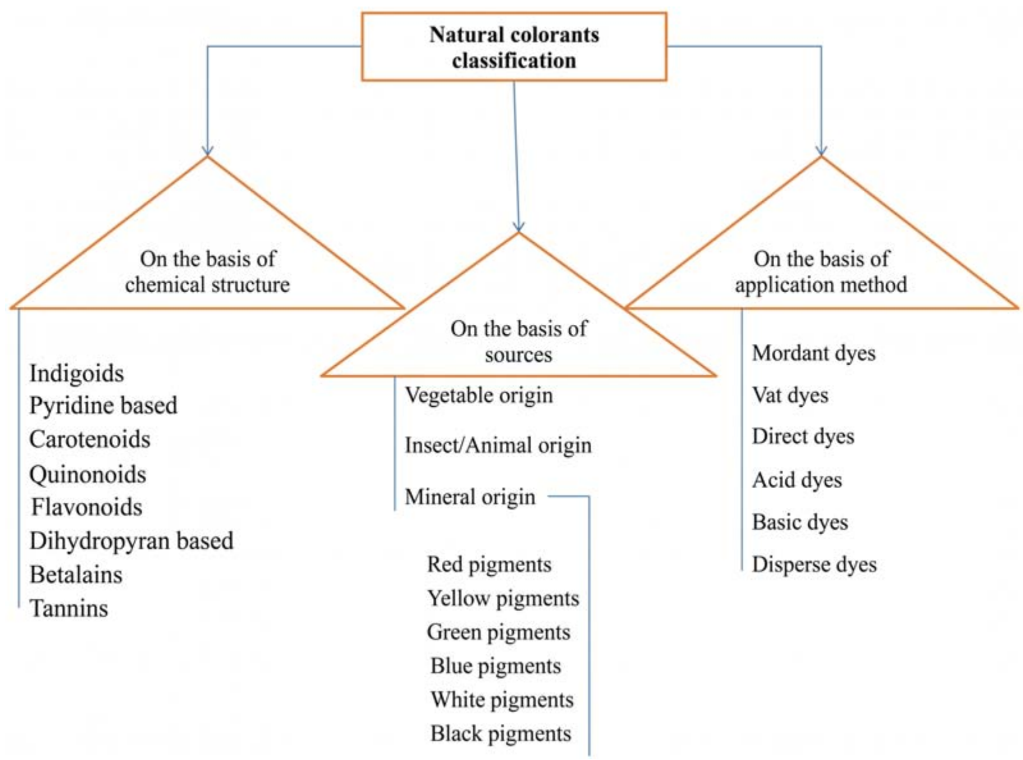

Fig. (1). Classification chart for natural colorants.

Plants

The vast majority of natural dyes have historically been extracted from plants. Roots, leaves, twigs, stems, heartwood, bark, wood shavings, flowers, fruits, rinds, hulls, husks, and other plant parts can all be used as natural dyes [3].

In many civilizations, plant-based dyes have long been used to color textiles, crafts, and artwork. These dyes come from a variety of plant parts, such as the roots, leaves, stems, flowers, and fruits, as well as from the biomass of the plants that yield a broad spectrum of hues. Numerous plant species are well known for their vivid and unique hues, which have been used to dye clothing, cosmetics, and other items. These plants' active chemical components are frequently what give them their hues. Indigo, madder, turmeric, henna, logwood, onion, black walnut,

CHAPTER 3

Natural Dyes *vs.* Synthetic Dyes: Pros, Cons, and Sustainability

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Abstract: This chapter examines the characteristics, benefits, drawbacks, and effects on the environment of natural and synthetic dyes. Natural dyes are derived from minerals, plants, and animals, whereas synthetic dyes are created in labs using chemicals. This chapter describes how both kinds of dyes function, how to apply them, and how their color strength, fastness, consistency, and simplicity of use vary. It also draws attention to the effect of both dyes on the environment and carbon footprint. Knowing their advantages and disadvantages can help us choose more effective and sustainable dying techniques.

Keywords: Color fastness, C footprinting, Greenhouse gases, Natural fibers, Synthetic dyes.

INTRODUCTION

Textiles, paper, food, and other objects can be colored with dyes. Natural dyes, which are derived from nature, and synthetic dyes, which humans create through chemical processes, are the two primary categories of dyes. Each has special qualities and applications. Minerals, microbes, plants, and animals can all be used to make natural dyes. Although they are renewable, biodegradable, and less damaging to the environment, they might not provide vibrant, long-lasting color without proper care. Because of their wide range, vibrant hues, and reliable performance, synthetic dyes are produced in laboratories and are used extensively

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in the textile industry. But they frequently use hazardous substances that can contaminate the environment. In this chapter, natural and synthetic dyes are compared according to their manufacturing processes, ease of application, consistency, and environmental impact. It assists readers in weighing the benefits and drawbacks of each and determining which is best suited for specific uses.

Before the first synthetic dye was discovered in 1856, the only dyes that humans could use to color fabrics were those made from natural materials, including plant leaves, roots, bark, insect secretions, and minerals. Rapid advancements in synthetic chemistry, aided by the industrialization of textile production, produced a variety of synthetic dyes in a wide range of hues and colors that eventually drove natural dyes to extinction, in addition to creating synthetic substitutes for widely used natural dyes. However, in the final decades of the 20th century, consumer interest in natural dyes was once again rekindled by environmental concerns surrounding the manufacture and use of synthetic dyes. There is already a niche market for fabrics dyed with natural dyes, which are preferred by people who care about the environment. However, because of specific technical and sustainability issues with their production and application, such as their limited and non-reproducible shades, unsuitability for machine use, and lack of readily available standard forms, the overall share of natural dyes in the textile industry is only about 1%. Although natural dyes are sustainable in and of themselves because they are biodegradable and renewable, the textile industry's enormous demand cannot be met by them due to the preferential use of land for food and feed. Additionally, overusing natural resources to make colors might imperil endangered species and cause deforestation. Because of these factors, the Global Organic Textiles Standard (GOTS) forbids the use of natural colors derived from endangered species while allowing the use of safe synthetic dyes. Given their enormous environmental benefits, numerous research projects have been conducted worldwide to address the drawbacks of natural dyes [1].

Fundamentals of Natural Dyes and Synthetic Dyes

The chemical makeup of various materials determines how intensely they color, and dye is a substance that can bind to other substances. The earliest coloring agents were from plants (foh, indigo, *etc*.) and animals (*e.g*., cochineal). Nowadays, dyes have been produced, especially those with basic and acidic characteristics, and they are employed in food and clothes. Natural dyes and synthetic dyes, which are categorized into several varieties such as azo, carmine, and saffron, are the two categories of dyes. In practically every aspect of our everyday lives, dyes are used to color clothing, food, cosmetics, paper, and other materials. For almost 4,000 years, textile dyes have been made from natural plant, animal, and mineral pigments [2].

Natural Dyes

In essence, dye is a color that is typically applied to various materials to stain them. Around 2600 BC, the first natural dye was discovered. Natural pigments were first combined with water or oil as a foundation to create colors. Plants (like indigo and saffron), insects (like cochineal beetles and lac scale insects), animals (like particular species of mollusks or shellfish), microbes (like pseudomonas, bacillus, and rhodococcus), and minerals (like ferrous sulphate, ochre, and clay) can all be used to make natural dyes without the need for chemicals [3].

Nearly every kind of natural fabric may be dyed using natural dyes. They can also be used to dye certain synthetic textiles, according to recent studies. In addition to being utilized in textiles, natural dyes are also employed in the coloring of food, medications, toys, handicrafts, and leather. Many plants that produce dye are also used as medicines in a variety of traditional medical systems [1]. Natural colorants have the following advantages as compared to synthetic colorants, but natural dyes have some disadvantages too.

Natural dyes are non-toxic, non-polluting, less harmful to health, and non-carcinogenic. Compared to synthetic dyes, the majority of natural dyes are regarded as environmentally beneficial since they are generated from renewable resources (derived from non-renewable petroleum resources and synthesized in an intermediate route involving many chemical hazards). They produce a calming shade, have colors that harmonise, and are delicate, soft, and subtle.

In contrast to the non-renewable fundamental raw materials used in synthetic dyes, natural colors derived from plants are typically agro-renewable or vegetable-based goods that are also biodegradable. Numerous benefits of natural dyes include their non-toxicity, environmental friendliness, eye-pleasing hue, unique scent, and freshness of shade. Simple extraction and purification, no production of wastewater, Renewable resources, mild dyeing conditions, and extremely high sustainability [4]. Numerous natural dyes and finishing chemicals have antibacterial and UV-protective properties. Thus, natural textiles that are dyed with appropriate natural colorants and polished with particular natural finishing agents can offer defense against UV radiation, bacteria, and even mosquito bites. As with Ayurvedic medicine, natural dyes such as myrobalan, turmeric, madder/manjistha (MJ), Arjuna, safflower, *etc*., have therapeutic benefits [5]. With a mix-and-match technique, natural dyestuffs can also create a vast array of hues. Numerous new hues can be produced with a very slight change in the dyeing method, the use of different mordants with the same dye, or the application of varied mordant concentrations on the same dye [6].

CHAPTER 4

Bio-based Textile Materials Towards Green Chemistry in the Fashion Industry

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Abstract: The fashion industry has a significant impact on the environment and society, largely due to the prevalence of fast fashion, complex supply chains, and substantial textile waste. Substituting sustainable methods, such as using eco-friendly materials and recycling, is essential to reduce pollution, resource use, and environmental damage. Textile materials made from renewable sources, such as plants and microorganisms, are a good substitute for synthetic fibers because they break down naturally and have a lower carbon footprint. Development in green chemistry, bioengineering, and new dyeing and recycling approaches also helps create more eco-friendly manufacturing procedures. Although there are challenges such as recycling mixed fibers and high expenses, continued research, industry cooperation, and effective government policies are crucial for developing a sustainable textile industry. Using these eco-friendly plans can significantly lower the industry's impact on the environment and support worldwide efforts to achieve conservation, sustainability, and responsible consumption.

Keywords: Bio-based fibers, Environmental impact, Eco-friendly, Green chemistry, Sustainable textile.

INTRODUCTION

The fashion industry is increasingly in the spotlight and plays a significant role in global environmental and social issues. Life Cycle Assessment is a standard tool used to study the ecological impacts of all stages of a product's life [1].

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Vinitha Moolchand Thadhani (Ed.)

OVERVIEW OF THE FASHION INDUSTRY'S ENVIRONMENTAL IMPACT

Over the past few decades, the fashion industry has seen significant shifts in trends. It has evolved into a complex, widespread, and global network primarily focused on encouraging people to constantly buy new items and dispose of old ones. The rise of "fast fashion" encourages people to quickly replace their clothing as trends change rapidly. This business model has significant negative impacts on the environment and society, especially for workers involved in manufacturing. To reduce costs, companies often produce clothing in developing countries where labor is inexpensive and environmental and social regulations are less stringent [2, 3]. Declining clothing prices and faster production cycles, along with poor quality and planned obsolescence, have led to an increase in the global volume of consumer clothing [4]. There are significant problems with clothing waste, as most clothing and textile waste ends up in landfills.

Recycling or Reusing [2, 4]: In 2000, global clothing sales were $1 trillion, with one-third of sales in Western Europe, one-third in North America, and one-quarter in Asia [2]. This not only increases the extent of environmental impacts, but also exacerbates the issues of disposing of the large amounts of textile waste produced. In the 1990s, the fashion industry faced a public backlash due to the lack of social responsibility and accountability among factories located in developing countries [1]. Negative publicity about "sweatshop" labor pushed the fashion industry to create codes of conduct, sourcing policies, and Corporate Social Responsibility (CSR) practices [1, 5]. Like many other industries, fashion increasingly recognizes that companies have responsibilities to a wide range of stakeholders. These concepts have become integrated into the management and operation of many fashion companies, as considering stakeholders and analyzing their needs has been linked to improved organizational performance [6]. Growing awareness and stakeholder concerns have prompted the fashion industry to gradually address the environmental and social effects of its production [7]. Although "green" fashion was initially criticized in the early 1990s for being expensive and low quality, the past decade has seen the rise of "eco-fashion" (or "sustainable fashion"), which suggests a commitment to sustainability.

While terms like "ethical," "green," and "eco" lack standardized definitions within the industry, their frequent use suggests that more brands are attempting to attract mainstream customers with sustainable clothing. Successful ethical brands, such as People Tree, American Apparel, and Edun, have emerged. Major retailers, including H&M, Nike, Levi's, and Zara, have also introduced products made with eco-friendly materials such as organic cotton, Tencel, and recycled polyester [1].

Importance of Sustainability in Textiles

The clothing and textile industry is a global polluter facing complex and interconnected sustainability problems. It's a key topic in discussions about climate change, chemical use, water shortages, and human rights. The way we produce and consume textiles and clothing raises questions about our political, social, and economic lives. These challenges stem from shared social and personal habits and conflicting values related to production and consumption. Many different groups are involved, including corporations, governments, non-profit organizations, media outlets, and individuals.

While technology can solve some problems, others require action from consumers, NGOs, governments, and businesses on a global scale. Businesses and consumers are particularly important because of the nature of the textile and fast fashion industries. Policymakers and activists are considering how to encourage businesses and consumers to take responsibility, voluntarily improve sustainability, or even be required to change their behaviors. The fundamental question is how much responsibility they can take for ensuring sustainable textile and clothing production.

Researchers stress that the problems in global textile and clothing production are very complex. Beyond technological improvements, changing behaviors and habits requires changing the values associated with production and consumption, while considering diverse cultural, geographical, and political contexts [8].

Environmental sustainability is crucial for the textile and apparel industry, which makes a significant contribution to socio-economic development in developing countries [8 - 10]. For instance, cotton textile production employs seven percent of the workforce in these countries [11, 12]. However, textile production consumes substantial resources and can cause severe environmental damage. Therefore, businesses should prioritize environmental sustainability, striking a balance between economic efficiency and environmental impact [13 - 15]. The concept of environmental sustainability originates from sustainable development [16, 17], which acknowledges the interconnectedness of environmental, economic, and social sustainability [18, 19]. While environmental issues are the initial focus of environmental sustainability assessments, economic and social factors are also essential. Research emphasizes the importance of considering all these factors together when evaluating environmental sustainability [20 - 22].

The fashion industry is a major polluter, second only to the oil industry. To address this, the EU launched the “European Clothing Action Plan” in 2019. This initiative aims to make the textile industry more sustainable, from the design stage to the disposal of clothing. A significant issue is the substantial amount of textile

CHAPTER 5

Valorization of Tea Waste for Sustainable Fabric Dye

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Abstract: The textile sector is significantly dependent on synthetic dyes, which lead to considerable negative environmental impacts, including water contamination, the accumulation of hazardous chemicals, and health risks for workers. With the increasing demand for environmentally friendly and sustainable dyeing methods, natural dyes from waste materials present promising alternatives. This chapter presents a comprehensive study of transforming tea waste of black, oolong, white, and green leaves into a sustainable fabric dye, serving as a viable alternative to synthetic dyes within the textile industry. It reviews the chemical constituents of tea leaves, compares different extraction methods, and analyzes key process parameters that influence color yield. The chapter evaluates key extraction parameters that influence dye yield and color intensity, providing guidance on how to optimize these variables for improved performance. The application of extracted dye on textile substrates, along with its limitations and future potential, is also discussed. Additionally, recent advances such as far-infrared and gamma irradiation pretreatments are highlighted for their potential to enhance pigment availability and improve extract color characteristics, offering new opportunities for strengthening tea-waste-based dye systems. Overall, the findings indicate that optimized tea-waste dyes provide stable coloration and offer a viable pathway toward sustainable textile production.

Keywords: Aqueous extraction, Antioxidant, Eco-friendly dyeing, Dyeing using spent tea, Phenolic compounds, Tea.

INTRODUCTION

The textile industry has recently transitioned towards sustainable dyeing practices in response to the release of highly toxic chemicals, synthetic dyes, and hazardous metallic elements into water from traditional dyeing methods. Each year, the con-

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ventional dyeing process utilizes approximately 100,000 distinct dyes, resulting in the generation of around 300,000 tons of wastewater that increases the levels of BOD, COD, TDS, and TSS in the water [1 - 5]. This environmental challenge has led to an urgent demand for alternative dyeing techniques that align with the principles of a circular economy and meet the growing global sustainability objectives.

The emergence of the circular economy highlights the importance of resource efficiency and waste valorization, aiming to mitigate environmental impact while concurrently enhancing the value of waste materials [6, 7]. Due to its polyphenols, tannins, and natural pigments, *Camellia sinensis*, tea, which is one of the most frequently consumed beverages, has the potential to be utilized as a dye. Consequently, it is an untapped resource for producing eco-friendly dyes [8, 9]. Several studies have demonstrated that the dye extracted from tea can serve as an effective colorant for fabric dyeing, enhancing color strength and providing remarkable color fastness against washing, rubbing, and light exposure on cotton, jute, and wool fabric [9 - 13]. Additionally, the extracted dyes improve the biodegradability of the dyed fabric. Several methods, such as Solvent Extraction (SE), Pressurized Extraction (PE), Ultrasound-Assisted Extraction (UAE), Soxhlet Extraction (SoE), Supercritical Fluid Extraction (SFE), and Enzymatic Extraction (EE), are employed to extract dyes from tea waste, including spent tea leaves derived from black, white, oolong, and green tea. These methods use water and ethanol as solvents [14]. Tea waste is the byproduct produced during the manufacturing processes of different tea varieties, such as green, white, black, and oolong. The byproduct comprises the leaves, stalks, and stems that are eliminated during the manufacturing process. Furthermore, spent tea is commonly known as tea waste, which involves drying tea leaves following the steeping process in hot water [15]. Utilized tea bags and leaves fall under the classification of tea waste [16]. Additionally, leaves and stems obtained from the factory or the farmer that are not used in tea production are classified as tea waste [17, 18]. The waste from this tea is utilized for dye extraction through the specified extraction method. So, optimizing various extraction parameters, such as temperature, concentration, pressure, and the material-to-liquor (M: L) ratio, is crucial for enhancing the extracted dye's color fastness and color strength characteristics. Modern statistical optimization approaches, such as Response Surface Methodology (RSM), are used to allow systematic investigation of multiple interacting variables with fewer experiments than traditional methods [19 - 21].

This chapter explores the potential of tea waste, including black, oolong, white, and green, collected from households, factories, and farmers as a natural dye source, positioning it as a viable alternative to synthetic dyes. It begins by discussing the various types of tea and their chemical compositions, highlighting their antimicrobial properties and potential benefits against UV radiation. The chapter then covers several extraction techniques, including aqueous extraction, ultrasound-assisted extraction, and microwave-assisted extraction. Subsequently, optimized parameters for upscaling tea waste (black, green, oolong, and white) into a sustainable dye and its application to various fabrics are examined. Furthermore, various empirical studies and recent developments are discussed, establishing a clear framework for the broader use of dyes derived from tea waste in the textile sector. Additionally, the chapter examines the collection of tea waste from households, factories, and agricultural producers.

TEA WASTE: COMPONENTS AND DYE POTENTIAL

Types of Tea Waste and Their Bioactive Components

Tea waste contains lignocellulosic biomass, including lignin, cellulose, hemicellulose, and catechins (Fig. **1**), along with amino acids, carbohydrates, caffeine, and other bioactive compounds (Table **1)** [14, 22]. The composition of tea waste typically matches that of regular tea [23], exhibiting comparable quantities of its constituents [22, 24]. Among various tea types, green tea is particularly rich in catechins, amino acids, and carbohydrates. It also contains smaller amounts of lipids, caffeine, and polyphenols [25]. Oolong tea contains 22.7% protein, 17.5% lignin, 17.5% cellulose, and small quantities of purine alkaloids and polyphenols [26, 27]. Black tea is characterized by its significant concentration of polyphenolic compounds, catechins, and caffeine. Black tea contains hot water-soluble polysaccharides and proteins, and hot water-insoluble proteins [28, 29].

Table 1. Chemical composition of various types of tea [23].

Types of Tea	Components	% (w/w) of Dry Biomass	Refs.
Green tea	• Catechins • Amino acids • Carbohydrates • Other polyphenols • Caffeine and others • Lipid	30 12 11 4 3 3	[25]
Oolong tea	• Protein • Lignin • Cellulose • Hemicellulose • Purine alkaloids • Polyphenols	 22.7 19.5 17.5 16.4 	[26, 27]

CHAPTER 6

Method of Application of Waste Tea Dye

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Abstract: The use of tea waste as a natural dye offers sustainable and eco-friendly methods for dyeing. These methods serve as an effective alternative to synthetic dyes, decreasing toxicity and promoting a circular economy through the reduction of industrial waste. This chapter outlines a structured process for extracting and applying tea-derived dyes to cotton, silk, wool, and flax, covering substrate preparation, dyeing, and post-dyeing treatments. Experimental findings across multiple studies consistently show improved dye uptake, higher color strength, and enhanced wash and rubbing fastness when optimized pretreatments—such as tannic acid treatment, cationization, enzymatic bioscouring, plasma, or UV-assisted modification are applied. Advanced dyeing approaches, including solvent extraction, ultrasound-, microwave-, and plasma-assisted dyeing, further contribute to greater coloration efficiency and reduced chemical demand, despite variations in dyeing conditions among different investigations. In summary, waste tea demonstrates clear, measurable improvements in color performance and environmental impact. This chapter provides a structured pathway for its application and establishes waste tea as a practical and sustainable dye source for future textile processing.

Keywords: Circular economy, Green tea waste, Natural dyeing, Sustainability, Tea waste.

INTRODUCTION

Natural dyes have been utilized since the Stone Age, with many ancient civilizations, including Indian, Egyptian, Roman, and Greek, employing them in various applications [1 - 3]. The synthesis of synthetic dyes in 1856 led to a decline in the use of natural dyes due to the lower cost, greater durability, wider color range, the inability of natural sources to meet the growing dye demand driven by increased textile production, and ease of application associated with

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synthetic dyes [4]. Synthetic dyes bring toxicity and environmental concerns due to the presence of heavy metals and carcinogens, which pose health risks. Consequently, it is banned in several nations [5 - 9]. The utilization of natural dyes extracted from plants, minerals, and animal sources is increased because natural dyes are biodegradable, renewable, and environmentally friendly [10].

Tea (*Camellia sinensis*) serves as a sustainable and natural dye source. The composition primarily includes phenolic compounds like catechins and flavonoids. Within the flavonoid family, therubigins and theaflavins are the main natural dyeing agents for natural fabrics. The primary coloring pigment responsible for the brown color in fabrics is catechin, a naturally occurring pigment found in tea leaves [11 - 13]. The dye is extracted from tea and utilized to dye cellulosic fabric. Microwave irradiation and ultrasound mechanisms are utilized for extraction. Various dyeing methods, including ultrasound and microwave-assisted dyeing, mordant dyeing, pad-stream dyeing, and simultaneous dyeing, are employed, with fabrics undergoing pre- and post-treatment processes [14 - 16].

Tea leaves serve a dual role in the dyeing process, acting both as a natural dye and a mordant, thereby eliminating the need for synthetic or metal-based mordants. This is due to the presence of tannins, which have inherent mordanting properties that enhance dye fixation on fabrics. The natural tannins in tea form strong complexes with textile fibers, improving the uptake and retention of color. As a result, fabrics dyed with tea exhibit enhanced color fastness properties, making them more resistant to washing and light exposure. However, to further improve the durability and depth of the color, heavy metal mordants such as alum, copper sulfate ($CuSO_4$), and ferrous sulfate ($FeSO_4$) are sometimes employed. These mordanting agents create stronger bonds between the dye and the fabric, resulting in richer shades and improved resistance to fading over time [1, 16, 17].

Furthermore, advanced techniques such as cationization, pre- and post-mordanting, pad-stream dyeing, microwave-assisted dyeing, and dip-dyeing have been utilized to enhance the colorimetric properties of tea-dyed fabrics. These methods improve dye uptake, color uniformity, and fastness, ensuring deeper and more stable shades on textile fibers [12, 15, 18, 19].

This chapter examines practical methodologies for applying waste tea-derived dyes to various fabrics, including cotton, wool, silk, and flax. It emphasizes sustainable and efficient techniques suitable for small-scale artisanal use and industrial application. The outline of the method of application of the waste tea dye is shown in Fig. (**1**). The potential of tea waste as a natural dye is recognized; however, standardized protocols for its extraction, application, and fixation are still lacking. This discussion covers various dyeing methods, including fabric preparation and post-treatment techniques to improve dyed fabrics' color fastness and intensity. This chapter connects theoretical knowledge with practical application, providing researchers, textile engineers, and eco-conscious industries with strategies to utilize waste tea as an eco-friendly alternative to synthetic dyes, promoting circular economy principles in material design.

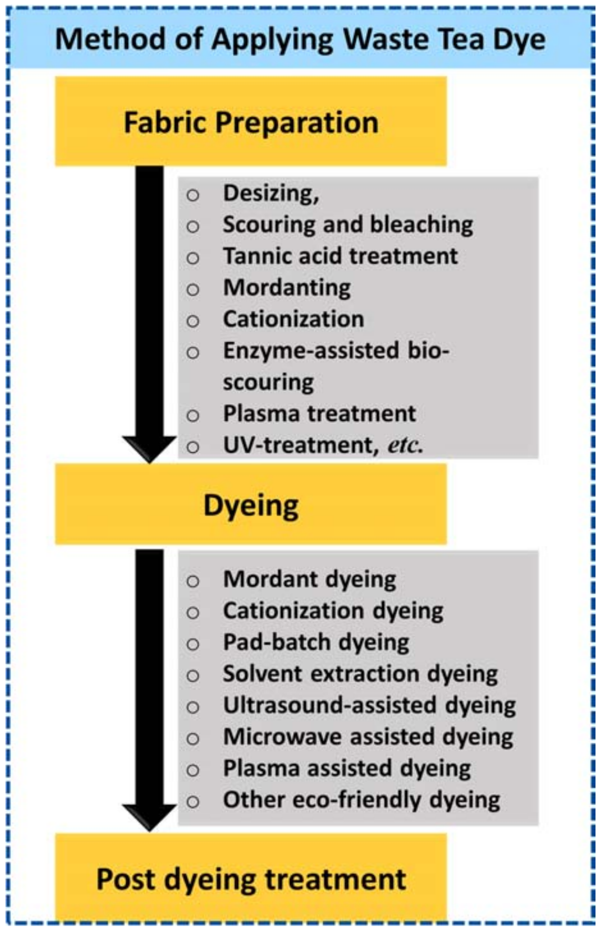

Fig. (1). Outline of the method of applying waste tea dye.

METHOD FOR APPLYING WASTE TEA DYE

Fabric Preparation

Proper fabric preparation is essential to ensure effective dye absorption. Before dyeing, impurities such as oil, dirt, and dust must be removed from the fabric surface. In woven cotton fabrics, starch is commonly applied to the warp and weft

CHAPTER 7

A Success Story of Transforming Ready to Drink Tea Waste into Fabric Dye

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Abstract: Numerous studies on the natural dyeing methods of tea (*Camellia sinensis*) for different textile materials can be found in the literature. Furthermore, there are only a few studies in the literature that specifically focus on the textile dyes generated from tea waste. However, for industrial applications, specialist laboratory-scale research might not be enough. This study establishes the discarded phenolic fraction of the Ready To Drink (RTD) tea manufacturing process as an effective fabric dye, at an industrial scale for cotton, linen, nylon, wool, and their blends, with an effective concentration of tea dye ranging from 1-10%, depending on the fabric type and desired colour. The method was exaggerated to obtain different shades with the required fastness properties.

Unlike acid, disperse, and reactive dyes, utilizing waste as an effective fabric dye results in negative CO_2 emissions.

Further, the main challenges of commercial application of Tea as a natural dye, namely, supply chain, cost, reproducibility, and consistency, have been overcome by utilizing waste generated from the world's largest RTD manufacturing plant. The technology has been commercialized and adopted by numerous reputable textile brands worldwide.

Keywords: Cost-effective, Chitosan, Fastness-properties, Ready to Drink, Sustainable, Tea waste.

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INTRODUCTION

The gigantic global textile industry is the second-highest greenhouse gas emitter after the oil industry. The textile industry generates around $ 1 trillion, comprises 7% of the total world exports, and employs around 35 million workers worldwide [1, 2]. Simultaneously, it is responsible for 8% of global carbon emissions and 20% of global clean water pollution, with an anticipated 50% increase in greenhouse gas emissions by 2030 [3]. Synthetic dyes are a significant contributor to the carbon footprint and water pollution associated with the textile industry. Annual synthetic dye production worldwide is estimated to be 7×10^{5} tons [4], with a market share of USD 17.6 billion in 2023. It is projected to grow from USD 19.5 billion in 2024 to $21.79 billion in 2025, at a Compound Annual Growth Rate (CAGR) of 11.5% [5], despite its significant environmental impact.

Therefore, a ban on textiles based on non-eco-friendly synthetic dyes is being enforced. This has driven global research towards replacing synthetic dyes with natural colours which can come from biodegradable natural sources including from Catechu, Gamboge tree, Indigofera leaves, Tea leaves, Coffee beans, Madder root, Chestnut hulls, Walnut hulls, Mangosteen peel, Pomegranate rind, Berries, Cherries, Red & Pink Roses, Beets, Cochineal insects, Murex snails, Octopus/Cuttlefish and others [6]. However, to exploit these on a commercial level, the supply chain, cost, and, most importantly, reproducibility, to ensure consistency in production, are the main challenges.

There is ample literature reporting the use of Tea (*Camellia sinensis*) as a good source of colorant due to the presence of colored polyphenolic compounds [7-15]. Even after ample literature reports on this subject, there are very few examples of industrial applications of tea dye, mainly due to its poor wash and Light fastness properties; thus, it has to be used in conjunction with various mordants for its commercial applications [10, 16, 17].

This study describes a method for extracting an antibacterial tea dye powder from waste, specifically tea cream generated during the iced tea powder manufacturing process, as an effective fabric dye with desired fastness properties. By utilizing waste generated from Ready-to-Drink tea plants as an effective fabric dye, a negative CO_2 emission is achieved. Negative emission means reducing the amount of carbon by capturing it, in other words, extracting it from waste and storing it as a dye in textiles.

Due to its numerous health benefits, the Ready-To-Drink (RTD) tea market is expected to grow from its current CAGR of 5.4% to a CAGR of 6.12% in the coming five years [18]. During the instant tea powder manufacturing process, a significant quantity (approximately 25%) of the hot water tea extract, obtained through a hot water counter-current extraction process, is discarded as haze or tea cream. This is to ensure that RTD tea powder is soluble in cold water and suitable for mixing with ice [19]. In other words, nearly ¼ of the tea extract rich in coloured phenolic constituents is discarded to make RTD tea extract soluble in cold water. Particularly, water-soluble coloured flavonoids in tea extracts are separated from coloured glycosylated phenolic compounds during the RTD ice tea manufacturing process. Herein, we establish the fabric dyeing properties of this discarded fraction, namely tea cream, and elucidate how the discarded tannins and other glycosylated phenolic compounds can be used as an effective fabric dye with the desired fastness properties [20, 21].

THE PROCESS OF MANUFACTURING READY TO DRINK TEA (RTD)

What is Ready to Drink Tea

Ready-To-Drink Tea (RTD) powder is a concentrated tea extract that has been processed to dissolve easily in water. RTD tea requires no brewing or steeping, and thus offers greater convenience compared to loose-leaf Tea or tea bags, making it a quick and easy option for those with busy lifestyles or limited time.

Tea leaves are extracted with hot water, and the resulting hot water extract is concentrated and spray-dried to obtain tea extract in powder form, which is referred to as RTD tea powder.

Manufacturing Process of Ready-to-Drink Instant Tea

Raw Material

The main raw material used to produce RTD tea in Sri Lanka is black tea (*Camellia sinensis*) rejects, namely Broken Mixed Fannings (BMF), which are small bits of tea that are left over after higher forms of tea leaves are gathered and processed. Approximately 30,000 MT of BMF is generated for the 350,000 MT of high-quality black tea exported each year from Sri Lanka. Sri Lanka has become the primary sourcing unit for the global instant iced tea market, accounting for nearly 70% of the global supply of the Ready to Drink volumes sourced from Pepsi Lipton International, utilizing only 10,000 MT of BMF, while a further 20,000 MT of BMF remains unutilized.

Extraction

The active substances of the tea leaves are extracted using aqueous extraction in hot water in continuous extraction systems. Counter-current extraction is typically used when the solid material and the liquid (solvent) flow in opposite directions,

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Vinitha Moolchand Thadhani

Vinitha Moolchand Thadhani is a distinguished Sri Lankan research scientist with over two decades of experience in academic and industrial research. She is a prolific innovator with patents, publications, and numerous accolades. Her multifaceted expertise led to her current research on creating sustainable natural dyes for the textile industry using tea waste from the world's largest ready to drink tea plant. These findings have been adopted by several reputable brands worldwide, generating significant revenue for Sri Lanka and earning multiple sustainability awards. She is also a strong advocate for young researchers, co founding the Global Young Academy and the Sri Lankan Academy of Young Scientists. Currently, she serves as a freelance consultant to national and international industries, offering specialized, project based expertise.