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Comprehensive Assessment of Pollution Dynamics in Lake Como: Zooplankton, Microplastics, and Sustainable Water Management Strategies.

Jassica Lawrence

Supervisor: Professor Roberta Bettinetti

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Contents

Abstract

Lake Como in Northern Italy is a vital freshwater ecosystem that supports a range of socioeconomic activities, including tourism, agriculture, and energy generation. This multifunctional role, however, has led to increased pollution pressures, particularly through the influx of microplastics and other aquatic debris, exacerbated by high tourism volume impacts. Despite growing concerns over microplastic contamination in freshwater systems, most existing research focuses on marine environments, leaving a critical knowledge gap regarding lakes. This thesis aims to address this gap by investigating the sources, distribution, and ecological impacts of plastic debris (and its derivatives e.g. microplastics) pollution in Lake Como, with a particular emphasis on effects on zooplankton, an essential component of the lake's food web and a key bioindicator of water quality. This research pursues four main objectives: (1) to analyse the concentration, composition, and spatial distribution of microplastics in Lake Como through systematic sampling and laboratory analysis; (2) to assess how climate change is affecting the functioning of wastewater treatment plants (WWTPs) in the region and their ability for effective water treatment; (3) to explore the effects of algal bloom-induced turbidity on debris detection and ecological assessment, using advanced remote operating vehicle (ROV) technology for monitoring; and (4) to investigate the application of circular economy principles in waste management, with a specific focus on recycling textile waste as a strategy to curb pollution in freshwater systems. Fieldwork conducted over multiple seasons involved sampling eight sites across Lake Como, coupled with ROV monitoring to document both floating and submerged debris. Preliminary results reveal a heterogeneous distribution of plastics, with higher concentrations near populated and tourist areas, indicating localized pollution sources. Analysis shows that the types of microplastics range from fragments to fibres, implicating both municipal waste and industrial discharge as contributors. Furthermore, climate-related stressors, such as extreme weather events and increased runoff, have been shown to impair WWTP efficiency, complicating efforts to control microplastic contamination. The findings highlight an urgent need for innovative waste management strategies. Circular economy practices, particularly textile waste recycling, are proposed as viable solutions to reduce microplastic inputs and enhance sustainable waste utilization. This study not only contributes to the limited to growing literature, on freshwater microplastic pollution, but also offers practical recommendations for pollution mitigation and ecosystem health preservation in Lake Como as well as similar freshwater bodies. These recommendations include policy interventions and infrastructure

improvements that can help manage anthropogenic pressures on freshwater ecosystems in a changing climate.

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This thesis is as much yours as it is mine.

Chapter 1 Introduction

1. Background of Lake Como

Microplastics, aquatic debris monitoring is also a growing concern in aquatic environments, particularly in how debris accumulation affects water quality and the overall health of the ecosystem (Neha et al., 2024; Castelnuovo et al., 2024; Schultz et al., 2015). Lake Como is a famous tourist destination, particularly Como Bay. The highest number of tourists arrive in Spring and Fall with a weekly rise on weekends. There is an average upsurge of 14.0% during weekends and 10.8% in peak tourism period in high season weekends than weekdays in the low season, thus suggesting patterns are strongly affected by recreational and tourism activities on the lake (Vavassori et al., 2022). Potable water consumption, wastewater, municipal solid waste, are related and also influenced by the tourism of people living particularly in NW Lombardy and neighboring Canton Ticino (Switzerland) (Giurea et al., 2022; Giussani et al., 2006; Lichtmannegger et al., 2024; Rada et al., 2014; Ragazzi et al., 2024). Moreover, cases of water and wastewater contamination were reported in heavily populated and industrialized areas (Foris & Pleşca, 2017; Giussani et al., 2008; Su, 2023). Lake Como is a prominent famous place for tourism, culture, and historical prose heritage. It serves multipurpose i.e. aesthetics, water sports, recreational, irrigation hydropower, and flood risk prevention alongside shores. Lake Como is an important lake in the North of Italy. It also collects water utilized for irrigation in the Po Valley downstream (Fuso et al., 2021).

Freshwater lakes play an essential role in rendering ecosystem services (Dodds et al., 2013). Anthropological activities create disturbance to the core of the ecosystem. Thus, it harms key aquatic organisms such as phytoplankton, fish, and most importantly zooplankton are impacted by lake pollution (Bettinetti et al., 2016). Zooplankton is commonly used as an environmental risk indicator in aquatic ecosystems (Bettinetti et al., 2012). It is a food and energy transfer organism among the food webs between primary producers (phytoplankton) and the upper levels (invertebrate predators and fish) and is receptive to changes in abiotic factors through space and time (Dodson et al., 2008; Jeppesen et al., 2011; Van Egeren et al., 2011).

Underwater monitoring in lakes provides useful information on lake pollution particularly the debris objects being accumulated on the sediments due to human activities and impacts the health of lakes, rivers, oceans, and the ecosystem (Fornaroli et al., 2016; Statzner et al., 2005).

1.1 Problem Statement

Few studies have been conducted on microplastics in freshwater lakes as most work is done on the marine environment. Studies accountable for fresh water and microplastics are estimated to be less than 4% (Alfonso et al., 2021; D'Avignon et al., 2022; Dusaucy et al., 2021; Lambert & Wagner, 2018). Based on this limitation, it was found that a conspicuous fraction of MPs are found in fresh water (Akdogan & Guven, 2019) following a heterogenous distribution pattern (Klein et al., 2018). Alongside microplastics, aquatic debris, including larger waste fragments, poses significant challenges for the ecosystem of Lake Como, necessitating efficient monitoring and mitigation strategies.

1.2 Aims and Objectives

Aim: To understand the impact of microplastic pollution in zooplankton in Lake Como's ecosystem and the functioning of WWTPs in the context of climate change.

Objectives:

1. To analyze the presence of microplastics in Lake Como.
2. To investigate the effects of climate change on WWTP functioning in Como.
3. To assess how algal bloom-induced turbidity affects debris detection in freshwater ecosystems.
4. To explore the role of circular economy principles in enhancing waste management practices, specifically focusing on the utilization of textile waste, and its implications for reducing pollution in freshwater ecosystems.

1.3 Thesis Structure

This thesis is organized into seven chapters, each focusing on a different aspect of the research on microplastic pollution, wastewater treatment plants (WWTP), aquatic debris monitoring via Remote Operating Vehicle (ROV) and the circular economy in Lake Como.

- **Chapter 1: Introduction** This chapter introduces the study by providing background information on Lake Como, the importance of zooplankton as bioindicators, and the problem of microplastic pollution. It also outlines the research aims, objectives, and the broader significance of the study.
- **Chapter 2: Literature Review** The literature review explores previous research on freshwater ecosystems, the impact of microplastics on zooplankton, and the relationship between climate change and WWTP functioning. It also discusses the role of the circular economy in managing plastic waste, identifying gaps in the current body of knowledge.
- **Chapter 3: Microplastic Analysis in Lake Como** This chapter presents the methodology and results of the microplastic analysis conducted on samples from Lake Como. It provides a detailed account of the types and concentrations of microplastics found in the lake and discusses the implications for aquatic life and ecosystem health.
- **Chapter 4: Climate Change and WWTP Functioning** This chapter examines how climate change affects the functioning of wastewater treatment plants in Como, drawing on data from conference papers. It highlights the potential impact of changing environmental conditions on the effectiveness of WWTPs in controlling pollution, including microplastics.
- **Chapter 5: Monitoring of Aquatic Debris** In this chapter, the methods and findings from monitoring aquatic debris in Lake Como are presented. It analyses the types of debris collected, discusses their potential contribution to microplastic pollution, and considers the broader impact on freshwater ecosystems.
- **Chapter 6: Circular Economy and Waste Utilization** This chapter discusses the application of circular economy principles in waste management, particularly concerning plastic waste. It reviews current approaches to waste utilization and recycling, assessing their effectiveness in reducing the input of plastics and microplastics into aquatic environments.
- **Chapter 7: Poster Presentation Overview**
- **Chapter 8: General Discussion and Conclusion** The final chapter synthesizes the findings from the previous chapters, discussing the broader implications for pollution control, waste management, and freshwater ecosystem health. It also suggests

potential directions for future research and offers policy recommendations to mitigate microplastic pollution in freshwater systems.

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Chapter 2 Review paper

This chapter serves as the foundational review, with the subsequent chapters building on and extending these ideas to the detailed investigation of pollution in Lake Como conducted for three years. First, it presents the introduction, discussion, and main findings of my paper titled "Freshwater Lacustrine Zooplankton and Microplastic: An Issue to Be Still Explored", which I published during the second year of my research. The review paper focuses on the relationship between microplastics and zooplankton in freshwater lakes, particularly exploring the gaps in existing research. For reference, the full citation of this publication is as follows: Lawrence, J., Santolini, C., Binda, G., Carnati, S., Boldrocchi, G., Pozzi, A., & Bettinetti, R. (2023). Freshwater lacustrine zooplankton and microplastic: An issue to be still explored. *Toxics, 11*(12), 1017. https://doi.org/10.3390/toxics11121017. The following section will briefly summarize the key findings of my published review paper. However, it is important to note that the topics discussed here will be further expanded upon in subsequent chapters of this thesis. For instance, while the review paper addresses the impact of microplastics in zooplankton populations, Chapter 3 will explore in more detail the effects of climate change on wastewater treatment plants (WWTPs) in Lake Como, as well as the use of Remote Operating Vehicles (ROVs) for monitoring aquatic debris in the region. Additionally, the concept of circular economy and its practical application in various industries, including the fashion sector, will be discussed further in Chapter 4.

2. Background

Microplastics (MPs), defined as plastic particles under 5 mm, are an emerging global pollutant with detrimental effects on freshwater ecosystems (Wright et al., 2013). Global plastic production reached approximately 370 million metric tons in 2019, with around 4.6% entering aquatic systems (Dris et al., 2018; Güven et al., 2017). Common MPs in freshwater include polyethylene, polypropylene, polystyrene, and polyethylene terephthalate (Nava et al., 2023). However, research has primarily focused on marine systems, leaving the implications for freshwater environments less understood (Wagner et al., 2014).

2.1 Problem

Studies on MPs in freshwater lakes make up less than 4% of total MP research (Alfonso et al., 2021; D'Avignon et al., 2022), despite their prevalence due to land-based pollution sources and atmospheric deposition (Klein et al., 2018; Norling et al., 2024; Rochman & Hoellein, 2020). This gap limits our understanding of MP impacts on key freshwater species like zooplankton, crucial for ecosystem stability and food web health.

2.2 Significance

Much MP research is laboratory-based, limiting insights into their real-world impacts on ecosystems. Field-based studies are needed to assess how prolonged MP exposure affects zooplankton and to develop accurate, ecosystem-wide risk assessments. For example, PS-MP exposure reduced zooplankton reproductive capacity (Zhu et al., 2022), while smaller MPs often caused oxidative stress due to lipid membrane damage (Jeong et al., 2018). The toxicity of MPs also varies by size, with smaller MPs generally posing greater risks (Rehse et al., 2016; Jemec Kokalj et al., 2018). This research gap underscores the need for comprehensive field studies to evaluate the cumulative effects of MPs on freshwater zooplankton and ecosystems.

2.3 Studies on Zooplankton and Microplastics in Freshwater Lakes

Field studies monitoring the environmental concentration of microplastics (MPs) in zooplankton are scarce, especially in freshwater lakes. In this review, we focused on studies reporting MPs in environmental samples of zooplankton from lacustrine ecosystems. However, it is important to clarify that while these studies reported MPs of various sizes and polymers associated with zooplankton samples, the specific ingestion or other exposure routes were unfortunately difficult to determine. Pazos et al. (2018) investigated the impacts of microplastics on zooplankton with respect to their morphological structure and dimensions in the freshwater body Río de la Plata estuary, South America. Lusher et al. (2018) detected microplastics in zooplankton from Lake Mjøsa, finding that microplastics were present in all samples, with 97% of the detected particles smaller than 1 mm. Rubber particles were commonly found in these zooplankton samples. Alfonso et al. (2021) published a review highlighting zooplankton as a tool for assessing MPs in water, focusing on particle ingestion. They claimed that the ingestible MP size was below 50 µm and observed irregular fragments of varying polymer types in the environmental samples. Pastorino et al. (2023) investigated biotic (zooplankton, fish, and tadpoles) and abiotic samples (water and sediment) and did not detect MPs in zooplankton or water, although MPs were present in sediments. Wu et al. (2020) published a review on the impacts of microplastics on zooplankton in freshwater bodies of China, noting adverse effects on the digestive tract of zooplankton, particularly concerning grazing, fecundity, and overall growth development. There is ambiguity in the field due to a knowledge gap, as some articles suggest that the quantity of microplastics may increase significantly when focusing on smaller particles. Similarly, limited data are available on the fate of microplastics in the water column and their influence on lake zooplankton. This study highlights the lack of substantial evidence of microplastic ingestion by zooplankton in natural environments but underscores the clear possibility of trophic transfer of microplastics within lake food webs through a range of aquatic organisms. Da Silva et al. (2022) examined the effects of varied-size MP particles on zooplankton communities from a lake in the Upper Paraná River floodplain, Brazil. Their study demonstrated that MP particles can have serious impacts on the trophic web, particularly at the base of the food chain, where primary producers and small herbivores are most affected.

2.4 Main Findings and Conclusion of the Review Paper

The review identifies significant research gaps, especially regarding trophic transfer of MPs in freshwater ecosystems. Most studies focus on lab-based, secondary food chains, leaving real-world dynamics underexplored. Additionally, the lack of standard protocols for MP concentration assessments complicates risk evaluations. Future research should prioritize multilevel trophic studies, particularly involving top predators, to better understand MP impact in freshwater systems.

Climate Change and Wastewater Treatment Plants (WWTPs)

2.5 Background

Climate change impacts the operation of WWTPs in two main ways. First, extreme weather events, such as floods, increase untreated sewer overflows, while droughts reduce water flow, impacting WWTP efficiency. Secondly, temperature shifts affect treatment processes, as higher temperatures can enhance removal efficiency in both natural and non-mechanized treatment systems (Tchobanoglous et al., 2003; Sperling & de Lemos Chernicharo, 2005; Tram Vo et al., 2014).

2.6 Problem

While studies primarily focus on pollution and water treatment, few evaluate the direct effects of climate change on WWTPs (Abdulla & Farahat, 2020; Kirchhoff & Watson, 2019; Plósz et al., 2009). In Lake Como's Como Bay, tourist numbers vary seasonally, particularly during spring and fall weekends, with a 14% rise in tourism during peak seasons (Vavassori et al., 2022). These fluctuations affect WWTP demands due to increased human activity around the lake.

2.7 Significance

Lake Como's multiple uses—including recreation, irrigation, hydropower, and flood control—make it highly sensitive to seasonal climate shifts and tourism, challenging the performance of its WWTPs (Fuso et al., 2021). To address these issues, I published the study, "The Impact of Seasonal Variations in Rainfall and Temperature on WWTP Performance for Lake Como Environmental Protection", to assess how seasonal temperature and precipitation affect WWTP processes and identify optimal performance strategies. For reference, the full citation of this publication is as follows: Lawrence, J., Giurea, R., & Bettinetti, R. (2024). The Impact of Seasonal Variations in Rainfall and Temperature on the Performance of Wastewater Treatment Plant in the Context of Environmental Protection of Lake Como, a Tourist Region in Italy. *Applied Sciences, 14*(24), 11721.

2.7.1 Main Findings and Conclusion

The study's key findings on WWTP performance under seasonal variations in Lake Como include:

1. **Seasonal Stability**: pH levels remained stable across weather changes, highlighting plant resilience.
2. **Phosphorus and Pollutant Removal**: The plant consistently met regulatory phosphorus and contaminant removal levels, adapting to seasonal conditions.
3. **Suspended Solids and Nitrogen Removal**: Efficient removal of suspended solids, nitrogen, and ammonium persisted throughout seasonal shifts.
4. **Rainfall and Temperature Impact**: Seasonal variations affected chemical and microbial processes, but pollutant removal efficiency remained high.

The study recommends further exploration of optimized WWTP operations under variable weather and tourism impacts, aiming to enhance resilience in changing conditions.

Monitoring of Aquatic Debris Using ROV Technology

2.7.2 Background

Recent advancements in Remote Operating Vehicles (ROVs) have revolutionized underwater debris monitoring, allowing for real-time data collection and continuous video capture across varied aquatic environments (Neha et al., 2024; Castelnuovo et al., 2024; Schultz et al., 2015). Environmental conditions such as water turbidity and light attenuation—particularly during algal blooms—pose challenges to ROV performance by diminishing detection efficiency (Chung et al., 2015; Foglini et al., 2019).

2.7.3 Problem

Algal blooms, typically fueled by nutrient-rich agricultural runoff and urban wastewater, increase water turbidity, which severely impacts the effectiveness of electro-optical (EO) imaging systems on ROVs (Hu et al., 2023; Qin et al., 2016). This turbidity can alter the color spectrum and obstruct light transmission, hindering debris detection capabilities (Bovio et al., 2006; Consoli et al., 2018). The relationship between water transparency, algal growth, and visibility is well-established, with studies noting that algal growth reduces water clarity and complicates underwater assessments (Kulshreshtha & Shanmugam, 2017). For example, Tapia González et al. (2008) demonstrated the use of water transparency as a reliable eutrophication indicator. Limited clarity thus constrains the efficacy of remote sensing, especially in turbid conditions (Hou et al., 2013; Yuan et al., 2022), making aquatic debris monitoring even more challenging. To address this issue, I published a conference paper titled "Preliminary Exploration of Underwater Debris in Lake Como, Italy during the High Tourist Season for Environmental Protection". The full reference is: Lawrence, J., Castelnuovo, N., Giurea, R., & Bettinetti, R. (2024). Preliminary exploration of underwater debris in Lake Como, Italy during the high tourist season for environmental protection. In *Proceedings of the Proteus Association Conference*, Villa Geno, Como, Italy, pp. 1-8, IEEE. This study identified common underwater debris on lake sediments during peak tourism in summer, proposing mitigation measures to aid environmental management. A follow-up study, "Monitoring Aquatic Debris in a Water Environment Using a Remote Operating Vehicle (ROV): A Comparative Study with Implications of Algal Bloom Detection in Lake Como (Northern Italy)". The full citation for this paper is as follows: Lawrence, J., Castelnuovo, N., & Bettinetti, R. (2024). Monitoring aquatic debris in a water environment using a remotely operated vehicle (ROV): A comparative study with implications of algal detection in Lake Como (Northern Italy). *Environments, 12*(1), 3. https://doi.org/10.3390/environments12010003. which further explores the impact of algal blooms on ROV detection, discussed in detail in Chapter 5.

Circular Economy and Waste Utilization

2.7.4 Background

The circular economy focuses on reusing and recycling materials to maximize resource efficiency. It aims to reduce waste by encouraging the preparation, use, and responsible disposal of products with a clear purpose. The aim of circular economy is to minimize waste generation and utilization of the resources to its maximum potential (Domenech, 2014; Baskar et al., 2022; Hedlund et al., 2020; Hegedűs & Longauer, 2023; Kirchherr et al., 2023; Rada et al., 2017).

2.7.5 Significance

The principles of the circular economy focus on mitigating the negative impact of an activity at all stages while enhancing the use of materials and products by rejuvenating the ecological system (Anaruma et al., 2021; Domenech, 2014; Gabriel & Delgado, 2020; Mazur-Wierzbicka, 2021; Rajput & Singh, 2019; MacArthur, 2017). These principles include designing for longevity, promoting reuse and repair, recycling and resource recovery, implementing closed-loop systems, reducing waste generation, adopting sustainable sourcing, and encouraging product-as-a-service models.

2.7.6 Problem

Although there are several countries which practice clothes recovery including Denmark, Norway, Sweden and China, yet there is need to understand more about the clothes recovery program as the practical implications such as product life extension, reuse, recycle, recycling in the end of life and resource preservation practice among different countries (Gazzetta Ufficiale, 2020; Khan & Rundle-Thiele, 2019; Sandberg, 2023).

2.7.7 Conclusion

A balanced approach to incorporating sustainability and circular economy principles throughout all phases of production, consumption, and waste management is essential to minimize environmental impacts and promote long-term resource efficiency. However, despite ongoing efforts, the effective implementation of circular economy practices remains limited. This is primarily due to challenges such as high costs, shifting consumer preferences, and rapidly changing fashion trends. Nevertheless, the steps taken by some companies demonstrate that applying circular economy concepts is achievable in practical ways. This investigation highlights two key areas for improvement. First, addressing external challenges, including consumer behaviour and the aesthetic appeal of garments. Second, fostering collaboration with local industries to align with circular economy policies and sustainability regulations. Further research is needed to evaluate the progress of the Swedish fashion industry in adopting circular economy practices. Sweden was chosen due to its reputation for innovation and sustainability initiatives, providing a valuable case study to explore how circular economy practices are implemented. Additionally, comparing Sweden with other countries, such as Italy and Switzerland, highlights the varying degrees of adoption and the challenges faced by different regulatory and market environments The review indicates that common challenges exist throughout the supply chain in implementing circular economy principles for garment recovery. In the case of luxury fashion brands, circular economy practices are particularly limited, as these brands often discard prototype garments. While there are efforts to promote circular economy adoption across different segments of the textile and fashion industry, significant work remains to bridge the gap between circular economy goals and reducing environmental impacts.

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Chapter 3: Microplastic analysis in zooplankton

3.0 Background

The presence of microplastics in freshwater bodies is a growing concern. Lake Como's ecosystem lacks comprehensive data on microplastic contamination. This chapter addresses this gap by analysing eight samples of zooplankton from the lake, providing a detailed account of microplastic presence and its implications for aquatic life, particularly zooplankton.

3.1 Methodology

Sample Collection and Conservation

Zooplankton samples were collected from the Como basin using a 200 µm mesh plankton net. Vertical hauls were conducted from a depth of 20 meters to the water surface. After collection, samples were transferred into glass containers filled with ethanol to ensure sample preservation and minimize degradation and microbial contamination, in accordance with established protocols for zooplankton and microplastic sampling (Ribeiro et al., 2024; Rumin et al., 2015). For analysis, a 10 ml subsample of the preserved zooplankton was taken from each collection, lyophilized, and the dry weight recorded. This lyophilized material provided the baseline for the subsequent microplastic quantification, to standardize the results per milligram of dry weight (Shruti et al., 2022).

Sample Digestion

To remove organic matter from the zooplankton samples and preserve plastic particles, a digestion protocol was employed using approximately 50 ml of 30% hydrogen peroxide (H_2O_2). Samples were incubated at 40°C for 48 hours. This digestion process ensures the integrity of microplastic particles, as hydrogen peroxide effectively degrades biological material, while maintaining the structure of synthetic polymers (Rumin et al., 2015).

Filtration

Following digestion, the samples were filtered using a vacuum filtration apparatus, a Büchner funnel, and glass fibre filters (Whatman® GF/C, 47 mm diameter, 1.2 µm pore size; Sigma Aldrich). This filtration protocol (developed by the University of Brescia) was essential for isolating potential microplastic particles on the filter for subsequent analysis. Each filter was transferred to a sterile glass Petri dish to minimize contamination and prepared for the staining procedures (Shruti et al., 2022).

LIFE CASCADE
TEXTILE MICROPLASTICS PFAS RISK

Filtration protocol

Step A: Preparation of reagents:

Filter the reagents (0,1% Triton X solution in milliQ water and ethanol) with glass fiber filters to remove impurities. Use only milliQ water for the preparation of the solutions and for the filtration!

Step B: Prewashing of the filter (when applicable):

1. Place the filter in 0,1% Triton X solution and sonicate in a water bath for 10 minutes.
2. Remove the Triton X solution and rinse with milliQ water.
3. Place the filter in ethanol and sonicate in a water bath for 10 minutes.

Step C: Preconditioning of the filter:

(for 10 – 13 mm filters)

1. Mount the filtration apparatus.
2. Filter 5 ml of 0,1% Triton X solution.

(for 25 – 47 mm filters)

1. Mount the filtration apparatus.
2. Filter 10 ml of 0,1% Triton X solution

Step D: Filtration of the sample and washing

(for 10 – 13 mm filters)

1. Filter the sample volume.
2. Rinse the sample container with milliQ water (half sample volume) and filter.
3. Rinse the sample container with 5 ml of 0,1% Triton X solution and filter.
4. 2 steps of washing of the apparatus with 5 ml of 0,1% Triton X solution (slide the solution onto the glass walls of the apparatus).
5. 1 step of washing of the apparatus with 5 ml of milliQ water.
6. 1 step of washing of the apparatus with 5 ml of ethanol.

(for 25 – 47 mm filters)

1. Filter the sample volume.
2. Rinse the sample container with milliQ water (half sample volume) and filter.
3. Rinse the sample container with 10 ml of 0,1% Triton X solution and filter.
4. 2 steps of washing of the apparatus with 10 ml of 0,1% Triton X solution (slide the solution onto the glass walls of the apparatus).
5. 1 step of washing of the apparatus with 10 ml of milliQ water.
6. 1 step of washing of the apparatus with 10 ml of ethanol.

Figure 1. Microplastic analysis protocol

Staining of Microplastics

To facilitate visual identification and differentiate microplastic particles from organic matter, two staining procedures were applied sequentially described in Figure 1.

1. **Nile Red Staining**: The first filter staining was conducted using Nile Red dye at a concentration of 1 µg/ml. Nile Red solution was prepared by dissolving the dye in acetone, as described by Rumin et al. (2015). A few drops were applied to each

filter, which was then placed in an oven at 40°C for 30 minutes to enhance dye absorption by synthetic polymers. The filters were subsequently rinsed with 10 ml of Milli-Q water to remove any excess dye and to ensure only microplastics retained the stain under UV light (Rumin et al., 2015; Shruti et al., 2022)

2. **Rose Bengal Staining**: Following Nile Red application, each filter was stained with Rose Bengal at a concentration of 200 mg/L (Ribeiro et al., 2024). Rose Bengal, prepared in Milli-Q water, was applied in a few drops and allowed to stain the filter for 5 minutes at room temperature. Rose Bengal binds selectively to organic material, aiding in the differentiation of biological particles from microplastics under visible light. Filters were then rinsed again with 10 ml of Milli-Q water to remove any unbound Rose Bengal dye (Rumin et al., 2015; Ribeiro et al., 2024).

Throughout the staining procedures, procedural blanks were utilized to assess the possibility of presence for potential contamination, following best practices in microplastic analysis (Shruti et al., 2022).

Microscopic Analysis and Quantification

Each filter was examined under a digital microscope (Keyence VHX-7000 Series) equipped with UV illumination at 65 nm. Observations were conducted at a magnification of 100X. Half of the total filter area was visually inspected under UV light, with the final count doubled to estimate the entire filter area. Microplastic particles were identified as fragments or fibres that fluoresced under UV light and did not appear fuchsia under normal visible light (Rumin et al., 2015; Ribeiro et al., 2024).

Results from the microscopic analysis were expressed as the number of microplastic particles per milligram of zooplankton dry weight (MPs/mg dry weight), providing a standardized metric for microplastic quantification across samples (Shruti et al., 2022) as shown in Figure. 2.

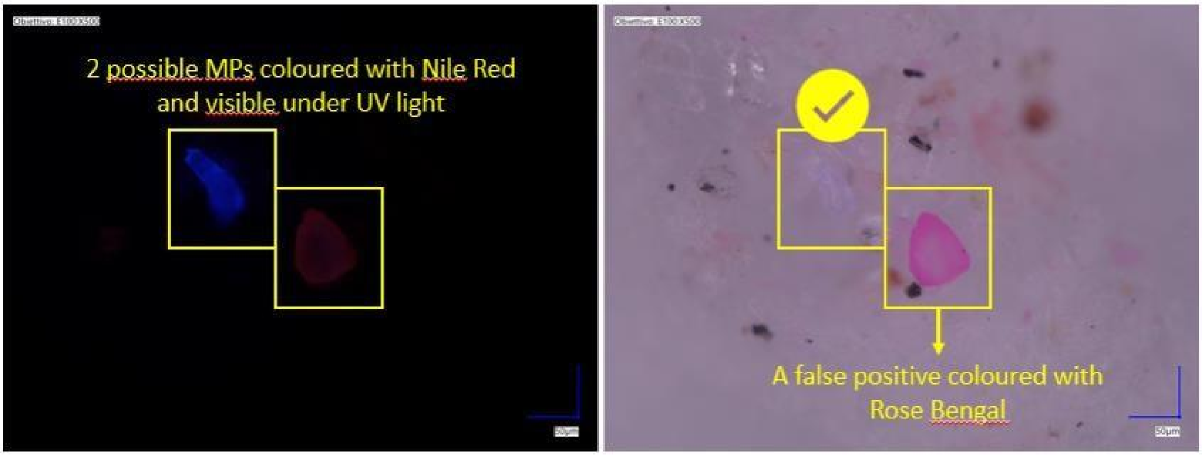

Figure 2. Microplastics examined on filter under a digital microscope

3.2 Results

Table 1. Microplastic Concentrations in Dry Weight Samples (MPs/mg dry weight) from Lake Como's Branches.

Lake's Branch	Data	Sample Code	Dry Weight (G)	Tot MPs	Fragments	Fibers	Mps/G Dw	Mps/MG Dw
COMO	05/06/2018	1	0.0424	20	14	6	471.7	0.5
COMO	30/07/2018	2	0.0658	16	14	2	243.2	0.2
LECCO	06/08/2018	3	0.0251	18	14	4	717.1	0.7
COMO	28/08/2018	4	0.0145	4	0	4	275.9	0.3
LECCO	26/04/2018	5	0.0335	2	0	2	59.7	0.1

Overview of Microplastic Quantification in Zooplankton Samples

Analysis of microplastics (MPs) in zooplankton samples collected from the Como and Lecco branches of the lake across different dates in 2018 revealed variability in MP abundance, type (fragments vs. fibers), and density per dry weight of zooplankton. Microplastic density was measured as MPs per gram dry weight (MPs/g dw) for a broader scale comparison and as MPs per milligram dry weight (MPs/mg dw) to capture finer variations in smaller sample sizes, providing a more detailed understanding of microplastic contaminations described in Table 1.

Microplastic Counts and Types by Sample

1. **Como Branch Samples -** Sample 1 (05/06/2018): With a dry weight of 0.0424g, this sample contained a total of 20 MPs, consisting of 14 fragments and 6 fibres. This yielded a density of 471.7 MPs/g dw and 0.5 MPs/mg dw, making it the highest density observed in the Como branch samples.

- Sample 2 (30/07/2018): The dry weight for this sample was 0.0658 g, with 16 MPs identified, predominantly fragments (14) and a smaller proportion of fibres (2). This sample's density was 243.2 MPs/g dw and 0.2 MPs/mg dw.
- Sample 4 (28/08/2018): A dry weight of 0.0145 g was recorded for this sample, with 4 MPs present, all identified as fibres. The resulting density was 275.9 MPs/g dw and 0.3 MPs/mg dw.

2. **Lecco Branch Samples -** Sample 3 (06/08/2018): This sample, with a dry weight of 0.0251 g, contained a total of 18 MPs, composed of 14 fragments and 4 fibers. This sample recorded the highest MP density across all samples, with 717.1 MPs/g dw and 0.7 MPs/mg dw.

- Sample 5 (26/04/2018): This sample had a dry weight of 0.0335 g and contained only 2 MPs, both identified as fibres. It showed the lowest MP density, with 59.7 MPs/g dw and 0.1 MPs/mg dw.

Observed Trends and Patterns

The Como branch samples showed variability in MP counts, with the highest density in early June (471.7 MPs/g dw) and moderate densities in subsequent months (243.2 and 275.9 MPs/g dw). The Lecco branch samples, however, presented more extreme density variations: the highest MP density (717.1 MPs/g dw) was observed in early August, while the lowest (59.7 MPs/g dw) was detected in April. This pattern suggests potential seasonal or locational differences in MP presence.

Fragments were the most common type of MPs in samples with high densities (e.g., Sample 1 and Sample 3), while samples with lower MP counts, such as Sample 4 and Sample 5, contained only fibres. These differences in MP composition may reflect varying sources or environmental conditions influencing MP distribution within the lake.

3.3 Conclusion

This study reveals a preliminary evaluation of a significant variability in microplastic (MP) densities in zooplankton across the Como and Lecco branches, with the highest concentrations in the Lecco branch during August, possibly due to seasonal or environmental factors. Notably, fragments dominated high-density samples, while fibres were more prevalent in low-density samples, suggesting differences in MP sources or environmental dispersion patterns. These results underscore the widespread presence of MPs in freshwater ecosystems and the importance of ongoing monitoring to understand their ecological impacts and guide targeted conservation strategies.

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Chapter 4: Climate Change and WWTP Functioning

This chapter includes the introduction, discussion, and main findings from my published paper in the Applied Sciences journal (doi.org/10.3390/app142411721). For reference, the full citation of this publication is: Lawrence, J., Giurea, R., & Bettinetti, R. (2024). The Impact of Seasonal Variations in Rainfall and Temperature on the Performance of Wastewater Treatment Plant in the Context of Environmental Protection of Lake Como, a Tourist Region in Italy. *Applied Sciences, 14*(24), 11721.

The paper examines how seasonal variations in rainfall and temperature affect the performance of wastewater treatment plants (WWTPs) in the context of protecting Lake Como, a popular tourist region in Italy. Additionally, this chapter references a conference paper titled "Preliminary Correlations Between Climate Change and Wastewater Treatment Plant Parameters". The full citation for this publication is: Lawrence, J. (2024). Preliminary correlations between climate change and wastewater treatment plant parameters. In *WIT Transactions on Ecology and the Environment, Volume 262*, Sustainable Development and Planning, 957. Section 4.4 summarizes and concludes the key findings from the journal paper on the "Impact of seasonal changes on WWTP performance and their implications for the environmental protection of Lake Como".

4. Introduction

Urbanization, population growth, emerging contaminants, and increasing water scarcity challenge sustainable wastewater treatment systems (WWTPs) (Matheri et al., 2022). Climate change worsens these issues, as rising temperatures and inflow rates disrupt microbial processes, reducing oxygen solubility and impairing Biological Oxygen Demand (BOD), which harms aquatic ecosystems (Hughes et al., 2021; Ranieri, 2003). Future climate shifts could further increase costs and reduce efficiency, especially with higher temperatures and intense rainfall (Bassin et al., 2021; Reznik et al., 2020; Tolkou & Zouboulis, 2016). To promote circular sustainability, strategies like water recycling, resource recovery, and digital systems are essential for integrating wastewater into the circular economy (Collivignarelli et al., 2020; Cosoli et al., 2015; Giurea et al., 2018; Waikar & Sadgir, 2024). This study examines the seasonal impacts of climate change on WWTP operations in Lake Como.

4.1 Discussion

Alisawi et al. (2020) reported a steady maintenance of pH, phosphate (0.29–0.54 mg/L), nitrate (0.32–6.5 mg/L), nitrite (0.06–2.4 mg/L), and COD (48–1,180 mg/L) removal despite temperature fluctuations (18–25 °C). However, they observed seasonal COD variation, with higher values in summer and autumn due to municipal effluent contributions. Similarly, our study observed higher COD values in winter, followed by summer and autumn, reflecting seasonal variations and similar mechanisms. Regarding nitrogen compounds, while nitrate levels exceeded safety limits during summer, our findings indicated reduced total nitrogen levels with rising temperatures, suggesting enhanced microbial activity in warmer conditions. However, the observed phosphorus levels exceeded the South African target limit of 5 µg/L which was used as a reference due to the study being conducted in the Northwest Province of South Africa, indicating undiscovered phosphorus sources in the water system, indicating undiscovered phosphorus sources in the water system. Despite this, our results showed a minimal impact of temperature on total phosphorus removal, demonstrating plant stability (IRSA-CNR, 2003, Section 4000).

Seasonal temperature effects on organic matter breakdown were also evident. Vidal et al. (2023) and Skoczko et al. (2017) attributed elevated winter COD levels to reduced microbial activity in colder conditions, which aligns with our findings of decreased organic matter breakdown during winter. On the other hand, Tunçsiper et al. (2019), who analysed the Kabd WWTP in Kuwait, observed pH stability (around 7.7) across seasons, matching our findings. In terms of solid and organic matter removal, our influent and effluent TSS and BOD_5 levels align with seasonal trends reported by Tunçsiper et al. (2019), albeit with slightly lower pollutant loads in our effluent. This difference may be attributed to advanced treatment methods or variations in influent characteristics. Most parameters, including BOD and phosphorus levels, showed high removal efficiencies (>71% and >91%, respectively). However, denitrification processes were limited in colder conditions, as noted by Abou-Elela et al. (2016). Finally, seasonal variations also influenced industrial wastewater treatment efficacy. Mahgoub et al. (2016) observed the lowest COD removal efficiency during winter, with better performance in summer. This is consistent with our study, where warmer seasons showed higher BOD and COD removal efficiencies.

4.2 Main findings and Conclusion

This study investigated the impact of extreme weather conditions on the performance of the Como, Italy, wastewater treatment plant (WWTP) in terms of influent (inf) and effluent (eff) quality parameters. During winter (October-December), the average temperature was 8.76°C ± 11.43°C with 7.01 mm rainfall, while summer (May-September) averaged 23.24°C ± 6.2°C with 5.2 mm rainfall. Despite seasonal variations, pH levels remained consistent. Phosphorus removal was efficient, with winter influent averaging 4.16 ± 5.53 mg/L and effluent 0.33 ± 1.06 mg/L, and summer influent 3.53 ± 2.9 mg/L and effluent 0.31 ± 0.75 mg/L. COD and BOD_5 levels showed seasonal trends, with higher winter-influent COD (450.43 ± 560.56 mg/L) than summer (410.96 ± 302 mg/L). Winter influent BOD averaged 249.57 ± 220.42 mg/L, with effluent at 2.95 ± 2.04 mg/L, while summer influent BOD was 214.44 ± 345.5 mg/L, with effluent at 3.01 ± 7.5 mg/L. TSS and Total-N showed similar seasonal patterns, with slight decreases in TSS removal efficiency during warmer months. Despite rainfall influencing phosphorus and organic load concentrations, the plant maintained over 90% pollutant removal efficiency, demonstrating resilience and compliance with regulatory standards. WWTP's consistent COD and BOD_5 reduction highlights its robust performance amid climate variations. This study explores the impact of seasonal rainfall and temperature on a wastewater treatment plant in Lake Como. Despite extreme weather shifts, key parameters like pH remained stable, ensuring effective treatment. Phosphorus, organic pollutants, suspended solids, nitrogen, and ammonium were consistently removed, showing the plant's adaptability and compliance with regulations. Future research should focus on hydraulic loading's effect on phosphorus removal and the interplay between seasonal climate, tourism, and wastewater systems. These findings offer practical insights into improving WWTP performance in changing weather conditions.

4.3 Discussion and main findings (Conference paper)

This discussion is based on the conference paper I presented at the International Conference Sustainable Development 2024. Rainfall and temperature significantly influence wastewater treatment processes, affecting parameters like BOD, COD, and TSS by increasing water influx and altering microbial activity (Ranieri, 2003). In the present conference paper study of five months, key wastewater parameters—including COD, BOD, TSS, pH, Total Phosphorus, Nitrogen, and Ammonia—were analysed for both influent and effluent, alongside rainfall and temperature data. pH remained stable despite extreme weather conditions, while NO_2 and NO_3 were irregularly measured and showed no significant fluctuations, thus excluded from further analysis in this study.

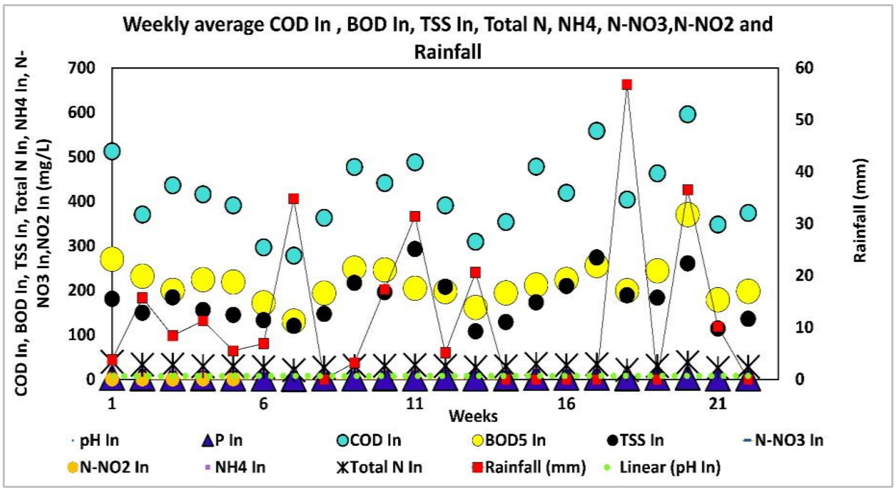

Figure 3. WWTP incoming parameters with respect to rainfall.

The highest rainfall was 56.80 mm in May (week 18), while the lowest was 3.80 mm (week 1). During maximum rainfall, influent values for COD, BOD, phosphorus, TN, and NH_4 were lower (COD 404.12 mg/L, BOD 199.20 mg/L) compared to minimum rainfall (COD 512.5 mg/L, BOD 270 mg/L), indicating influent dilution. Effluent quality was better during high rainfall, with lower COD (12 mg/L), BOD (1.96 mg/L), and phosphorus (0.39 mg/L), compared to low-rainfall periods as represented in Figure 3.

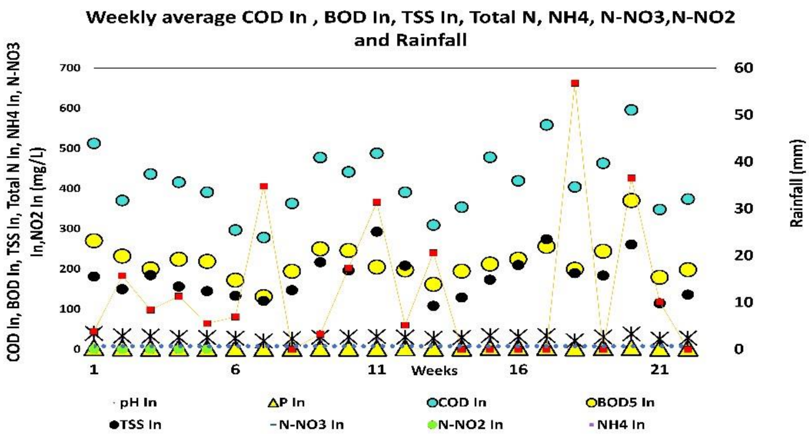

Figure 4. WWTP outgoing parameters with respect to rainfall.

Consequently, Figure 4. evaluates how the quality of the influent directly impacts the effluent quality. The analysis covers key parameters such as COD, BOD, phosphorus, and TN for both influent and effluent, allowing for a comprehensive assessment of wastewater treatment performance. With maximum rainfall the effluent quality for COD 12.40 mg/L, BOD 1.96 mg/L, phosphorus 0.39mg/L, TN 6.47 mg/L was less as compared to effluent on minimum rainfall COD 23.25 mg/L, BOD 2.75 mg/L, phosphorus 0.41 mg/L, TN 8.25 mg/L. Overall, NH_4 in the outflow was consistently removed to a minimum.

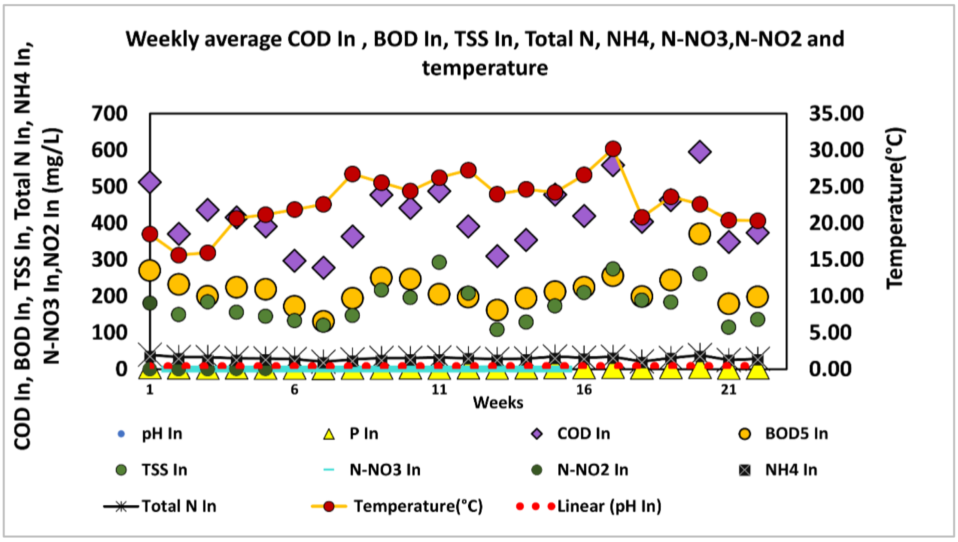

Figure 5. WWTP incoming with respect to temperature

Figure 5. demonstrates the highest temperature was 30.18°C (week 17), and the lowest was 15.62°C (week 2). During higher temperatures, influent COD (558.6 mg/L), BOD (256 mg/L), TSS (274 mg/L), phosphorus (5 mg/L), TN (34 mg/L), and NH_4 (29.54 mg/L) were greater than at lower temperatures (COD 370.4 mg/L, BOD 232 mg/L). This suggests that warmer temperatures increase influent wastewater strength, particularly BOD, COD, and TSS, as elevated temperatures enhance microbial activity (Abdulla & Farahat, 2020). Nitrogen compounds, however, were lower at warmer temperatures due to intensified nitrification and denitrification, helping maintain ammonium levels within regulatory limits (Marius Adrian et al., 2019). Nonetheless, future temperature increases may negatively impact plant operations.

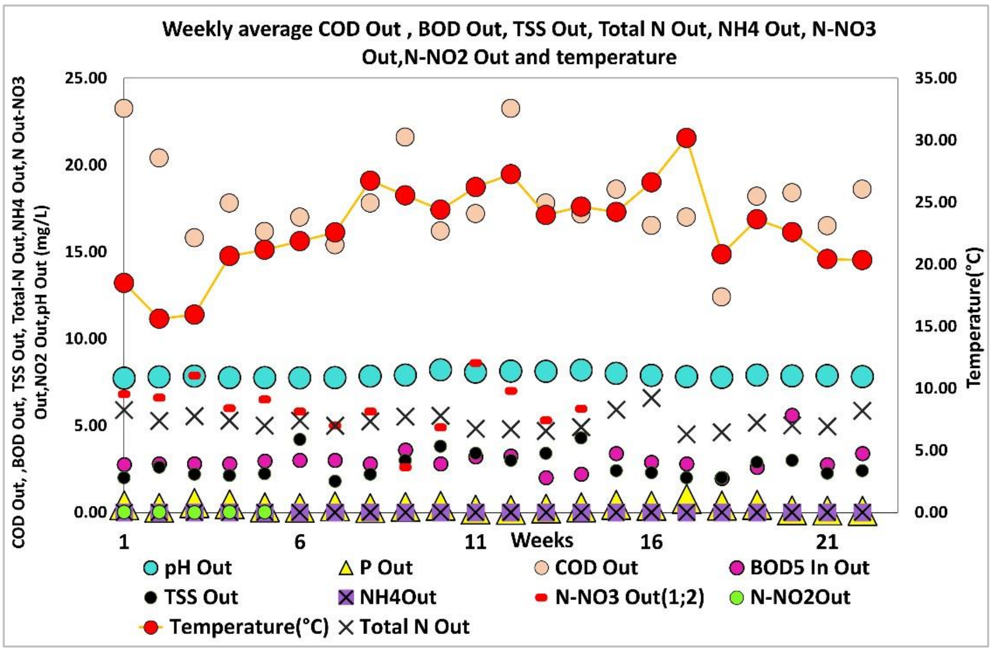

Figure 6. WWTP outgoing parameters with respect temperature

In comparison the effluent at maximum and minimum temperature results show the effluent results at high temperature were COD 17 mg/L, BOD 2.80 mg/L, phosphorus 0.78 mg/L, TN 6.30 mg/L, as compared to minimum temperature i.e. COD 20.40 mg/L, BOD 2.80 mg/L, phosphorus 0.26 mg/L, TN 7.38 mg/L. Surprisingly, quality at the peak temperature is similar to the minimum temperature illustrating enhanced plant performance as demonstrated in Figure. 6.

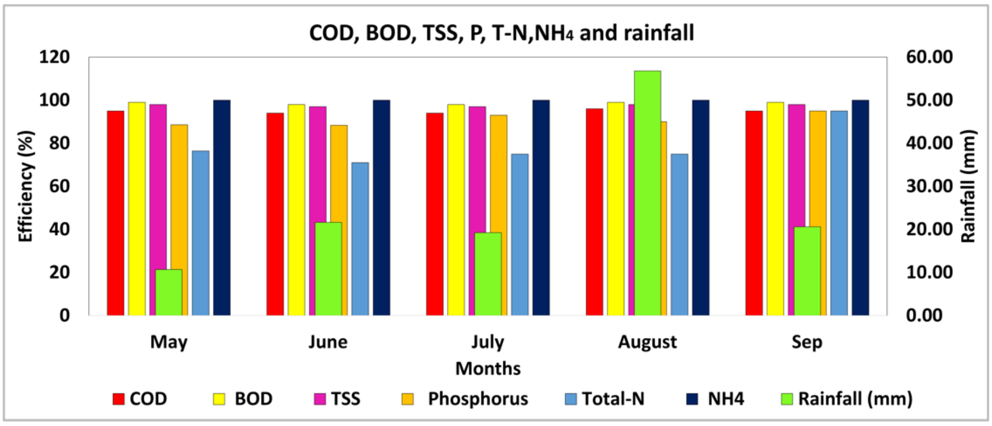

Figure 7. Monthly efficiency of WWTP with respect to rainfall

Figure 7. represents August, with the highest rainfall (56.80 mm), the WWTP achieved high removal efficiencies: COD 96%, BOD 99%, TSS 98%, phosphorus 90%, NH_4 100%, while TN was slightly lower at 75%, likely due to flow fluctuations and potential pipe leaks

affecting nitrogen removal (Bugajski et al., 2017; Kozłowski et al., 2021). Rainfall, contributing 75% of sewage inflow, diluted the influent, improving treatment efficiency without exceeding plant capacity (Marius Adrian et al., 2019; Mines et al., 2007) . Even during the lowest rainfall (10.70 mm), treatment remained stable, with rainfall generally improving effluent quality by diluting wastewater (Kozłowski et al., 2021; Marius Adrian et al., 2019; Rouleau et al., 1997)

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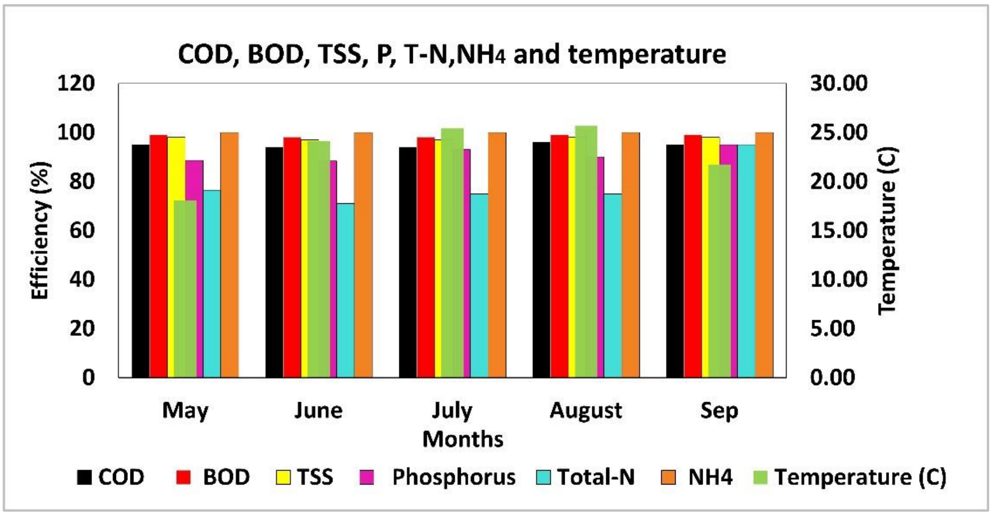


Figure 8. Monthly efficiency of WWTP parameters with respect to temperature

Figure 8. demonstrates August, the highest temperature recorded was 25.67°C, with removal efficiencies of BOD 99%, TSS 98%, COD 96%, phosphorus 90%, TN 75%, and NH_4 100%. In May, the lowest temperature was 18°C, with similar performance: BOD 99%, COD 95%, TSS 98%, phosphorus 89%, and TN 76%. Phosphorus removal slightly decreased at lower temperatures due to reduced microbial activity (Liu & Li, 2015) . Overall, temperature had minimal impact on performance, possibly due to the plant's effective system and the lack of significant temperature extremes during the study (Skoczko et al., 2017). pH remained stable (6.5–8.4) regardless of rainfall or temperature changes.

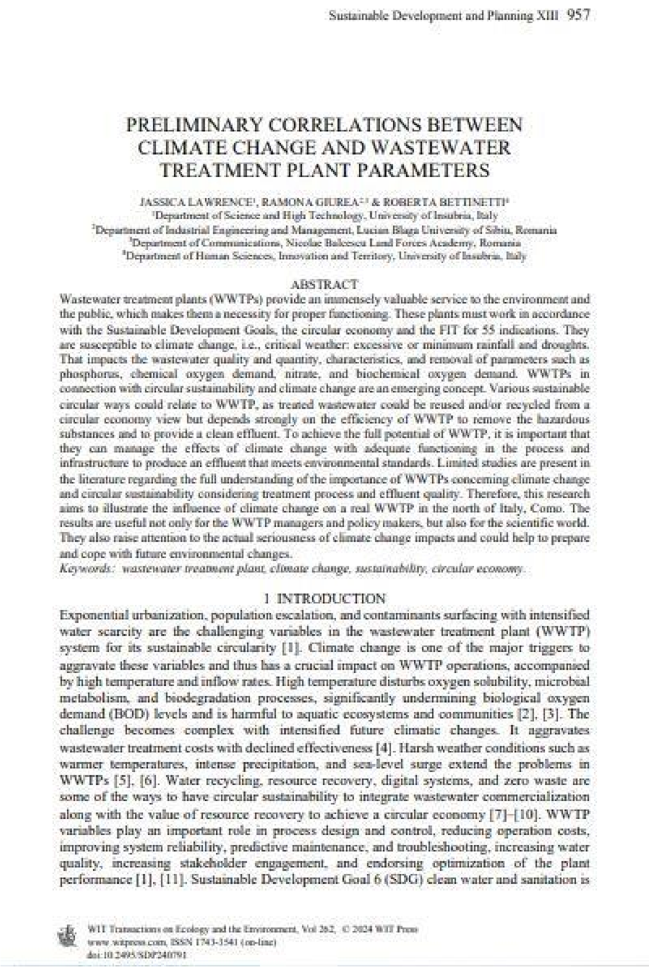
Extreme weather, especially increased rainfall, significantly affects wastewater treatment plants, with economic, socio-cultural, and environmental consequences:

- **Economic Impact:** Flooding and spillage raise residential costs, cause business losses, particularly in seafood and recreation sectors, and increase maintenance expenses for water quality management (Curtis et al., 2017; Europe et al., 2013; Fatorić et al., 2017; Wang et al., 2017).

- **Socio-Cultural Impact:** Poor water quality leads to health risks, mental health issues, infections, and disrupts communities, negatively affecting tourism and recreational activities(Ahern et al., 2005; Carmichael et al., 2018; Durette et al., 2009; Europe et al., 2013; Fatorić et al., 2017; King, et al., 2013; National Institute for Occupational Safety and Health (NIOSH), 2012.; Rirsch & Zhang, 2010; Vardoulakis et al., 2015; Wang et al., 2017).
- **Environmental Impact:** Unrestricted wastewater discharge during heavy rainfall degrades water quality, reduces waterway resilience, and is further exacerbated by sea-level rise, which can lead to coastal flooding and increased groundwater intrusion, compromising drainage systems and intensifying pollutant loads. Temperature extremes also contribute to these challenges (Hughes et al., 2021).

4.4 Conclusion

In conclusion, climate change significantly affects municipal wastewater treatment plants by altering influent composition and flow due to extreme rainfall and temperature. This preliminary study indicates the need for longer-term research to understand plant behaviour under these conditions. Weekly averages of influent and effluent quality reflect weather impacts on treatment performance. Furthermore, the relationship between WWTP operations and climate change has cascading effects on the circular economy and sustainability, highlighting the importance of further investigation to adapt to future climate challenges. The Figure 9. represents the abstract of the conference paper titled “Preliminary Correlations Between Climate Change and Wastewater Treatment Plant Parameters”.



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PRELIMINARY CORRELATIONS BETWEEN CLIMATE CHANGE AND WASTEWATER TREATMENT PLANT PARAMETERS

JASSICA LAWRENCE[1], RAMONA GIUREA[2,3] & ROBERTA BETTINETTI[4]
[1]Department of Science and High Technology, University of Insubria, Italy
[2]Department of Industrial Engineering and Management, Lucian Blaga University of Sibiu, Romania
[3]Department of Communications, Nicolae Balcescu Land Forces Academy, Romania
[4]Department of Human Sciences, Innovation and Territory, University of Insubria, Italy

ABSTRACT

Wastewater treatment plants (WWTPs) provide an immensely valuable service to the environment and the public, which makes them a necessity for proper functioning. These plants must work in accordance with the Sustainable Development Goals, the circular economy and the FIT for 55 indications. They are susceptible to climate change, i.e., critical weather: excessive or minimum rainfall and droughts. That impacts the wastewater quality and quantity, characteristics, and removal of parameters such as phosphorus, chemical oxygen demand, nitrate, and biochemical oxygen demand. WWTPs in connection with circular sustainability and climate change are an emerging concept. Various sustainable circular ways could relate to WWTP, as treated wastewater could be reused and/or recycled from a circular economy view but depends strongly on the efficiency of WWTP to remove the hazardous substances and to provide a clean effluent. To achieve the full potential of WWTP, it is important that they can manage the effects of climate change with adequate functioning in the process and infrastructure to produce an effluent that meets environmental standards. Limited studies are present in the literature regarding the full understanding of the importance of WWTPs concerning climate change and circular sustainability considering treatment process and effluent quality. Therefore, this research aims to illustrate the influence of climate change on a real WWTP in the north of Italy, Como. The results are useful not only for the WWTP managers and policy makers, but also for the scientific world. They also raise attention to the actual seriousness of climate change impacts and could help to prepare and cope with future environmental changes.

Keywords: wastewater treatment plant, climate change, sustainability, circular economy.

1 INTRODUCTION

Exponential urbanization, population escalation, and contaminants surfacing with intensified water scarcity are the challenging variables in the wastewater treatment plant (WWTP) system for its sustainable circularity [1]. Climate change is one of the major triggers to aggravate these variables and thus has a crucial impact on WWTP operations, accompanied by high temperature and inflow rates. High temperature disturbs oxygen solubility, microbial metabolism, and biodegradation processes, significantly undermining biological oxygen demand (BOD) levels and is harmful to aquatic ecosystems and communities [2], [3]. The challenge becomes complex with intensified future climatic changes. It aggravates wastewater treatment costs with declined effectiveness [4]. Harsh weather conditions such as warmer temperatures, intense precipitation, and sea-level surge extend the problems in WWTPs [5], [6]. Water recycling, resource recovery, digital systems, and zero waste are some of the ways to have circular sustainability to integrate wastewater commercialization along with the value of resource recovery to achieve a circular economy [7]–[10]. WWTP variables play an important role in process design and control, reducing operation costs, improving system reliability, predictive maintenance, and troubleshooting, increasing water quality, increasing stakeholder engagement, and endorsing optimization of the plant performance [1], [11]. Sustainable Development Goal 6 (SDG) clean water and sanitation is

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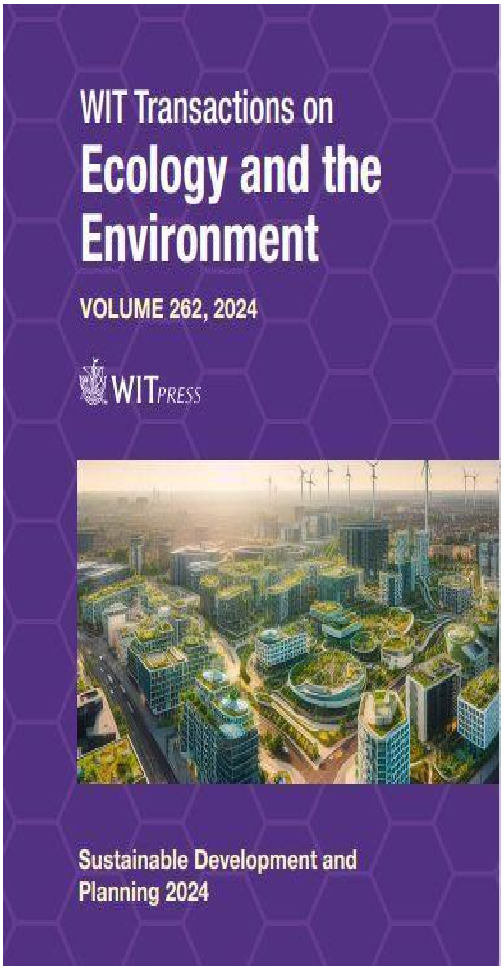

Figure 9. Preliminary Correlations Between Climate Change and Wastewater Treatment Plant Parameters

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Chapter 5: Monitoring of Aquatic Debris

In this chapter, I discussed the introduction, discussion and main findings of research work I published i.e., "Monitoring Aquatic Debris in a water environment using a remote operating vehicle (ROV): A Comparative Study with implications of algal bloom detection in Lake Como (Northern Italy)". The full citation for this paper is as follows:

Lawrence, J., Castelnuovo, N., & Bettinetti, R. (2024). Monitoring aquatic debris in a water environment using a remotely operated vehicle (ROV): A comparative study with implications of algal detection in Lake Como (Northern Italy). *Environments, 12*(1), 3. https://doi.org/10.3390/environments12010003. and the conference paper "Preliminary exploration of underwater debris in Lake Como, Italy during the high tourist season for environmental protection during my final year. The full reference is Lawrence, J., Castelnuovo, N., Giurea, R., & Bettinetti, R. (2024). Preliminary exploration of underwater debris in Lake Como, Italy during the high tourist season for environmental protection. In *Proceedings of the Proteus Association Conference*, Villa Geno, Como, Italy, pp. 1-8, IEEE. Figure 10. represents the published article "Monitoring aquatic debris in a water environment using a remotely operated vehicle (ROV): A comparative study with implications of algal detection in Lake Como (Northern Italy)".

5. Introduction

Monitoring aquatic debris in freshwater systems is crucial because it presents a growing threat to biodiversity, ecosystem health, and water quality worldwide. Traditionally, this monitoring involved manual methods like visual inspections by motorboats, which are time consuming and limited in scope (Bajaj et al., 2021; Jambeck et al., 2015). Recent advancements in Remote Operating Vehicles (ROVs), however, have significantly improved the process. These automated technologies offer scalable solutions, enabling real-time data collection and continuous video capture across various aquatic environments (Neha & Krishnan, 2024; Castelnuovo et al., 2024; Schultz et al., 2015). Nevertheless, environmental conditions such as water turbidity and reduced light, especially during algal blooms, can hinder ROV effectiveness, decreasing detection accuracy (Chung et al., 2015; Foglini et al., 2019). This study addresses the gap in understanding how environmental visibility challenges, specifically caused by algal blooms—affect the performance of ROV-based debris detection in real-world conditions. Unlike prior research conducted under controlled or optimal settings, this study compares the effectiveness of ROVs in detecting submerged debris during two distinct years—2019 and 2024—in Lake Como, Northern Italy. The observations revealed that reduced water clarity caused by algal blooms in 2024 significantly impacted the visibility of debris on the lakebed, which was not as challenging in 2019. By documenting these visibility challenges and comparing the debris counts between the two survey periods, the study highlighted the limitations of ROV-based debris monitoring in freshwater systems under reduced visibility conditions. This research further provides valuable insights into the types of debris observed and emphasizes the need to consider environmental factors such as algal growth when conducting underwater debris assessments.

5.1 Discussion and main findings

5.1.1 Influence of Algal Growth on Debris Detection

In 2024, algal growth during warmer months likely reduced water clarity in Lake Como, hindering the ROV's ability to detect debris. Thus, the decreased debris counts may reflect visibility challenges rather than a true decline in debris accumulation (Lund-Hansen et al., 2028; Upadhyay & Papadakis, 2024; Watanabe et al., 2019). Previous studies using ROVs for underwater monitoring also highlighted the disturbances caused by algae (Watanabe et al., 2019). While algal blooms complicate ecosystem monitoring (Codd et al., 2005; Corbel et al., 2014; Lan et al., 2024), our focus was on debris detection. For instance, in our study, visibility declined from March to June 2024, coinciding with peak algal activity, whereas data from January to February, when algal levels were lower, likely provides a more reliable measure of debris. This emphasizes the need for timing in monitoring and suggests using alternative detection technologies or scheduling surveys during low algal periods. These results align with other reports of clarity issues in water caused by algae (Volent et al., 2007; Johnsen et al., 2020).

5.1.2 Interpretation of Debris Count Differences and Statistical Significance

In this study, all data were collected using a remotely operated vehicle (ROV), not an underwater drone. This distinction is important, as the ROV was specifically suited for detailed underwater surveys, while drones are typically used for aerial surveys. The statistical analysis was performed using a t-test to compare the data from the same months across different the two studied years (2019 and 2024). The significant decrease in visible debris in 2024, as indicated by the t-test results, likely reflects the impact of algal blooms and increased turbidity, which hindered visibility. Although the total debris counts in 2024 were visibly lower than in 2019, the paired t-test result ($p = 0.061$) suggests that this difference is not statistically significant at the 0.05 threshold. This outcome might seem surprising given the large numerical difference, but several factors may explain the result: 1) Small Sample Size: The analysis was based on data from just three months (April, May, and June), A paired t-test was selected as the appropriate statistical method for this analysis, as it compares data collected from the same periods (i.e., identical months across two years) out of total eleven months of study between 2019 and 2024, which limits the statistical power of the test. With such a small dataset, even large differences in observed counts may not reach statistical significance. 2) High Variability in 2019 Data: The debris counts in 2019 varied significantly, particularly the high count recorded in May (111 objects). This variability contributes to a higher standard deviation in the 2019 dataset, which reduces the statistical strength of the observed decline in 2024. 3) Environmental Factors in 2024: The reduced water clarity in 2024, likely caused by algal blooms, may have affected the ROV's ability to detect debris, leading to potential underreporting. This introduces a detection bias that complicates direct comparisons between the two years. While the p-value (0.061) is close to the significance threshold, it remains insufficient to reject the null hypothesis. Therefore, additional data collection is necessary to better understand whether the observed reduction represents a genuine trend in debris accumulation or is influenced by environmental and methodological factors. This dramatic decrease in both metal and plastic debris suggests that external factors influenced debris levels. However, the reduced debris count in 2024, especially the near absence of metal items in later months, may not be solely attributed to an actual reduction in debris.

5.2 Conclusion

This study provides valuable insights into the aquatic debris present in Lake Como by comparing debris counts and types between 2019 and 2024 using remotely operated vehicle (ROV) technology. The significance of this research lies in its ability to highlight the dynamic changes in debris composition and the challenges of monitoring aquatic environments over time. Our findings show a noticeable reduction in both plastic and metal debris in 2024 compared to 2019, suggesting potential improvements in waste management, natural sedimentation processes, or changes in environmental conditions. In 2019, metal items like soda cans and plastic debris such as candy wrappers were the most common, with counts peaking in the spring months (April and May). In contrast, 2024 saw a marked decrease in these items, with a total of only 39 debris items recorded during the same period. This change underscores a possible trend toward cleaner aquatic conditions, though it is important to note that the environmental factors, such as algal blooms and increased water turbidity in 2024, significantly impacted visibility. These conditions made it difficult to detect smaller or submerged debris, potentially leading to undercounts, particularly in March and April 2024. Despite the visual differences, statistical analysis using a paired t-test showed no statistically significant difference between debris counts in 2019 and 2024 ($p = 0.061$). This lack of statistical significance suggests that while there were clear visual reductions in debris, the ability to accurately detect debris in 2024 was hindered by challenging environmental conditions. This finding highlights the complexity of debris monitoring and the need to account for such factors when interpreting the results. The study contributes to the field by emphasizing the critical role of environmental factors, such as turbidity, sedimentation, and algal blooms, in influencing the effectiveness of debris detection methods, particularly when using ROVs. The results indicate the need for continuous improvement in monitoring techniques to overcome these challenges, including the integration of complementary technologies, such as sonar, to enhance debris detection in low-visibility conditions. In conclusion, this research provides important insights into the debris dynamics of Lake Como and stresses the necessity for ongoing monitoring of freshwater systems to track the trends in aquatic pollution. Although the study did not find statistically significant differences between the two years, the observed reduction in debris points toward positive environmental changes and improved waste management. Continued research with enhanced methodologies will be crucial for addressing the challenges of aquatic debris and guiding effective conservation strategies in freshwater ecosystems.

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Monitoring Aquatic Debris in a Water Environment Using a Remotely Operated Vehicle (ROV): A Comparative Study with Implications of Algal Detection in Lake Como (Northern Italy)

Jassica Lawrence [1,*], Nicola Castelnuovo [2] and Roberta Bettinetti [3,*]

[1] DISAT Department of Science and High Technology, University of Insubria, Via Valleggio 11, 22100 Como, Italy
[2] Proteus Association, Center for Environmental Education and Scientific Dissemination, Villa Geno, 22100 Como, Italy; castelnuovonicola@hotmail.com
[3] DiSUIT Department of Human Science and Innovation for the Territory, University of Insubria, Via Valleggio 11, 22100 Como, Italy
* Correspondence: jlawrence@uninsubria.it (J.L.); roberta.bettinetti@uninsubria.it (R.B.)

Abstract: This study investigates underwater debris in a freshwater lake using remotely operated vehicles (ROVs) during two distinct survey periods: 2019 and 2024. The primary objective was to count and document visible debris (metal and plastic) on the lakebed based on ROV video recordings. A total of 356 debris items were observed in 2019, while only 39 items were recorded in 2024. The notable decrease in debris visibility in 2024 is likely attributed to dense algal growth during the survey months, which hindered the visual identification of objects on the lakebed. The study highlights the challenges of monitoring underwater debris in freshwater systems, particularly during periods of high algal activity, which can significantly impact visibility and detection efforts. While ROVs have proven effective in identifying submerged debris in clear water, this research underscores their limitations under reduced visibility conditions caused by algal blooms, turbidity diminishing the video quality. The results provide valuable insights into the temporal variation in debris visibility and contribute to ongoing efforts to improve freshwater debris monitoring techniques.

Keywords: debris; ROV; lake; algal blooms

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1. Introduction

Aquatic debris poses a growing threat to biodiversity, ecosystem health, and water quality on a global scale. Traditionally, debris monitoring relied on manual methods such as visual inspections by motorboats, which are labor-intensive and limited in scale [1–3]. In recent years, remotely operated vehicles (ROVs) have emerged as valuable tools for underwater environmental monitoring [4–8]. They enable precise spatial and temporal surveys of marine ecosystems and scattered debris. However, challenges such as high manufacturing costs, significant weight, and large size can limit their effectiveness for broad-scale or dispersed area monitoring [4,5,8–13]. Despite these constraints, ROVs remain efficient for large-scale surveying due to their adaptability and accuracy [14–17].

However, advancements in ROVs have transformed underwater debris monitoring by providing automated, scalable solutions capable of real-time data collection and continuous video capture in different aquatic environments [18–20]. Despite these technological advancements, environmental factors such as water turbidity and light attenuation, partic-

Environments **2025**, *12*, 3 https://doi.org/10.3390/environments12010003

Figure 10. Monitoring aquatic debris in a water environment using a remotely operated vehicle (ROV): A comparative study with implications of algal detection in Lake Como (Northern Italy)

5.3 Discussion and main findings (Conference paper)

Figure. 11 represents the published article "Preliminary exploration of underwater debris in Lake Como, Italy during the high tourist season for environmental protection". Among the debris, metal, and plastic objects were the predominant material types found in May, while glass and wood debris were the least common. In May the highest count of metal objects was 65, followed by 43 in August and 39 in November, while 31 in June and the lowest (25) were counted in April. The most common plastic object was candy wrapping packaging found in all the months. The highest counted was in April and November i.e., (20). The second highest candy wrapping packaging was counted in May i.e., (15). Besides, in April, 8 disposable cups, 6 short plastic pipes, 4 plastic bottles, 3 plastic chairs, 1 plastic shovel, and 1 table were counted. In May, 7 plastic chairs, 4 disposable cups, 4 plastic bottles, 2 short plastic pipes, 2 tires, 1 plastic shovel, 1 plastic table, 1 croc shoe, 1 disposable fork, 1 plastic wire, and 1 plastic toy were counted. In June, 6 candy wrapping packaging, 2 tires, 2 umbrella plastic parts, 1 disposable cup, 1 plastic chair, 1 short plastic pipe, 1 toy, 1 lamp stand, 1 camera stand, and 1 plastic part beach bed were counted. Whereas, in August 13 candy wrapping packaging, 2 disposable cups, and 1 plastic bottle were counted. Finally, in November, 7 disposable cups, 3 buckets, 1 short plastic pipe,1 tire,1 straw, 1 dust bin, and 1 plastic goggle were counted. The results show that metal and plastic were present on the Lake Como sediments.

In this study Lake Como concerning seasonal and tourist aspects were investigated from May 2020 to August 2021. The intense pressure was found on Lake Como particularly during weekends in summer (up to +14% than weekdays in winter), indicating tourism is the crucial reason. The results suggested a strong correlation between human activities and lake-water quality related to human activities and tourism (Vavassori et al., 2022). The Italian legislative framework for the prevention of plastic pollution encompasses the following measures: • Italy has become the first European country to implement the Charter banning the use of plastic microbeads in certain cosmetics (excluding soaps and detergents) (Giurea et al., 2018). This study is exploring the significance of environmental conservation and management in popular tourist destinations such as Lake Como, Italy, where the presence of underwater debris represents a potential threat to the ecosystem. A preliminary investigation of underwater debris in Lake Como during the peak tourist season serves to highlight the necessity of sustainable tourism practices to preserve the environment for future generations and it also identifies a pressing need for environmental optimization in touristic areas in order to protect natural resources (Giurea et al., 2018) and (Schiavon et al., 2022).

5.4 Conclusion

The waste objects accumulate on lake sediments. However, the objects such as chairs and beach beds constantly accumulate due to nearby commercial restaurants. Due to lake sedimentation the objects underwater get covered in sand and some of them are moved due to tides. This unusual dynamic needs more research in detail given its serious impact. However, this study can be a guide to highlight the issue in Lake Como and stimulate the environmental agencies to focus on sustainable tourism and pollution prevention.

Preliminary exploration of underwater debris in Lake Como, Italy during the high tourist season for environmental protection

Jassica Lawrence
Department of Science and High Technology
University of Insubria
Como, Italy
jlawrence@uninsubria.it

Ramona Giurea
[1]Department of Industrial Engineering and Management
Lucian Blaga University of Sibiu
Sibiu, Romania
[2]Communications, IT and Cyber Security Department, Nicolae Balcescu Land Forces Academy
Sibiu, Romania
ramona.giurea@ulbsibiu.ro

Nicola Castelnuovo
Proteus Assiciation, Villa Geno
Como, Italy

Roberta Bettinetti
Department of Human Sciences, Innovation and Territory
University of Insubria
Como, Italy
roberta.bettinetti@uninsubria.it

***Abstract*—. This study presents baseline information on the status of debris accumulation on Lake Como sediments, including the type and quantity of debris over various months during the high tourist season. The study highlights its ecological and human impacts and suggests the management strategies necessary for environmental protection. This research contributes to environmental conservation efforts in Lake Como by encouraging the implementation of measures to prevent lake pollution. The results indicate that in May, 70% of the objects found in Lake Como were made of metal, while 41% were made of plastic. This raise concerns as Lake Como is a frequented spot for tourists and recreational activities. Therefore, understanding the pattern of debris accumulation over time and identifying debris hotspots can be useful in taking proactive measures to protect the environment.**

***Keywords*— environmental protection, management strategies, debris, impacts, pollution prevention, tourist attraction.**

I. Introduction

Lake Como is a famous tourist destination particularly Como Bay highest number of tourists arrive in Spring and Fall with a weekly rise on weekends. There is an average upsurge of 14.0% during weekends and 10.8% in peak tourism period in high season weekends than weekdays in the low season, thus suggesting patterns are strongly affected by recreational and tourism activities on the lake[1] . The major municipalities are Como and Cernobbio. Their populations, 84,250 and 6,498 inhabitants, give a density of 2,300 and 536 inh./km^2, respectively as reported by ISTAT[2] . Potable water consumption, wastewater, municipal solid waste, are related and also influenced by the tourism of people living particulary in NW Lombardy and neighbouring Canton Ticino (Switzerland)[2], [3], [4], [5], [6]. Moreover, cases of water ans wastewater contamination were reported in heavily populated and industrialized areas[7], [8], [9]. Lake Como is a prominent famous place for tourism, culture, and historical prose heritage. It serves multipurpose i.e. aesthetics, water sports, recreational, irrigation hydropower, and flood risk prevention alongside shores. Lake Como is an important lake in the North of Italy. It also collects water utilized for irrigation in the Po Valley downstream[10].

Freshwater lakes play an essential role in rendering ecosystem services[11] . Anthological activities create disturbance to the core of the ecosystem. Thus, it harms key aquatic organisms such as phytoplankton, fish, and most importantly zooplankton are impacted by lake pollution[12] . Zooplankton is commonly used as an environmental risk indicator in aquatic ecosystems[13] . It is a food and energy transfer organism among the food webs between primary producers (phytoplankton) and the upper levels (invertebrate predators) and is receptive to changes in abiotic factors through space and time[14], [15], [16]. Underwater monitoring in lakes provides useful information on lake pollution particularly the debris objects being accumulated on the sediments due to human activities and impacts the health of lakes, rivers, oceans, and the ecosystem [17], [18].

Underwater debris is human-produced waste found in water bodies and is a serious environmental concern. The debris puts enormous risk to aquatic ecosystems, human health, and water transportation. Such as debris damaged the habitat of 4 to 10 million crabs a year in Louisiana[1] and caused damages like propeller entanglement to fishing boats [19]. Therefore, it is vital to monitor the debris emergence and warn the authorities to take preventive measures to avoid possible risks[20]. Studies present the presence of DDT, PCB, plastic, and pharmaceuticals in Lake Como[12], [20]. The purpose of this study is to indicate the predominant objects and materials found underwater on lake sediments, particularly during summer when tourism is at its peak suggested mitigation measures for environmental protection and help environmental management authorities to take better management steps to prevent environmental damage.

II. Methods

Study area: The study site Village, Lake Como is a peninsula Villa Geno locality, extending slightly to the centre of the first part of the Lake Como basin (Lake Como, Northern Italy), 1 km north of the city of Como. This site gives supportive access to the lake, and thus, aids with easier handling of drones. The start point of monitoring is the parking area at the site. The surface of the lake is slightly tilted but is levelled at the end of the location where most of the accumulation gathers.

Tool: The drone Remote Operating Vehicle (ROV) was used to record the debris objects. It is a water drone, attributed to reasonable price, are optimum devices to record underwater videotaping. The model used in the present is a Trident from Open Rov snc. Trident is associated with Raspberry Pi shield programmed to record a video from a CCD sensor and to manage information from a controller, cabled to the surface with a 100 meters tether. It is assembled with LED lights (approximately 200 luminosity of brightness), thermometer, depth sensor and internal digital compass for navigation. In this study, a smart phone (iPhone) was used to control the drone and application. Alternatively, a control pad (i.e. a gaming pad) connected via Bluetooth may be used to increase the precision. Data, such as depth, temperature, direction, and battery life, are visible from the application in real time via On-Screen Display (OSD).

Littoral videos in the months of (April, May, June, August, and November 2019) were considered to count the number of objects due to better quality in the same area to understand the pattern of accumulation, The drone Remote Operating Vehicle (ROV) was installed 10 m depth below the water surface.

Video Quality: Each month has six video transects to understand and count the debris. For this study, it was better to consider littoral HQ videos rather than profound ones due to the better quality.

III. RESULTS AND DISCUSSION

Among the debris, metal, and plastic objects were the predominant material types found in May, while glass and wood debris were the least common. In May the highest count of metal objects was, i.e. 65, followed by 43 in August and 39 in November. While 31 in June and the lowest 25 were counted in April.

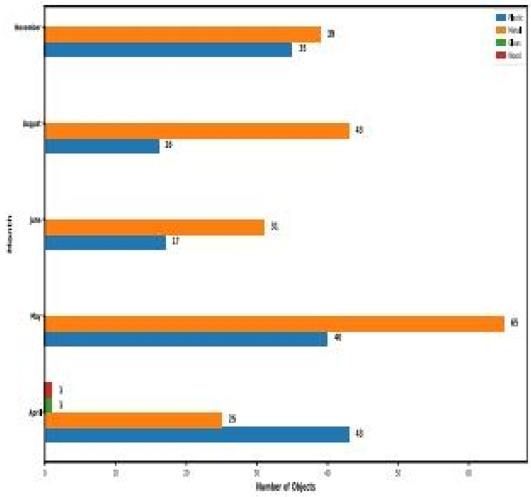

Fig. 1. Material category distribution with respect to months.

Furthermore, Fig.2 illustrates the composition of debris material over the five months. The percentage of metal was 57% metal and plastic was 43%.

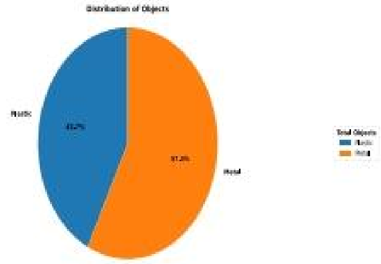

Fig. 2. Debris material composition by percentage

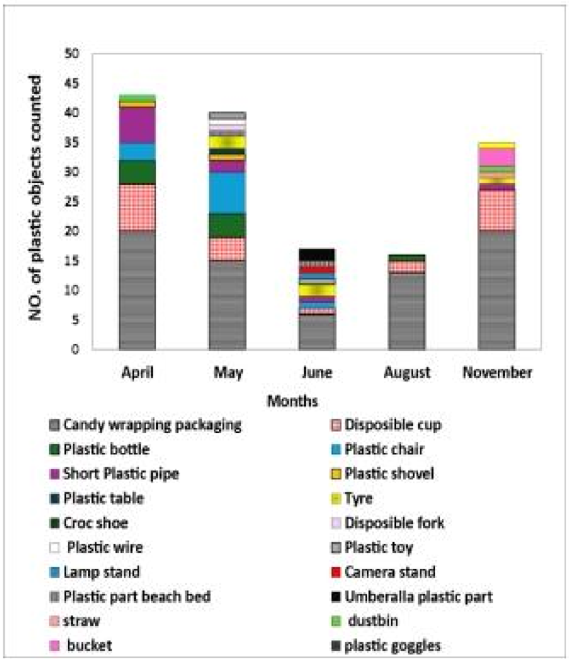

Fig. 3. Total plastic objects per month.

In Fig.3 among the plastic objects the highest number of total plastic objects, were in April i.e. 43. The dominant plastic object found in all months was candy wrapping packaging. The highest candy wrapping packaging counted was in April and November i.e. 20, followed by May 15, August 13 and June 6. The second highest object found in all months was disposable cup particularly highest in April i.e. 8, followed by November 7, May 4, August 2 and June 1. The rest of the objects were not present in all the months constantly. The highest count was attributed to the fact that April is one of the peak months for tourism, although the entire season is full of tourists due to school holidays and favourable weather conditions [2]. It has been concluded based on preliminary monitoring and quantification, that there is potential waste accumulated at the bottom of the lake. Therefore, it is important to understand the pattern and sources of this waste to effectively mitigate and manage the underwater debris.

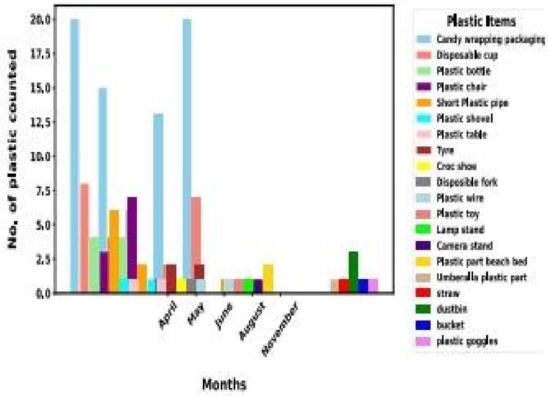

Fig. 4. Comparison of plastic objects per month.

The most common plastic object was candy wrapping packaging found in all the months. The highest counted was in April and November i.e. 20. The second highest candy wrapping packaging was counted in May i.e. 15. Besides, in April, 8 disposable cups, 6 short plastic pipes, 4 plastic bottles, 3 plastic chairs, 1 plastic shovel, and 1 table were counted. In May, 7 plastic chairs, 4 disposable cups, 4 plastic bottles, 2 short plastic pipes, 2 tires, 1 plastic shovel, 1 plastic table, 1 croc shoe, 1 disposable fork, 1 plastic wire, and 1 plastic toy were counted.

In June, 6 candy wrapping packaging, 2 tires, 2 umbrella plastic parts, 1 disposable cup, 1 plastic chair, 1 short plastic pipe, 1 toy, 1 lamp stand, 1 camera stand, and 1 plastic part beach bed were counted. Whereas, in August 13 candy wrapping packaging, 2 disposable cups, and 1 plastic bottle were counted. Finally, in November, 7 disposable cups, 3 buckets, 1 short plastic pipe,1 tire,1 straw, 1 dust bin, and 1 plastic goggles were counted. The results show that metal and plastic were present on the Lake Como sediments. Anthropogenic activities are the fundamental causes of eutrophication and water pollution.

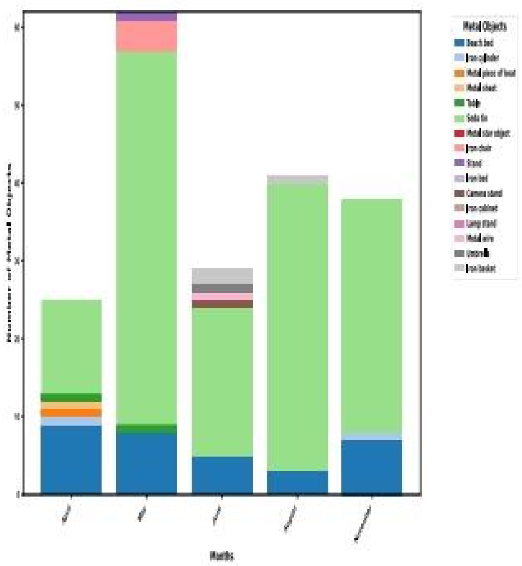

Fig. 5. Total count of monthly metal objects per month

Among the metal objects, the highest count was observed in May, i.e. 65. The dominant metal object found in all the months was soda tin. The highest count of soda tin was in the month of May i.e. 48 followed by August, 37 and November, 30. The second most object found in all the months was the beach bed. The highest count was observed in April (9) followed by May (8) and November (7), June (5) and the least was in August (3 were counted). The rest of the objects were not present in all the months constantly.

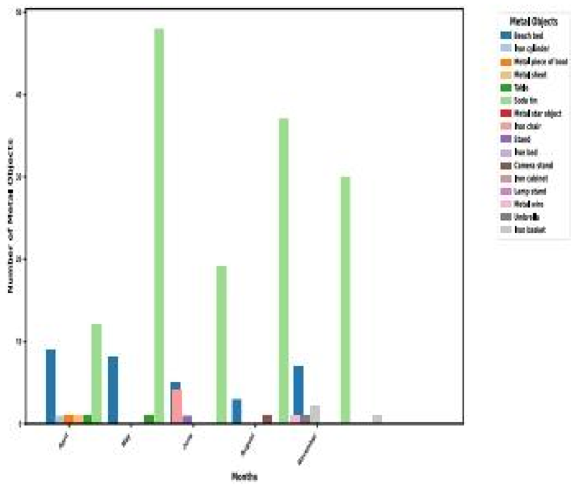

Fig. 6. Comparison of metal objects per month

In Fig 6 the object table in April, May and November was counted 1 of each. Whereas in April iron cylinder, metal piece of boat, and metal sheet were counted 1 of each. While in May metal star object, iron stand, metal part of umbrella and iron bed were counted to be 1 of each. While in June, 2 iron cabinets and 2 umbrellas were counted. Also, metal wire, lamp stand, and camera stand 1 of each were counted. While in August, 2 iron stands and 1 iron basket were counted. Finally, in November the other counted object was iron cylinder i.e..1.

In this study Lake Como concerning seasonal and tourist aspects was investigated from May 2020 to August 2021. The intense pressure was found on Lake Como particularly during weekends in summer (up to +14% than weekdays in winter), indicating tourism is the crucial reason. The results suggested a strong correlation between human activities and lake-water quality related to human activities and tourism[1] .

Amusement activities such as fishing swimming and boating etc have a direct impact on lakes. For example: boating disturbs aquatic plants and agitates the sediments which develops algal growth. Eventually, all sorts of tourist activities on the premises around lake catchments such as the construction of sports centers and holiday villages for vacations impact the lake ecosystem due to land use disturbances[21], [22] undermining the capacity of nutrients of natural waterways and promoting intense pollution loads [23].

Several studies investigated the impacts of water pollution and tourism ventures. The West Lake Basin in China was investigated to understand the impacts of tourism and pollution, on touristic business income and tourist waste spike and suggested that these variables have a direct correlation with each other[24]. In this study, the impact of anthropogenic activities such as land usage, soil degradation, and water quality decline in Plastira Lake in Greece was evaluated. The results revealed that the tourism business is one of the most crucial reasons to affect water quality and environmental disturbances [25]. Similarly, in our study, the debris objects were certainly present in all the tourist seasons on Lake sediments.

Ecological and human implications of debris accumulation: Debris accumulation by humans threatens aquatic organisms leading to detrimental ecological effects. Almost 82% of impacts were caused by plastic relative to other materials (e.g., metals, glass) and largely (89%) at sub-organismal levels (e.g., molecular, cellular, tissue) of aquatic organisms. Also, the other impacts were caused majorly by plastic debris objects such as rope, straws, and fragments leading to accelerated mortality of organisms, and disturbing the entire food web This study and all the literature privies sufficient evidence of debris accumulation in Lake Como sediments to take mitigation measures by the management and policymakers to prevent environmental pressure to go beyond repair [25]. Several human health risks are associated with food quality related to seafood and debris waste accumulation[26]. Among these micro debris pollution microplastic has become a major concern of human and environmental well-being[27]. Microdebris (0.1 um to 5 mm) synthetic, semi-synthetic, and naturally derived items capable of persistence and bioaccumulation.

Further, globally. plastic has apparently become a serious issue towards ecosystem[28].The annual plastic production rate was around 370 million metric tons in 2019 [29] and around 4.6% enters into marine waters through rivers and lakes[30], [31]. Large plastic parts are fragmented in microplastics (<5 mm in size—MPs) along with bioaccumulation properties which enhances with reducing size[32] and makes them convenient to enter the food web [33], [34].The transfer of microplastic through aquatic organisms from plankton and fish to birds and even mammals in the ecosystem occurs and eventually affects human health[35].

The Italian legislative framework for the prevention of plastic pollution encompasses the following measures:

- the "Save the Sea" rule permits fishermen to collect waste, including plastics, from the sea and to the coast for recycling;[36]
- since 2018, the use of biodegradable bags has been introduced as an alternative strategy to replace traditional plastic bags;[37]
- Italy has signed the "Ocean Plastic Charter" with the objective of reducing plastic waste and the non-essential use of single-use plastics, as well as advancing recycling and research into plastic alternatives[38];
- Italy has become the first European country to implement the Charter banning the use of plastic microbeads in certain cosmetics (excluding soaps and detergents) [39].

A. Mitigation measures

This study is exploring the significance of environmental conservation and management in popular tourist destinations such as Lake Como, Italy, where the presence of underwater debris represents a potential threat to the ecosystem. A preliminary investigation of underwater debris in Lake Como during the peak tourist season serves to highlight the necessity of sustainable tourism practices in order to preserve the environment for future generations and it also identifies a pressing need for environmental optimization in touristic areas in order to protect natural resources [39], [40].

The following solutions may be helpful in reducing the amount of debris and waste in the lake, were these solutions involve a number of different actors, including managers, inhabitants, tourists, businesses, companies, and many others. It is imperative that all parties involved in the issue communicate and act in unison to identify potential avenues for collaboration.

1. Both private and public sectors from the local to global level must take coordinated action[41]
2. Awareness among persons at all levels is essential Awareness sessions related to beach clean-ups, education programs, etc play a major role in changing the behavior of individuals[42], [43], [44], [45], [46], [47]
3. Behavior changes and awareness raising can be increased through citizen science. Environmental education as a subject must be taught to children at an early stage to understand the importance of cleanliness in the environment. It will be a major step to change the societal mindset[48], [49], [50]
4. Social media Facebook, Instagram, Twitter, etc must be used as an effective tool for establishing communication networks to spread awareness of lake pollution and sustainable tourism. The proper management agencies such as the Global Partnership on Marine Litter, the Marine Litter Network, and the Regional Seas Conventions and Action Plans (RSCAPs) are solid examples to act on the mitigation of lake pollution [51].

IV. Conclusion

The waste objects accumulate on lake sediments However, the objects such as chairs and beach beds constantly accumulate due to nearby commercial restaurants. Due to lake sedimentation the objects underwater get covered in sand and some of them are moved due to tides. This unusual dynamic needs more research in detail given its serious impact. However, this study can be a guide to highlight the issue in Lake Como and stimulate the environmental agencies to focus on sustainable tourism and pollution prevention.

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Figure 11. Preliminary exploration of underwater debris in Lake Como, Italy during the high tourist season for environmental protection

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Chapter 6: Circular Economy and Waste Utilization

6.0 Introduction

The concept of a circular economy focuses on resource utilization throughout the lifecycle of products—preparation, use, and disposal—with the goal of minimizing waste and maximizing resource efficiency (Domenech, 2014; Baskar et al., 2022; Hedlund et al., 2020; Hegedűs & Longauer, 2023; Kirchherr et al., 2023; E. Rada et al., 2021; E. C. Rada et al., 2017). It aims to reduce the negative environmental impacts of activities while enhancing material and product longevity, ultimately rejuvenating the ecosystem (Anaruma et al., 2021; Gabriel & Delgado, 2020; Mazur-Wierzbicka, 2021; Rajput & Singh, 2019). The circular economy plays a key role in achieving the United Nations' Sustainable Development Goals (SDGs), particularly SDG 12, which promotes sustainable consumption and production patterns through resource conservation and proper waste management (Abdelmeguid et al., 2022; Ahmed et al., 2022; Colucci & Vecchi, 2021; Gabriel & Delgado, 2020; Pensupa et al., 2017; Zhuang et al., 2023).

In the textile industry, circular economy practices are highly relevant due to the sector's rapid growth alongside population increases (Gray et al., 2022; Peter John & Mishra, 2023; US EPA, 2017). According to estimates by the United States Environmental Protection Agency (US EPA), in 2017, textile industries produced 16.9 million tons of waste, but only 15.2%—or 2.6 million tons—was recycled (Armstrong et al., 2015). The fashion industry, as a major player in the circular economy, consumes significant non-renewable resources, contributing to environmental degradation and leaving a large ecological footprint. Its production and consumption stages generate substantial pollution, threatening future resource availability (Shirvanimoghaddam et al., 2020).

To address these challenges, research has focused on the reuse and recycling of textile waste, promoting global efforts to repurpose materials and reduce waste (Angelova et al., 2023; Echeverria et al., 2019; Keßler et al., 2021; Hirman et al., 2022; Vėjelis et al., 2023). Recycling offers numerous benefits, such as reducing the need for raw materials, energy, and water, lowering carbon emissions and landfill waste, and creating employment opportunities through labour-intensive recycling processes. However, challenges remain, including high costs, financial and technological barriers, and policy gaps (Gulich, 2006; Paras & Pal, 2018).

Despite successful clothing recovery programs in countries like Denmark, Norway, Sweden, and China, there is still a need to further explore the practical implications of such initiatives across different nations (Gazzetta Ufficiale, 2020; Khan & Rundle-Thiele, 2019; Sandberg, 2023). This paper aims to analyse case studies of effective clothing recovery efforts, comparing their strategies, outcomes, and challenges to offer insights for broader implementation. Figure 12. represents my own published article “Investigating the effectiveness of clothes recovery programs in promoting a circular economy: a review”.

Investigating the effectiveness of clothes recovery programs in promoting a circular economy: a review

Jassica Lawrence[1*], *Roberta* Bettinetti[2], *Vincenzo* Torretta[3], and *Elena Cristina* Rada[3]

[1] University of Insubria, Department of Science and High Technology, 22100 Como, Italy
[2] University of Insubria, Department of Human Sciences, Innovation and Territory, 22100 Como, Italy
[3] University of Insubria, Theoretical and Applied Science Department, 21100, Varese, Italy

Abstract. Textile plays a crucial role in a circular economy and its traditional use needs to be replaced with sustainable ways. A circular economy gives repurpose and value to a resource in a continuous loop to be useful to its maximum extent at the end of stage life. Also, with the increase in population, consumption of resources, inflation, and environmental impacts are aggravated. Therefore, a literature review in this scenario which represents the solutions and the scope to incorporate circular economy with the clothes recovery is useful. The highlight of the review includes external hindrances such as consumer preferences, garment styles, and the need to involve indigenous productions in the regulations of the circular economy. In Swiss fashion firms, it's harder to set circular economy principles as compared to Italy. Further, rich fashion brands do not generally favour the idea of a circular economy. However, a few young businesses, despite the complexities of each stage, are inclined more towards a circular economy. The overview of the current review gives various ideas, limitations, and the future perspective for the application of circular economy integrated with textile. Also, it gives an opportunity to assess and compare the circular economy hindrances and scope among different countries.

1 Introduction

The circular economy related to reusing and recycling depicts the utilization of resources to prepare, use and discard with a purpose. The aim of circular economy is to minimize waste generation and utilization of the resources to its maximum potential [1-7]. The principals of circular economy focus to mitigate the negative impact of an activity at all stages along with enhanced use of materials and products by rejuvenating the ecological system [8-12].

Circular economy plays a pivotal role to achieve United Nation sustainable development goals (SDG) comprising 17 goals, especially the SDG 12 which emphasis on minimum use and proper utilization of materials and natural resources to promote sustainable patterns of consumption and production [13-16]. Thus, SDG 12 mainly focuses on the circular economy implementations [17,18]. The circular economy of clothes is relevant to the textile industries. Thus, it is one of the significant industries with increasing trend of population and textile production [19-21].

In the year 2017 based on the estimation of United States Environmental Protection (US EPA) the production by textile industries was 16.9 million tons and the recycled product rate was 15.2% with correspondence to 2.6 million tons [22]. The fashion business plays a crucial role in a circular economy; therefore, it may be termed circular fashion. It is one of the major industries with environmental and social impacts with intensive consumption of nonrenewable resources on a massive scale, resulting in depletion of natural resources with noticeable ecological footprint by disturbing nature. Its production and consumption stages generate tremendous amount of pollution; thus, making the future generations vulnerable to the availability of resources [23].

To overcome this issue , research is conducted in the area towards the reuse or recycle of textile waste world-wide to promote recycling and repurposing of textile waste [24-29]. Reuse or recycling of waste is extremely important due to the following advantages:

- The waste is potentially reusable and valuable
- It takes less raw materials, energy, and water to produce new clothes
- Carbon footprint and greenhouse gases in production of new garments is minimized
- Waste in landfills is reduced
- Pushes people to focus environment impacted by their actions
- Promotes livelihood and economic stability since recycling centers require intensive labor.

Despite the advantages there are certain challenges to recover and recycle textile waste such as high cost related to the process, finances, technology, policy and academic limitations [30-31].

* Corresponding author: jlawrence@uninsubria.it

Although there are several countries which practice clothes recovery including Denmark, Norway among the Nordic nations, Sweden and China, yet there is need to understand more about the clothes recovery program as the practical implications among different countries [32-34]. Therefore, the aim of this paper is to explore case studies of successful clothes recovery initiatives and compare their strategies, outcomes, and limitations. For an easier reading, in the present paper the commercial abbreviations have been omitted.

2 Comparison of clothes recovery program

2.1 Case study of successful recovery programs in the context of Italy

In [17] the authors investigated the implementation and challenges in Italian fashion industry. The investigation was made on the four companies namely Candiani Denim, WRAD, Dress you Can and Gucci. Candiani Denim, is one of the oldest, large scale and sustainable denim mill company. It was situated near Milan, founded in 1938. Due to its sustainable efforts, it is renowned to be" the green textile mill". The focus of the company is on reliable quality products, innovation in products and consideration of environment concerning resources.

WRAD is a small-scale important design company. It was established in 2015 to spread awareness about the environmental and social impacts related to the fashion business. The company claimed its position stronger in 2017 by developing recycled products manufactured using recycled graphite powder from industrial waste by Tecno EDM, a company in Turin, that produces electrodes to make Graphi-tee t-shirts. WRAD is a promising company in Italian fashion business and won several awards.

Dress you Can is the one of who initiated the "rental dress" in Italian fashion industry situated in Milan in 2014. The aim of the company was to fulfil the needs of women with online and offline service providence in terms of clothes, shoes, accessories particularly on occasions to promote reuse and recycling. It provides the customer with the relaxation to have variety of clothes on low costs thereby promoting circular economy. It promotes the sharing of each other's wardrobe and making designer clothes available for customers at low prices. In Italy renting clothes is still uncommon therefore Dress you Can put efforts to create awareness, communication, transparency, and outlet store with rent cloths availability.

Gucci is renowned fashion luxury brand which is strong influencer at large scale with the launch of clothing and many products such as bags, accessories etc. It was established in 1921 in Florence. Gucci developed "culture of purpose" comprising 10 years of sustainability plan focused on positive environmental and social impact on planet through Gucci Equilibrium platform.

3 Strategies adopted

The following sustainable strategies were adopted by companies based on four fundamentals reuse, recycle, product-life extension and resource preservation. It must be pointed out that the Italian Government recently set textile recycling as one of the priorities in the sector of waste management and ecological transition in agreement with the EU vision [35].

3.1 Product-life extension

Different companies have incorporated product life extension in various ways. For instance: WRAD and Candiani Denim focus on design, production, and resources whereas Gucci and Dress you can, focus consumer-based side where the companies inclined the consumer to retain the products for long time. Candiani Denim emphasizes product life extension from a design point of view. For instance: generating premium denim which is made to be reliable and recyclable thereby reducing the fast consumption and waste. It promotes a gradual fashions trend for example: a pair of jeans can be worn till its torn apart.

WRAD uses reusable and recyclable fibre to make the products lifelong. From the design point of view the reuse and recycle of packaging is promoted. While Dress you Can discourage the discard of products and encourages the extension of products' life. It makes consumers the clients and suppliers as it promotes the sharing of clothes that are second hand or not used among consumers. On the contrary, at Gucci, personalization on the consumers' side regarding product life extension is retrained. For example, in a well-established fashion brand one cannot do things freely as they desire.

3.2 Reuse

The following firms actively follow the reuse practices in all stages: materials utilized, production and end of life. Candiani denim production stages involve: water recovery for cleaning purpose, utilizing CO_2 emission for pretreatment of water used in production also to promote recycling and recovery of 100% cotton waste and minimize the acids used in production process. Whereas, in 2019 RAD started a reusable collection of garments made by reused fabrics and recycled organic cotton. The company strongly encourages and promotes "Fashion Revolution" movement focused on the conservation and restoration of environment.

Dress you Can focuses on the reuse of finals products in fashion business. It helps customers to have more variety to wear any dress on the occasions among large extent of shared wardrobes with the support of application to share economic logic with fashion world. Whereas Gucci highly supports reuse practices as in 2018 with the help of non-governmental organizations 11 tons of leather scraps were reused. It also supports the group of marginalized people to involve them in recycling activities. Besides, the example is "Re-verso" project which shows the efficient use of scraps of fine wool to prevent the use of cashmere to protect the Cashmere goats in Mongolia. Another project called "I was a Sari" initiated in 2013 by Stefano Funari in Mumbai, India, where he used discarded sari, a traditional garment as a cheap raw material to manufacture new accessories. He hired local women from Mumbai to promote their craft. These women were given training upcycling of saris. In 2017, Funari collaborated with Gucci to promote the garments on a flourished fashion platform with the application of Gucci's meticulous embroidery techniques.

3.3 Recycle

Candiani Denim promotes recycling since 1976 when the company promoted continuous regeneration with the installation of closed loop system and recycled cotton waste as part of its own production. WRAD supports recycling of resources such as in its signature T shirts Graphi-Tee is manufactured by 100% organic cotton with application of upcycled graphite. This helped to manage tons of graphite powder, which was supposed to be disposed of on landfill, later then used in proper recycled applications. Although, at Gucci recycling for differently designed garments doesn't take place as they are disposed of. But Gucci is involved in producing recyclable plant based synthetic fiber to be used as raw material in production phases. Similarly, it initiated the use of new life polyester manufactured from post-consumer bottles, also the ECONYL regenerated nylon. Also, Gucci prohibits the use of PVS in its products and uses recyclable plastic.

3.4 Recycling in End of life

At Candiani Denim, the separation of production waste takes place and handed over to certified waste managers, thereby reducing burden on landfills. External companies recycle the waste from jure bags and fibers. WRAD promotes take back programs to return the used products and recycle the fibres to form new clothes. Dress you can plans to recycle old clothes to form packaging.

3.5 Resource preservation practice

In this phase, technology plays a crucial role in the production phase. in the case of Candiani, WRÅD, and Gucci but also the introduction of a new paradigm in case of "Dress you can preserves" resources at best. In this aspect, Candiani Denim initiated using Kitotex, a sizing agent to weave the yarns to avoid breakage. Moreover, it's made of Chitin, an ecofriendly composition than the traditional sizing agent made of plastic. The integration of indigo juice and Kitotex, minimizes water and chemical consumption by 75% and 65%. The company conducts weekly monitoring of hazardous waste generated. Moreover, in 2018 Candiani Denim initiated the "ReLast" program generating innovative ecofriendly fabrics made of certified recycled elastic fiber and Global Organic Textile Standard (GOTS) certified cotton. Also, environment friendly dyes and clean technologies and biodegradable fabrics cable to be absorbed by soil is under consideration. Whereas WRAD uses more resources less harmful for environment including organic cotton, beeswax and hamp. The water consumption to produce Graphi-Tee is 90% less and CO_2 emission is reduced by 60% into the air as compared to the conventional T shirts. While Dress you Can promotes to preserve resource with extension of lifecycle of products with rental clothing. This helps to prevent exceeding production and consumption and provides monetary funds to customers via rent as they make money on their unused products. Similarly, Gucci initiated "Scrap less" project to minimize the use of leather [36]. It only takes the useful part of leather through tanning phase there by saving chemicals with enhanced quality. The Re-verso project has reduced 82% of minimizes energy consumption and 92% minimized water consumption and minimized CO_2 production of 97%

4 Circular Economy implementation challenges

Despite the successful implementation of clothes recovery programs there are certain limitation which needs to be addressed. For instance: there is lack of post-consumer recycling technologies at Candiani Denim to achieve the best quality products. In case of WARD, there is lack of communication with other business associates which makes the system complicated particularly based on the price of products as in Italy it's difficult to use good quality material and makes its price cheaper for instance the price of Graphi-Tee is not less than €60. Besides, at Dress you Can the challenge is over consumption behavior of consumers and waste generation, Moreover, proper take back programs are needed to set up. Furthermore, at Gucci personalization and prototype garments are the major hindrances. In a luxury fashion brand personalization is restrained and prototype garments must be discarded.

In [37], a study was made of circular economic principles in the fashion industry system in 19 Swedish companies. The companies were small, medium and large sized which manufacturers' products such as Children's' clothing, denim men and women, sustainable men's wear, second hand, etc.

Similarly, [38] conducted circular economic business study in the context of sustainability, finances and consumer preferences for clothes in Finland and identified the similar hinderances mentioned in the above studies. The results suggested a reasonable extent of attentiveness towards the product service system. Surprisingly people in Finland were keen and adaptive towards the return backs, exchange, cloth rental and recycling practices especially the young customers and older ones accepted more the customer services such as reusing, mend, remake etc. Moreover, among all the aspects of circular economy environmental restoration was given the most preference. Second, was the sentimental aspect related to the customers' trust for increased product reliability. Only a few expressed negative perceptions related to mistrust of service or discomfort in terms of usage. In terms of sentimental values circular economy model was successful in Finland despite limited material used in dress making. The alternative of "adapt ton it yourself" gave a purpose to people to enjoy and adapt an innovative skill.

5 Strategies adopted

The following strategies reported in Table 1, were adopted by the companies: take, make, and waste.

Table 1. Font styles for a reference.

Element	Style
Take phase	Promotion: The focus is more towards the application of natural fibers instead of synthetic fibers.
	Quantification: The quantification of environmental impacts of production phases.
	Reduction: Limiting the environmental impacts from production phases for instance reduce the amount of dyes wastewater, and energy etc.
	Relocation: Employers to work on closely to the raw materials.
Make phase	Transitional flexibility: It takes into account from season to seasonless collection.
	Engagement: To be engaged in practices for the retention of values on secondhand products.
	Relationship building: To build relationships with manufacturers to incorporate environmentally sustainable methods during manufacturing.
	Partnership: To adopt intermediate coordination to support monitoring in the production facilities.
Waste phase	Development of clothes recovery programs: Clothes rental or the resale of clothes to increase the life of clothes is encouraged.
	Encouragement to use clothes responsibly: To encourage the consumers to take good care of clothes such as wash less or mend when possible.
	Promotion of take-back programs: To introduce more and more take back clothes programs
	Investment in Circular economy: To invest in recycling programs to reduce burden on landfills.

6 Challenges of Circular Economy

6.1 Take phase

In this phase, the extraction of raw materials is aimed to make new products [39]. This study revealed that out of 18 companies only 1 uses existing upcycled material in their design phase while all others use new raw materials. The challenge among larger brands is the measurement of carbon emissions upon each garment. Although efforts and resources are put to overcome this limitation to operate in circular economic system, in case of company, for smaller brand lack of resources such as time or capacity makes it difficult to measure carbon emissions. Moreover, responsibility of taking sustainability measures comes upon small team. The company 18 (Sustainable men wear) are putting efforts to use natural fibres to make biodegradable clothes as circular economic practice. Although, this product can produce the same amount of CO2 emission as compared to non-biodegradable products. In the case of Company 15 (Outdoor Apparel), focuses on long life of products with use of technical fibres. The strategy used is the durability of clothes, for example: they use a good quality recyclable nylon to manufacture clothes and this nylon can be reused by many customers in many seasons. The perspective of Company 2 (Children Clothing) suggests that the environment is the focus of scavenging consumers idea of sustainability. The decisions taken in one phase may cause undermining impacts on other stages. For instance: Production in Turkey with organic cotton may increase the cost by 10 -30%. In this case, moving the production unit to Bangladesh to manage the cost of using expensive material can be a solution.

6.2 Make phase

In this stage fashions brands are involved in producing garments It incorporates design and manufacturing phases [38, 39]. The challenge in Sweden fashion industry is fast fashion which follows a business model in which style is given more preference than sustainable practices. In the case of company 9, fast fashion customers prefer fashionable looks of garments over to the matter of sustainability. Furthermore, price is a major problem as fast fashion has low price clothes and to produce long lasting clothes require increasing the price to improve and quality, design, and durability.

Independent fashion businesses focus on reputation than on cost based upon design. This long-term plan contributes to circularity as customers invest in their clothes for long term use rather than disposable clothes Suh as in case Company 8 (Designer Womenswear, Stockholm) and Company 12 (Independent fashion, Stockholm) the circular in fashion is buying a garment based on one's preference and use to for a long time by one or many consumers. It lessens the competition of cost.

A new development of business model in case of Company 18 (sustainable menswear) came into light in which a brand offers continuously a part of its collection along with seasonal collection. It helps to provide clothes best to the terms of fit, quality, lasting, and designing. Permanent collection gives an opportunity to work carefully on each garment and to understand the details of supply chain.

Although brands focus more on make phase than take phase. They focus on the quantification and improvement during production phases. On the contrary, in case of Finland an alternative option "do it yourself" was introduced which gives flexibility to customers to choose their own fabric, thread, embellishments to design their own clothes with the selection pf their own fashion kit to limit the use of cloth along with the opportunity to wear your own creativity. Another alternative suggested "customised design participation" in which customer finds pieces of clothes in shelves instead of complete dress or the shop offers two services either to choose components to make one's own garment or work with their designer to have your own specific garment. Third is, to avail the fashion house services by setting any specific theme for dress instance casual, party dress etc., provide ones' size and the fashion house is responsible to provide you the dress with minimal clothing consumed in the dress. All these strategies were to reduce landfill waste and increase cloth durability [38].

6.3 Waste phase

According to company 1, all the companies strive to make efforts to utilize waste in an efficient manner to promote sustainable consumption practices and minimize waste. They find ways to practice reuse, clothes rental, recycle, or repair models. Companies' initiative to practice clothes recovery programs more such as take back programs, clothes repair, educating about circular economy and environmental impacts by textile industries, more customer friendly instructions such as washing clothes with cold water, dry clean less. Some companies are involved to launch their own brand specific recycling programs.

The companies starting their own clothes recycling problem face technological barriers. Besides many companies accept willing the practice of resale and rental of clothes such as in the case of Company 3 (Children's Clothing) a recovery program for renting new-born clothing, and also the parent can sell or buy second-hand clothing. The problem with small companies is the limited staff to handle the work needed to accomplish the tasks to be done in the in -house recovery programs. In the case of Company 7, (Designer Menswear and Womenswear), the large fashion brand does not collect old garments in their store. They make premium, durable quality products and know a lot of customers sell their own brand name products. In the case of Finland, mend and remake of cloths was prioritised in terms of practicality and also the environmental advantages whereas youth was more inclined towards cloth rental, return cloth schemes and exchange [38]. Another solution was "advisory service" for instance shop offers this service online and in-store to offer suggestions to customers to use their dresses in innovative ways besides to utilize the already possessed items to restyle the garments. The advisory service may visit the house of customers to assist them to manage their closet in the best way.

7 Conclusions

In case of Italy, more research is needed upon the sustainable consumption of clothing as this could be an important factor in the hinder dance of circular model [39-41]. Firstly, it's important to implement circular economy and pay attention in all the aspects of the supply chain including consumers, manufacturers, designers, managers and final disposal [42,43]. Secondly, more studies are needed on specific segments, for instance rental clothing. Thirdly, new research could validate the hypothesis made in this study. Finally, an international comparison with other countries in terms of similar challenges faced in case of circular economy could be made, having as starting point this paper.

In case of Sweden, the investigation in future scope directs optimism related to circular economy and fashion sustainability as with the passage of time companies adopt more sustainable practices. Although, we still need to have a better perspective in terms of capitalization and waste being utilized with the principals of circular economy.

Based on the present review, future perspective goes in the favour to have policies, collaboration in the favor of circular economy particularly related to the environmental impacts such as resource depletion, climate change and the space to dump the waste.

The case study of Italy depicts that social and environmental sustainability are adopted by young businesses as they consider it a promising value. Also, the companies WRÅD, Dress You Can and Candiani in Italy are willing to accept the business models and practices which align circular economy. However, Gucci still follows the conventional paradigm, yet it is making small steps to fit with circular economy. All things considered, circular economy goals are achievable with dedicated efforts and innovative directions along with the introduction of hybrid models that can upgrade the exiting models in the context of circular economy.

However, the case study of Sweden illustrates the limitations faced by fashion industry may be reduced with the implementation of circular economy principles. The need for proper interventions in the phases of take and make is necessary to reduce the environmental impacts regarding waste. The focus should be on the integration and implementation of waste but in the supply chain of circular economy. Nonetheless, the fashion industry has a complicated supply chain system in which one decision may impact other decision in the next stages. Therefore, we need to have a balanced approach of incorporating sustainability and circular economy throughout all the phases. Despite, all the efforts still there are no proper implementation of circular economy principle in fashion industry, probably due to the hinderances related to costs, preferences, trends, in the fashion industry but still the steps taken by companies make the idea of circular economy conceivable in practical ways.

The investigation reveals two important perspectives. First is to deal with external limitations from consumers behaviour, garments outlook and style. Second is the collaboration with local industries concerning policies and regulations on circular economy or sustainability. More research is needed to assess the progress of Swedish fashion business with the alignment of circular economy.

From the present review, it is clear that there are common problems implementing the circular economic principles in clothes recovery, in each segment in the supply chain system. In the case of luxury fashion brands circular economy does not seem to be useful as in both cases the brands discard their prototype clothes. Despite the efforts to the acceptability and adoption in one segment or all the segments of the textile fashion industry yet extensive efforts are needed to meet the huge gap integrating circular economy and environmental impacts.

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Figure 12. "Investigating the effectiveness of clothes recovery programs in promoting a circular economy: a review".

6.1 Conclusion

The conclusion of my paper highlights the need for more research and efforts to implement circular economy principles in the fashion industry, particularly in Italy and Sweden. In Italy, sustainable clothing consumption and circular models require more attention, especially across the entire supply chain. While young businesses like WRÅD and Candiani adopt circular practices, larger brands like Gucci still follow traditional models, though they are making gradual shifts.

In Sweden, there's optimism as more companies adopt sustainable practices, but challenges persist in waste utilization and full integration of circular economy principles. Key issues include consumer behaviour, trends, and local policy collaboration.

Overall, both countries face obstacles in garment recovery and waste management, with luxury brands struggling to integrate circular economy principles. More research and stronger efforts are needed to close this gap.

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Chapter 7 Poster Presentation Overview

In my first year, I presented a poster titled “Lake Pollution by Pharmaceuticals: A Comparison of World Lakes” at the 5th International Symposium on Water Pollution and Treatment (ISWPT 2022) as represented in Figure.13.

Abstract: This study reviews around 200 papers on micropollutants, specifically pharmaceuticals, in lakes from 1998 to 2022. It highlights an assessment of 38 pharmaceuticals in Lake Como, Italy, with total pharmaceutical concentrations of 93 ng/L in the epilimnion and 41 ng/L in the hypolimnion. While these values are relatively low, the presence of antibiotics is concerning due to their potential impact on drinking water. Comparatively, erythromycin-H_2O in Taihu Lake, China, was reported at 624.8 ng/L, while in Lake Como, it was <0.01 ng/L. Similarly, sulfamethazine concentrations reached 252.7 ng/L in Taihu Lake but were only about 2 ng/L in Lake Como. In Lake Michigan (North America), sulfamethoxazole concentrations were 6.9 ng/L, while Lake Como had approximately 2 ng/L. Additionally, carbamazepine concentrations were 29 ng/L in Lake Michigan, compared to 7 ng/L in the epilimnion and 3.51 ng/L in the hypolimnion of Lake Como. This research underscores significant variability in pharmaceutical contamination across lakes, influenced by discharge intensity, lake size, and hydrology.

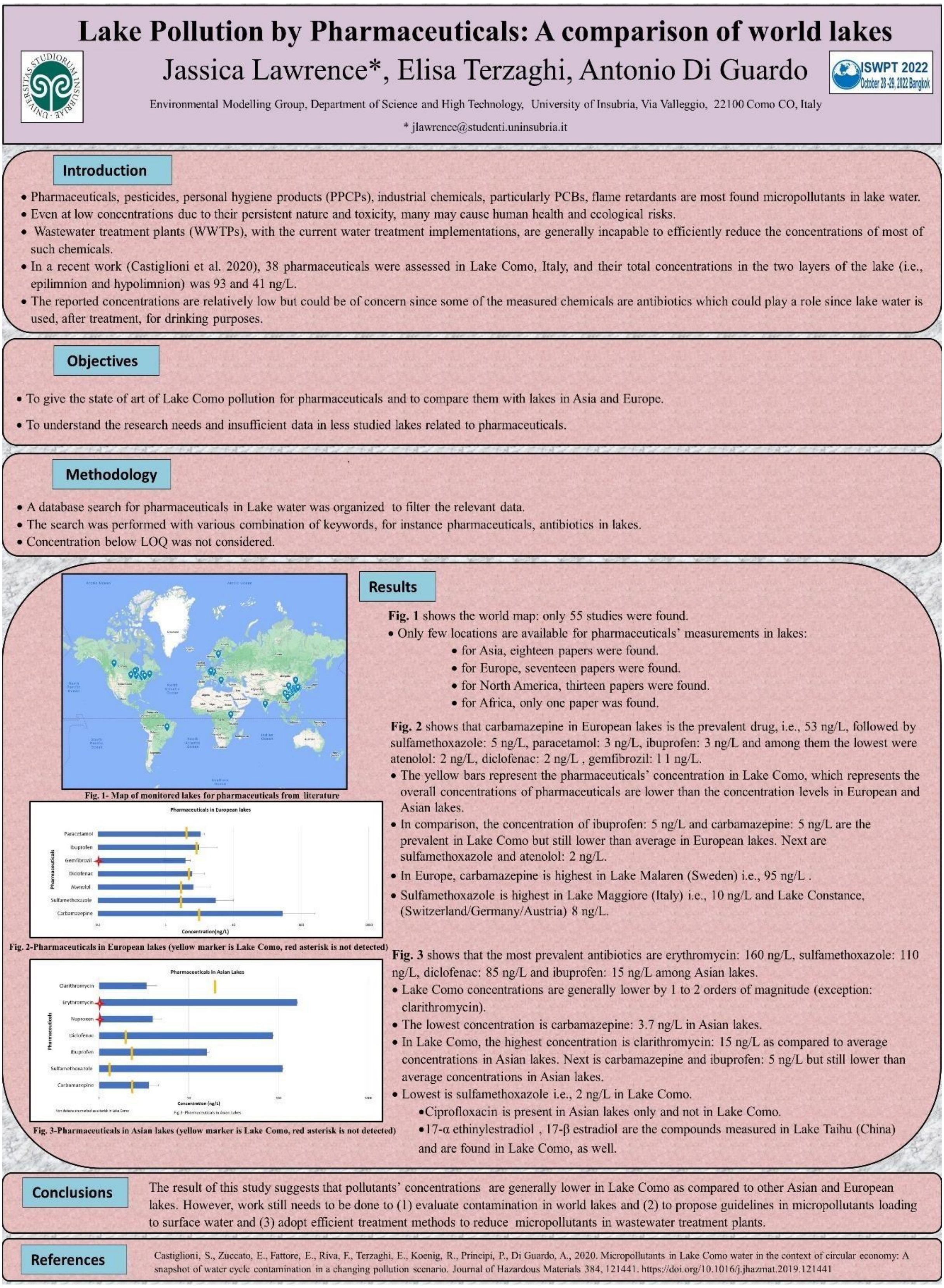

Figure 13. Lake Pollution by Pharmaceuticals: A Comparison of World Lakes

As part of my research, I presented a poster titled "Microplastic Pollution in Freshwater Ecosystems: Assessing the Ingestion of Microplastics by Zooplankton in Lake Como" during my 2nd year represented in Figure. 14. This study aimed to evaluate the presence of microplastics in zooplankton samples, focusing on their morphological characteristics, including shape, colour, and size.

Methodology: Zooplankton samples were digested with nitric acid, filtered, and stained with Nile red dye for visualization under UV light at 365 nm.

Key Findings: The analysis revealed that the predominant shapes of ingested microplastics were fibres and filaments, with common colours including blue, orange, yellow, and black. This research highlights the effectiveness of zooplankton as bioindicators of microplastic pollution, emphasizing the need for continued monitoring in freshwater ecosystems.

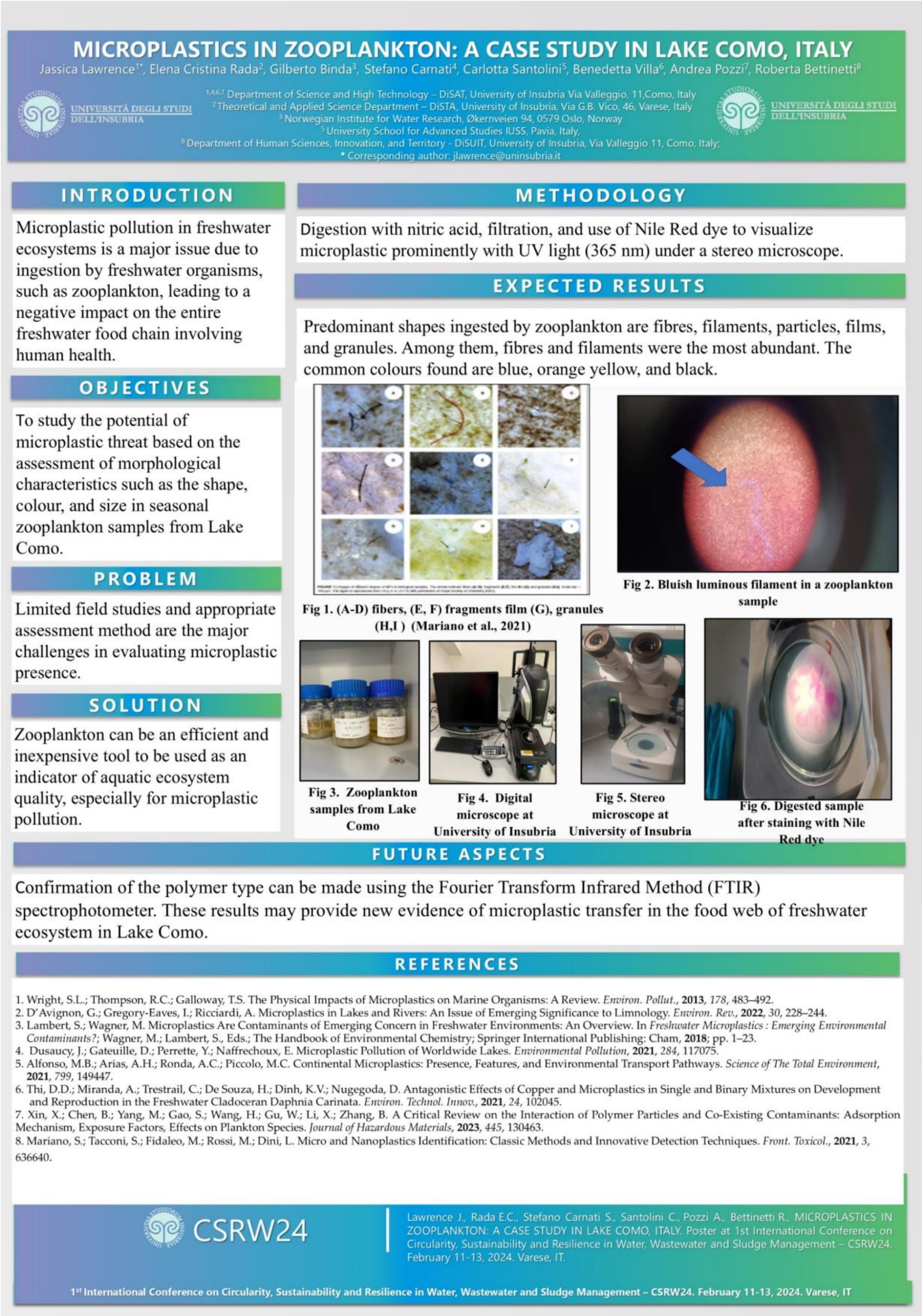

Figure 14. Microplastic Pollution in Freshwater Ecosystems: Assessing the Ingestion of Microplastics by Zooplankton in Lake Como.

Chapter 8: General Discussion and Conclusion

8.0 Summary of Key Findings

This thesis comprehensively examines pollution dynamics in freshwater ecosystems, with a specific focus on Lake Como. Through an integrated approach encompassing microplastic analysis, climate change impacts on wastewater treatment plants (WWTPs), aquatic debris monitoring, and circular economy solutions, several key findings emerge:

1. **Microplastic Analysis (Chapter 3)**
   The analysis revealed that microplastics are widespread in Lake Como, influenced significantly by seasonal tourist activities. The identification of various microplastic types and their concentrations highlighted the urgent need for targeted pollution management strategies, particularly during peak tourism seasons.

2. **Climate Change Impact on Wastewater Treatment Plants (Chapter 4)** The study demonstrated that climate change poses substantial risks to the effectiveness of WWTPs. Increased rainfall and higher temperatures can overwhelm treatment processes, resulting in the release of untreated or partially treated wastewater, including microplastics, into freshwater bodies. This finding underscores the necessity for adaptive management strategies and infrastructure improvements to enhance resilience against climate-related disruptions.

3. **Aquatic Debris Monitoring with Remote Operating Vehicles (Chapter 5)**
   Utilizing Remote Operating Vehicles (ROVs) for underwater monitoring provided valuable insights into the distribution and composition of aquatic debris. The comparison of data from 2019 and 2024 indicated a significant decline in debris levels, potentially reflecting improved waste management practices. However, the impact of environmental factors such as algal blooms on detection accuracy necessitates further investigation and technology integration.

4. **Circular Economy and Waste Utilization (Chapter 6)**
   The examination of circular economy practices in the textile industry revealed both successes and challenges. While countries like Denmark and Sweden are making strides in clothing recovery initiatives, the overall effectiveness of such programs varies. The findings emphasize the importance of consumer behavior, policy support,

and industry collaboration in enhancing recycling rates and promoting sustainable consumption.

8.1 Implications for Future Research and Policy

The findings of this thesis suggest several directions for future research and policy development aimed at improving pollution control in freshwater ecosystems:

- **Microplastic Source Identification**: Future studies should focus on pinpointing specific sources of microplastics in freshwater environments to inform targeted interventions. Understanding the relationship between human activities and microplastic concentrations can guide effective policy measures.
- **Resilient Wastewater Management Policies**: Given the vulnerabilities identified in WWTPs due to climate change, policies should promote investments in climate resilient infrastructure and technologies. Strategies such as decentralized wastewater treatment systems and enhanced treatment processes could significantly reduce pollutant discharge into freshwater ecosystems.
- **Advanced Monitoring Techniques**: There is a clear need for improved monitoring methodologies for aquatic debris. Integrating ROVs with advanced imaging and sensing technologies could enhance detection capabilities and provide comprehensive data for better management decisions.
- **Promotion of Circular Economy Practices**: Policies encouraging circular economic practices should be strengthened, particularly in the textile industry. Supporting initiatives that foster recycling, resource recovery, and sustainable production methods will be crucial in reducing overall waste and environmental impact.

8.2 Conclusion

This research sheds light on the complex interactions between human activities, climate change, and pollution in freshwater ecosystems. The comprehensive approach taken in analysing microplastics, assessing the resilience of WWTPs, monitoring aquatic debris, and exploring circular economy solutions provides a nuanced understanding of these interconnected issues. The significant findings regarding the prevalence of microplastics, the impact of climate change on wastewater management, the monitoring of aquatic debris, and the potential of circular economy practices underscore the urgent need for collaborative efforts among researchers, policymakers, and industry stakeholders. To effectively mitigate pollution in freshwater ecosystems, ongoing research and adaptive management strategies are essential. By leveraging innovative technologies and promoting sustainable practices, we can make meaningful progress toward preserving and protecting these vital ecosystems for future generations.