INDIGO DYEING WASTEWATER TREATMENT BY THE MEMBRANE BASED FILTRATION PROCESS

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ABSTRACT

INDIGO DYEING WASTEWATER TREATMENT BY THE MEMBRANE BASED FILTRATION PROCESS

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In the present study, the recovery of the indigo dyeing rinsing wastewater originating from a denim textile mill to the degree of reuse quality, which generally requires nanofiltration (NF), was investigated. In order to control flux decline and hence to maintain an efficient NF; coagulation, microfiltration (MF) and sequential MF plus ultrafiltration (UF) pretreatment process alternatives were tested. All pretreatment alternatives were optimized to reduce chemical oxygen demand (COD) and color load to NF. Coagulation process was investigated using the coagulants, aluminum sulfate ($Al_2(SO_4)_3.18H_2O$) and ferric chloride ($FeCl_3.6H_2O$) by running a series of jar tests. The results showed that coagulation process did not provide an effective and efficient pretreatment due to high dose of coagulant requirement. MF tests run by using 0.45, 2.5 and, 8 µm membranes indicated that MF through 0.45 µm pore-sized membrane is the best process providing 64% color and 29% COD removals, leading to a color value of 2493 Pt-Co and COD of 892 mg /L in the permeate. Application of sequential MF+UF filtration provided a significant benefit over single MF in terms of rejections and also permeate flux. UF applied after MF provided additional 62% color and 4% COD removals leading to 960 Pt-Co color and 856 mg/L COD. NF tests conducted using pretreated wastewater via single MF and sequential MF+UF indicated that single MF is the best pretreatment to NF and this treatment scheme provided 99% color, 97% COD and 80 % conductivity removals and satisfied reuse criteria.

Keywords: Coagulation, Membrane Filtration, Textile Industry, Indigo, Dyeing Rinsing Wastewater.

ÖZ

İNDİGO BOYAMA ATIKSULARININ MEMBRAN FİLTRASYON İLE ARITIMI

Ünlü, Meltem
Yüksek Lisans, Çevre Mühendisliği Bölümü
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Mevcut çalışmada denim üreten bir tekstil fabrikasına ait indigo boyama yıkama atıksularının tekstil endüstrisinde yeniden kullanılabilirliği araştırılmıştır. Tekstil endüstrisine ait geri kullanım kriterlerini sağlamak için genellikle nanofiltrasyon (NF) tekniğini kullanmak gerekmektedir. Membranın tıkanmasını kontrol etmek ve NF tekniğini etkili bir şekilde kullanmak amacıyla koagülasyon, mikrofiltrasyon (MF) ve ardışık MF-ultrafiltrasyon (UF) önarıtım proses alternatifleri test edilmiştir. Tüm önarıtım alternatifleri, NF testlerine verilecek atıksudaki kimyasal oksijen ihtiyacı (KOİ) ve renk yüklerini azaltmak için optimize edilmiştir. Koagülasyon prosesi aluminyum sülfat ve ($Al_2(SO_4)_3 \cdot 18H_2O$) demir klorür ($FeCl_3 \cdot 6H_2O$) koagülanları kullanılarak, bir dizi jar testi çalışılarak araştırılmıştır. Sonuçlar yüksek dozlarda koagülan gereksinimi nedeniyle koagülasyon prosesinin etkili ve verimli bir önarıtım sağlamadığını göstermiştir. 0.45, 2.5 ve 8 µm gözenek çaplı membranlar kullanılarak çalışılan MF testleri, süzüntü suyunda 2493 Pt-Co ve 892 mg/L kimyasal oksijen ihtiyacı (KOİ) ile sonuçlanan %64 renk giderimi ve %29 KOİ giderimi sağlayan 0.45 µm gözenek çaplı membran en iyi proses olduğunu göstermiştir. Ardışık MF+UF uygulaması, tek aşamalı MF'e göre giderimler ve süzüntü suyu akı değerleri bakımından önemli bir yarar sağlamıştır. MF'ten sonra uygulanan ultrafiltrasyon (UF), 960 Pt-Co ve 856 mg/L KOİ ile sonuçlanan, MF'e ilave olarak %62 renk ve % 4 KOİ giderimleri göstermiştir. Tek aşamalı MF ve ardışık uygulamalı MF+UF ile önarıtılmış atıksular üzerinde

denenen NF testleri tek aşamalı MF uygulamasının NF için en iyi önarıtım olduğunu göstermiştir, ve bu arıtım şekli %99 renk, %97 KOİ ve %83 iletkenlik giderimi sağlayarak geri kullanım kriterlerini sağlamıştır.

Anahtar kelimeler: Koagülasyon, Membran Filtrasyonu, Tekstil Endüstrisi, İndigo, Boyama Yıkama Atıksuyu

to my beloved family...

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ABBREVIATIONS

AB	Avrupa Birliği
AOX	Absorbable organic halides
BAT	Best Available Techniques Reference Documents
BF	Buchner funnel
BOD	Biochemical Oxygen Demand
BREF	Best Available Techniques Reference Documents
CFV	Cross flow velocity
COD	Chemical oxygen demand
DSIP	Directive-Specific Investment Plan
EC	European Commission
EKÖK	Entegre Kirlilik Önleme ve Kontrolü
EPA	Environmental Protection Agency
EU	European Union
IPPC	Integrated Pollution Prevention and Control
MCE	Mixed cellulose ester
MF	Microfiltration
MoEF	Ministry of Environment and Forestry
MWCO	Molecular weight cut-off
NF	Nanofiltration
PES	Polyethersulphone
PSD	Particle size distribution
R1	Rinsing Wastewater of Recipe 1
R2	Rinsing Wastewater of Recipe 2
R3	Rinsing Wastewater of Recipe 3
SPO	State Planning Organization
std.	Standard Deviation
TDS	Total Dissolved Solids
The Mixture	Mixture wastewater
TL	Turkish Liras
TMP	Transmembrane pressure
TSS	Total Suspended Solids

UF	Ultrafiltration
USEPA	United States Environmental Protection Agency
WW	Wastewater

CHAPTER 1

INTRODUCTION

1.1. General

In the European Union (EU) countries, pollution rising from industrial activities is managed by “integrated pollution management” concept. In this respect, a general approach covering pollution within the production phases is accepted rather than considering pollution control via end of pipe treatments and setting limit values for the discharges or emissions from industrial facilities. EU’s Integrated Pollution Prevention and Control (IPPC) Directive concentrates on the minimization of the environmental impacts of the industrial activities defined in the directive via Best Available Techniques Reference Documents (BREF) forming guideline for each industrial sector [1].

Turkey being a candidate country for full membership to the EU is in the period of adopting legal requirements and sanctions of the Union. Among many other Directives, the IPPC Directive is of priority as manufacturing industry is wide spread in Turkey and its implementation requires heavy investment. Meanwhile, throughout the EU, environmental concerns in manufacturing industry have increased recently since the IPPC Directive was published. Among those defined industries in the IPPC directive, textile is a water and energy intensive one [2].

The textile and clothing industry is the largest and one of the first industries established in Turkey [3]. Currently, there are about 40,000 companies active in the Turkish textile and apparel sector; 25 % of which are active exporters [4]. Turkey today is among the leading textile and apparel producer and exporter countries in the world. For that reason, quality tests, covering environmental aspects, before, during and after the production processes are of outmost importance that are required by many countries that import Turkish textiles (EU and the USA being the first) [2].

The textile industry is one of the longest and most complicated industrial chains in manufacturing industry composing of a wide number of sub-sectors, covering the entire production cycle from the production of raw materials (man-made fibers) to semi-processed (yarn, woven and knitted fabrics with their finishing processes) and final products (carpets, home textiles, clothing and industrial use textiles) [1]. Broadly defined, the textile industry consists of establishments engaged in spinning natural and manmade fibers into yarns and threads. These are then converted (by weaving and knitting) into fabrics. Finally, the fabrics and in some cases the yarns and threads used to make them, are dyed and finished [5].

The textile industry is known as a water intensive sector, which employs a wide variety of processes. The textile chain begins with the production of raw fiber continues with pretreatment, dyeing, finishing, printing, coating, and other processes. These processes represent the core of the applied processes. Among these processes dyeing and finishing are major water consuming processes that generate highly polluted effluents. The main source of residual chemicals in effluents is their incomplete exhaustion during production phases. Several common treatment options such as physical, chemical and biological methods are available for the treatment of these effluents, but the residuals are hard to remove, either by conventional or by advanced treatment processes. In the textile industry, the choice of the most effective and less expensive treatment processes or their combinations depends on the chemicals and methods used during the production [6].

The dyeing step in the textile production has the largest risk for the environment due to high concentrations of organic dyes, additives and salts used [7]. Therefore, among the processes applied in the textile industry, dyeing process wastewater should be dealt with seriously. Most of the time, this process constitutes the major part of the water consumption and generates wastewaters distinguished by high chemical oxygen demand (COD), high dissolved and suspended solids, and high color contents [8]. Thus, dyeing wastewaters originating from rinsing operations are great candidates for recovery and reuse. The stringent environmental regulations for discharge today and the scarcity of the water resources are forcing the textile manufacturers to assess the potential for reuse of water by innovative technologies.

The major problem in the reuse of colored textile wastewaters is the intense color. Many of the conventional and even advanced treatment technologies suffer the limitation of not being able to treat highly colored wastewaters from textile manufacturing. Therefore, innovative treatment techniques or the combinations of conventional and advanced treatment techniques are required in order to handle color removal problem. Membrane filtration technology assisted with the physico-chemical pretreatment methods is reported to be one of the most promising ones for the reclamation of textile effluents [9,10]. The significant drawback of membrane technology is the flux decline caused by membrane fouling. Implementation of the right pretreatment process is very important to minimize flux decline and hence maintain an efficient membrane separation process. The most commonly adopted pretreatment processes for textile effluents are coagulation, adsorption, sand filtration, membrane processes (microfiltration (MF), ultrafiltration (UF)), chemical precipitation, and ozonation [7]. Among these alternatives, microfiltration (MF) has been gaining a wider recognition since it is an economically competitive alternative. In the literature the use of MF to remove colloidal species from the exhausted dye bath effluents before nanofiltration (NF) has been proposed [11,12]. In a few of the past studies, decolorization of indigo dyeing wastewaters has been investigated with the target of indigo dye recovery without considering water reuse [13,14,15,16,17]. In fact, indigo dyeing wastewaters that originate from warp yarn dyeing in the production of blue denim textile are very high in volume. These wastewaters contain indigo dyes and their derivatives, which are defined as vat dyes. Vat dyes are normally insoluble in water, but they become water-soluble and substantive for the fiber after reduction in alkaline conditions.

1.2. Objective and Scope of the Study

The overall objective of the present study is to assess the treatability of indigo dyeing wastewaters via membrane filtration for the purpose of reuse. The feasibility of coagulation, and MF/UF as pretreatment to NF, and also NF of indigo dyeing wastewater for water reuse were investigated. Indigo dyeing wastewater samples from a mill located in Kayseri-Turkey were obtained and after characterization; subjected to jar-testing using the coagulants aluminum sulfate and ferric chloride. Thenafter, as alternative pretreatment techniques; MF and UF of the wastewater were investigated running bench-scale dead-end filtration tests. Based on the results obtained, the most feasible pretreatment process was selected and the effluent from this process was subjected to cross-flow NF in order to produce water reusable in the dyeing process.

The specific objectives of the study are to;

- Generate a generic treatment process chain for the reclamation of indigo dyeing wastewaters,
- Evaluate the performance of coagulation as pretreatment to NF,
- Compare the effectiveness of different coagulants,
- Evaluate the coagulant dose needed for coagulants tested,
- Determine the performance of MF and UF as pretreatment to NF,
- Select the best pretreatment process based on achieved effluent quality,
- Investigate NF of the pretreated effluent for the purpose of reuse, and also
- Assess the possibility of reclaiming indigo dyeing wastewaters in the denim mill in consideration.

In the denim mill considered, textile production starts with fiber manufacturing from cotton. Then fibers are subjected to a series of processes such as sizing, dyeing, weaving and finishing. The mill produces 20.000 tons of cotton fiber and 45 million meters of denim fabric per year with a daily water consumption of about 3500-5000 tons. Dyeing is one of the major water consuming lines. In the plant, more than 40% of the process water is used for dyeing and about 50% of the wastewater generation in the mill results from this process.

The fact that more than 400 different dyeing recipes are applied in dyeing process, implying a wide variation in terms of wastewater quality; the three most frequently used dyeing recipes (called as Recipe 1, Recipe 2, Recipe 3 in the present study, which all employ indigo derivative dyes) applied in the mill were identified by the help of the staff of the dyeing line. The selected three recipes correspond to about 50% of the total production (as of the year 2005) of the mill that actually applies more than 400 different dyeing recipes. It is evident that the mixture of the three dyeing recipes will mimic the total dyeing line effluent. The samples taken were the mixtures of the wastewaters resulting from both pre-rinsing (rinsing after pretreatment), and post-rinsing stages (rinsing after dyeing). These wastewaters are discharged continuously throughout the dyeing process. The effluents originating from the rinsing operation of each dyeing recipe and the mixture, which is formed in the laboratory by mixing the effluents of each recipe wastewaters on volume base of 1:1:1 ratio, were characterized. Afterwards, pretreatment alternatives were applied to wastewater samples in order to remove color and organics. Finally, NF of pretreated wastewater was optimized as the final treatment to satisfy the reuse criteria for the textile industry.

Quality criteria for reuse of water in textile industry show variation among plants owing to the different production schemes. Therefore, each plant sets its own reuse criteria regarding its process scheme and final product quality. In the literature, there is a wide range of water reuse criteria (Table 1.1). In the present study; in order to provide the plant, which processes cotton as raw material, with the reusable water for the dyeing process applied to the cotton fabric the criteria for the dyeing processes and the cotton fabric given in Table 1.1 were taken as the basis. However in real applications this criteria should be discussed with the plant staff and the water recovered should be tested whether there is any adverse effects of this water on the final product quality or not.

Table 1.1. The criteria for reusable water in the textile industry

Parameter	Reuse Criteria 1** [18]	Reuse Criteria 2*** [19]	Reuse Criteria 3 [20]	Reuse Criteria 4**** [21]
COD (mg/L)	-	0-160	30	178-218
TSS (mg/L)	-	0-50	-	-
TDS (mg/L)	150	100-1000	-	-
Hardness (mg $CaCO_3$/L)	75	0-100	270	1-3
Conductivity (µS/cm)	-	800-2200	1800	1650-2200
Alkalinity (mg $CaCO_3$/L)	-	50-20	-	32-73
Color	17 AU*	0-2 Lovibond unit	0.01 (426 nm absorption)	20-30
pH			7.8	6-7
Turbidity (FTU)	5		-	-

* AU: Absorbance units in 10 mm cell
** reusable water for preparation, dyeing and finishing of knitted cotton
*** reusable water for reactive and acid dyeing process
**** reusable for reactive dyeing on 100% cotton fabric

1.3. Thesis Overview

This thesis includes seven chapters. Chapter 1 (Introduction) presents a brief description of textile industry along with a very brief description of indigo dyeing wastewater problem. This chapter also introduces the objectives of the study. In Chapter 2 (Textile Industry and Wastewater Management), a brief description of textile manufacturing process and also the importance of textile industry for Turkey are given. Also presented in this chapter is the integrated wastewater management concept. Chapter 3 (Theoretical Background) reviews the fundamentals of coagulation and also membrane filtration processes. Chapter 4 (The Textile Plant Studied) describes the textile mill from which wastewater samples were gathered. Chapter 5 (Experimental Methods) details the methods used for coagulation and membrane filtration also the study approach. Chapter 6 (Results and Discussion) evaluates the applicability of coagulation and MF/UF as pretreatment to NF. Also evaluated in Chapter 6 is NF for the reclamation of indigo dyeing wastewater. Finally, Chapter 7 (Conclusions) summarizes the main conclusions of the present study and also the recommendations.

CHAPTER 2

TEXTILE INDUSTRY AND WASTEWATER MANAGEMENT

This chapter presents a brief description of textile industry, and also the importance of textile industry for Turkey with the pollution prevention and control approaches are given.

2.1. Textile Industry

The textile industry is one of the oldest industrial sectors in the World. Its history goes back to about 5000 B.C. starting with scraps of linen cloth found in Egyptian caves. Besides being one of the oldest, it is one of the longest and most complicated industrial chains in terms of the processes applied and manufacturing schemes [5,1]. The general process chain of the textile industry is given in Figure 2.1. These processes start from spinning natural and man-made fibers into yarns and threads continues with weaving and knitting in which fabrics are formed. [5]. Finally "finishing processes" (i.e. pretreatment, dyeing, printing, finishing and coating, including washing and drying) representing the core of the applied processes and techniques in textile industry take place.

The sequence of the processes is very variable dependent on the demands of the end-users therefore the finishing processes can take place at different stages of the production processes (i.e. on fabric, yarn, loose fiber, etc.) [1]. Regarding the demands mainly resulting from three end-uses, clothing, home-furnishing and industrial use, textile industry is characterized by-product specialization and it shows so much diversity that it is a fragmented and heterogeneous sector. A textile plant may use cotton as a raw material whereas wool or silk may be the raw material of another one. Small plants may specialize in spinning or weaving operations whereas larger ones may have production capacities of combining these two processes [5].

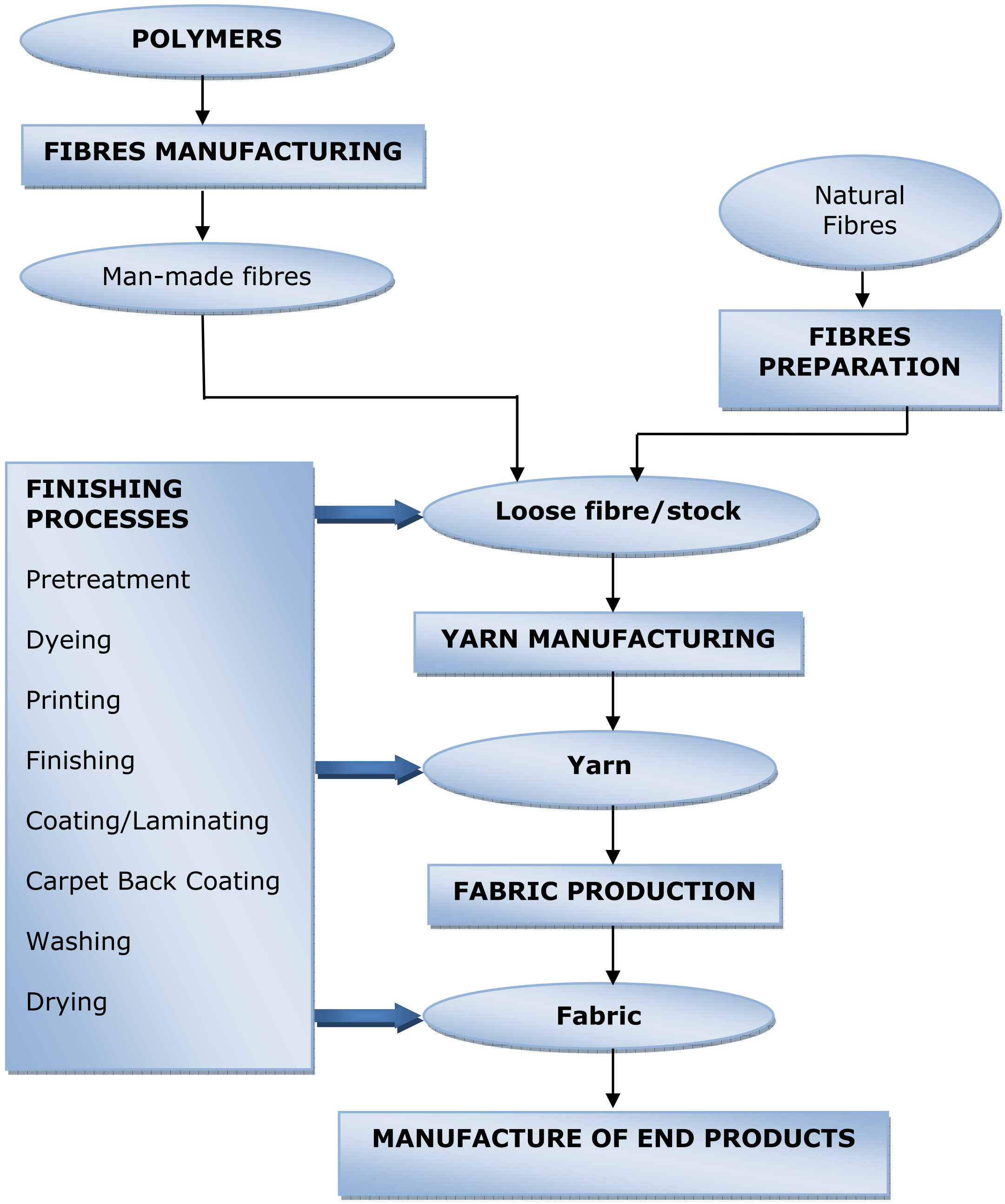


Figure 2.1. General diagram of processes in the textile industry [1].

The share of the main types of fibers as raw material used in the textile finishing industry is given in Table 2.1. Cotton manufacturing in textile industry constitutes approximately 50% of the total share of fibers in this sector. Therefore, it possesses great importance among the other fibers.

Table 2.1. The share of fibers in textile industry as percentage [22]

Fiber type	Share (%)
Cotton	45
Wool	8
Polyester	14
Silk	2
Viscose	12
Acrylic	4
Others	15
Total	100

2.2. Water Use in Textile Industry

Despite the heterogeneous structure of the sector, there is a common feature specific to the textile industry. The textiles industry has always been regarded as a water-intensive sector. A number of textile manufacturing processes are chemical wet processes. Wet processing operations, including preparation, dyeing, and finishing, generate the majority of textile wastewater. Water is the principal medium for removing impurities from raw materials, applying dyes and finishing agents, and for the generation of steam. Apart from a minor amount of water, which is evaporated during drying, the bulk is discharged as aqueous effluent. Main environmental concern is therefore about the amount of water discharged and the chemical load it carries. In rinsing operations removal of impurities from raw materials and removal of residual chemical reagents used for processing result in the production of wastewater. The water consumption is specific to the textile plants differing in terms of type of textile processing operation, the type of material or final product and the specific machine or technique used. However, the water demand for wet processing operations is invariably high more than 5000 m3/day for a large mill. The industry is thus perceived as generating large volumes of effluent that are extremely variable in composition and pollution load, the variability arising from the diversity in the types of transformation processes used and the wide range of chemicals involved. The amount of water used varies widely in the industry, depending on the specific processes operated at the mill, the equipment used, and the prevailing management philosophy regarding water use. Because of the wide variety of process steps, textile wastewater typically contains a complex mixture of chemicals. Furthermore, since the production vary widely during a year because of seasonal changes and fashion and over a single day according to the production programme, the resulting emissions are even more difficult to standardize and compare [1,5,23].

Textile industry being a water-intensive sector gives priority to sustainable consumption of water and where feasible, technically and economically, the reuse of water. When water consumption at different production processes is considered, dyeing and finishing steps were found to be best candidates for reuse [1,5].

Dyeing operations generate a large portion of the industry’s total wastewater. Large volume wastes include rinse water from preparation and continuous dyeing, alkaline waste from preparation, and batch dye waste containing large amounts of salt, acid, or alkali and by-products, residual dye, and auxiliary chemicals from rinsing operations. The primary source of wastewater in dyeing operations is spent dye bath and rinse water. Such wastewater typically contains by-products, residual dye, and auxiliary chemicals. In both continuous and batch dyeing processes, final washing and rinsing operations are water intensive steps that need to be taken into consideration. Washing and rinsing operations actually consume greater quantities of water than dyeing itself [1,5].

2.3. Textile Industry in Turkey

The shares of the main sectors in the manufacturing industry in Turkey are presented in Table 2.2. As seen, food and the textile industries are the two main sectors in terms of their shares in the total manufacturing industry production. The value of textiles and clothing industry production was around 27.7 billion dollars in 2002 and exported 44 percent of that amount [3]. Its corresponding share in the manufacturing industry production in 2002 was 21.5% as shown in Table 2.2.

Table 2.2. Percentage of the shares of the main sectors in manufacturing industry

Shares in manufacturing* (%)	**2000**	**2002**
Food industry	20.1	20.9
Textiles and clothing	20.2	21.5
Chemical industry	7.2	6.9
Automotive industry	6.5	4.8
Petroleum industry	5.6	6.9
Iron & steel industry	4.6	4.9

*Shares evaluated at 1998 prices [24]

Today, textiles and clothing industry is an outward oriented industry, uses modern technology, and can compete with that of other countries in international markets. The proximity to the EU market besides large domestic market and improvement in infrastructure are the main strengths of the textile sector in Turkey. The important part of the textiles and clothing exports, nearly two thirds, has been directed to EU. Geographical proximity, duty free access to the EU, relatively low wage levels, high quality of goods demanded by the EU are the main causes of the increase in the textiles and clothing industry exports. More than one third of total exports of Turkey was realized by the textiles and clothing industry in 2002 [3]. On the other side, as shown in Figure 2.2, Turkey is the main textile supplier of EU with a share of 10% and 16% of total textile import of EU in 1995 and 2002, respectively. Changes in the EU's external sourcing of textile imports are characterized by a sharp increase in Turkey's market share following the EU-Turkey customs union that entered into force in 1996. Switzerland, the fourth largest exporter in 1995, has fallen out of the list of the 10 largest exporters, while Bangladesh has entered the list and gained a significant market share. China has also increased its market share.

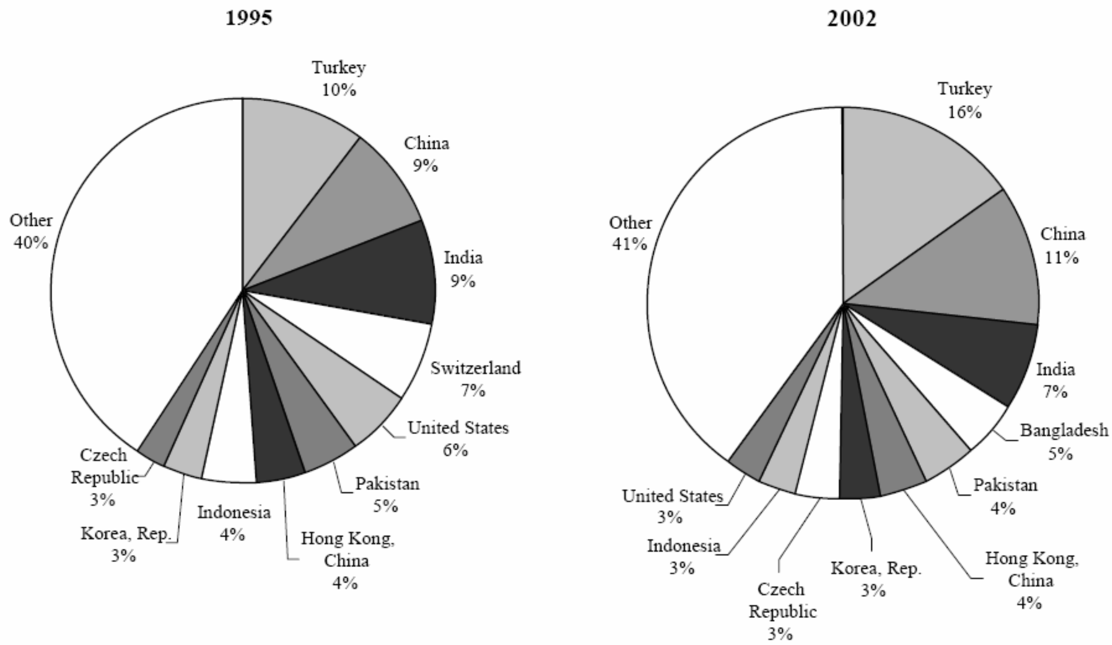


Figure 2.2. Sources of imports of textiles to the EU [25]

The main reason behind the good performance of the textile and clothing industry in Turkey is the increase in modern machinery imports and new investments in recent years. The performance of textiles and clothing industry affected positively by domestic cotton production, proximity to the EU market, trained work force, the progress achieved in infrastructure and telecommunication systems, together with the existence of large domestic market [3].

Turkey, as one of the largest manufacturers of textile and clothing products in the World, has the capability of serving full-package products. In the medium term, with decreasing lead times, better quality/price ratio and creation of brands, Turkey will still be one of the most competitive textile and clothing industries in the World [3].

Despite the fact that Turkey will face intensified competition in textile and clothing industry after quota elimination in 2005, Turkey with its geographical location, raw materials production, trained workforce, has still a potential in this industry. However, Turkish textile and clothing industry needs a restructuring by improving its quality, management and marketing skills, logistic performance, and certifications. In doing this, foreign investment can play particularly an important role. Foreign companies should be attracted to Turkey to increase the quality of the products and the organizations [3].

2.4. Pollution Prevention and Control in Textile Industry

2.4.1. Integrated Pollution Prevention and Control

In EU countries, pollution rising from industrial activities is managed by "integrated pollution management" concept. In this respect, a general approach covering pollution within the production phases is accepted rather than considering pollution control via end of pipe treatments and setting limit values for the discharges or emissions from industrial facilities. Therefore, a general concept of waste prevention and/or minimization techniques is adopted to all production phases to minimize discharges taking air, water and soil as a whole. IPPC Directive (96/61/EC), published in 1996 by EU, covers legal arrangements and requires the inspecting authorities to give permits to the industrial facilities and to monitor their environmental performances within this general approach [26]. Annex I to the IPPC Directive categorizes the industrial activities covered into six. These are energy production, production and processing of metals, minerals, chemicals, waste management, and others (pulp and paper, textile, tanning, food production and the intensive farming of poultry and pigs) [27].

Turkey being a candidate country for full membership to the EU is in the period of adopting legal requirements and sanctions of the Union. Among many other Directives, the IPPC Directive is of priority as manufacturing industry is wide spread in Turkey and its implementation requires heavy investment. Meanwhile, throughout the EU, environmental concerns in manufacturing industry have increased recently since the IPPC Directive was published. For that reason, many countries that import Turkish textiles (EU and the USA being the first) require quality tests, covering environmental aspects, before, during and after the production processes. Besides, those concerns are even declared as 'non-tariff barriers' in terms of exports in manufacturing industry nowadays [2]. Moreover, as water shortage is experienced water consumptions are to be minimized by utilizing technologies, which enable recovery in textiles industry in Turkey. This fact implies that Turkey has to invest millions of Euros for adaptation of its textile sector to the IPPC Directive. Nevertheless, of course this is not the only prerequisite for the adaptation. As the responsible authority, Ministry of Environment and Forestry (MoEF) has to install some capacity for the possible future enforcement of the Directive. More importantly, industry itself has to be informed about possible consequences of the Directive and prepared for the adoption of the integrated pollution prevention and control concept in waste management [26].

BREF Notes published by EU as guidance documents in the implementation of the IPPC Directive present an integrated approach to improve the management and control of industrial processes to ensure a high level of protection for the environment as a whole. The BREF Notes on textile industry covers the industrial activities specified namely "plants for pretreatment (operations such as washing, bleaching, and mercerization) or dyeing of fibers or textiles where the treatment capacity exceeds 10 tonnes per day". In this document, pollution prevention opportunities, control of raw materials, use of water and chemicals and their optimization, chemical substitutions, process modifications, recovery, reuse and recycle options are stated [1].

2.4.2. Textile Wastewater Management

As it is stated in previous sections, the textile industry is known as a water intensive sector typically 200-400 L water are needed to produce 1 kg of fabric [28]. Therefore, one should give importance to the textile wastewater management in terms of sustainable water consumption and reuse these potential wastewaters where feasible [1,5].

In the BREF textile document, well-accepted general principles for wastewater management and treatment are defined as:

- characterizing the different waste water streams arising from the process;
- segregating the effluents at source according to their contaminant type and load, before mixing with other streams. This ensures that a treatment facility receives only those pollutants it can cope with. Moreover, it enables the application of recycling or reuse options for the effluent [1].

The general principles of wastewater management and treatment defined in BREF textile document are supported by other researchers [29]. They state that identifying suitable pollution abatement or water recycling technologies is made difficult by combining effluent streams from individual operations, resulting in large variations in effluent chemical composition. Clearly, candidate waste treatment techniques need to be dedicated to individual process effluents, rather than the combined discharge, in order to be reliable and effective. Effluent reclamation and reuse thus only becomes viable for individual wastewater streams, where the compositional variability is reduced, and/or in cases where either the discharge consents are stringent (or else the discharge costs high) or the treated effluent has some added value. Both these criteria are pertinent to dyeing wastewater streams, where the possibility exists to both recover chemicals and recycle the treated wastewater.

When water consumption and wastewater generation at different production processes are considered, dyeing and finishing steps are found to be the best candidates for reuse [1,5]. Dyeing is the most water-intensive one of the unit processes, consuming up to 280 L water per kg of finished product [30]. This amount can vary depending on the production scheme, raw material, applied processes, etc. specific to each textile plant. Dyeing operations generate a large portion of the industry’s total wastewater, also have the largest risk for the environment because of its by-products, residual dye, and auxiliary chemicals present in rinse bath, and rinse water, which are the primary source of wastewater [7,8]. Dyeing wastewater quality and quantity depend mostly on the techniques used for a certain raw material such as wool or cotton, production method, and other general factors. Specific wastewater discharge varies between 40 m^3 and 300 m^3 per ton of finished product depending on the production method [31]. Such wastewaters are distinguished by high COD, high dissolved and suspended solids, and high color contents. In both continuous and batch dyeing processes, final washing and rinsing operations are water intensive steps consuming greater quantities of water than dyeing itself therefore they should be taken into consideration. Thus, dyeing wastewaters originating from rinsing operations are great candidates for recovery and reuse [7,8].

There are several methods applicable for the reclamation of dyeing wastewaters. One of the most common ones is activated sludge process, which is used to meet the wastewater discharge criteria set by legislations but not to produce reusable water. Because of the recalcitrant nature of the contaminants present in the wastewater, conventional activated sludge process or biological treatment processes cannot eliminate all the contaminants. Activated sludge process offers high efficiencies in COD removal, but does not provide complete color elimination and frequently operational problems like bulking appear. The use of flotation instead of sedimentation to separate the treated wastewater from the activated sludge solves this problem, but it increases the depuration costs and it makes complicated the plant operation. So, in order to have water that can be recycled in production cycles (especially dyeing processes), water needs further treatments (called tertiary or advanced treatments) [9,28]. Membrane filtration and advanced oxidation processes appear to be the indispensable alternatives for the tertiary treatment of the effluent from biological treatment.

Examples of advanced oxidation processes including ozonation, UV/H_2O_2, TiO_2/UV, Fenton's reagent oxidation, photo-Fenton and photoelectrocatalytic oxidation for the purification of water and wastewater are present in the literature [28,32]. Among these, advanced oxidation methods, ozone combinations are the most commonly applied advanced oxidation methods used before biological treatment to enhance biodegradability and remove color in textile wastewaters. However, the major disadvantage of using ozone is that it may form toxic by-products even from biodegradable substances [32]. Moreover, although chemical oxidation by ozone, or a combination of UV-radiation and ozone and H_20_2, have great interest but their costs are still very high to treat raw textile wastewater [9].

The performance and the limitations of the technologies used for the treatment of textile wastewater are given in Table 2.3.

Table 2.3. Evaluation of Various Technologies for the Treatment of Textile Effluents [33].

Process	**Stage**	**Performance**	**L imitations**
Fenton oxidation	Pre-treatment	• Full decolorization • Low capital and operational cost	
Electrolysis	Pre-treatment	• Full decolorization	Foaming and electrode lifespan
Foam floatation	Pre-treatment	• Removes 90% color and 40% COD • Cheap, compact	
Filtration (Membrane treatment)	Main or post treatment	• High performance • Reuse of water, salts and heat	Handling and disposal of concentrate stream, flux decline, cleaning cycles
Activated sludge	Main treatment	• Removes bulk COD, N.	High residual of COD, N, color and surfactants
Sequential anaerobic aerobic	Main treatment	• Better removal of COD, color and toxicants	High residual of COD and color
Fixed bed	Main treatment	• Better removal of COD, color	
Fungi/H_2O_2	Main treatment	• Full decolorization	
Coagulation	Pre-, main or post treatment	• Full decolorization • Water reuse	Not always effective, Sludge Disposal
Ozonation	Post-treatment	• Full decolorization • Water reuse	Expensive, aldehydes formed
Sorption	Pre- or post-treatment	• New sorbents are active and cheap • Water reuse	High disposal or regeneration costs
Photocatalysis	Post-treatment	• Near complete color removal • Detoxification	Only as final polishing step

In some case, after conventional biological treatment, additional treatment like membrane filtration could be necessary not only for compliance with environmental regulations but also for reuse in textile manufacturing. The possible approaches for the membrane purification treatment are NF or reverse osmosis (RO), since UF membranes can hardly remove COD and conductivity, having only a slight effect on color [10]. UF is effective only for removal of particles and macromolecules [28]. The removal of polluting substances is never complete in UF case. Even in the best cases, the quality of the effluent, especially concerning residual coloration, does not match those requirements set out for the effluent to be reused in delicate processes such as dyeing yarns in light coloration [34]. This idea was also supported by another recent study which proposes a membrane based treatment scheme for the recovery of the print dyeing wastewaters and the acid dye bath wastewaters of a carpet manufacturing industry [35].Water that is treated by UF alone therefore can be used only for 'minor' processes in the textile industry, and when residual salinity is not a problem. Microfiltration allows for a simple clarification of the wastewater. Therefore, it cannot be used as a sole treatment for textile wastewater recycling, but it can be used each time when an efficient method of removing suspended matter is required, for example as a pretreatment stage for another membrane process, or for ozonation [34]. NF does not reach the retentions of RO, but the permeate quality is good enough for the NF permeate to be reused in all wet textile processes, including the most demanding with regard to water quality. [10,33].

The significant drawback of membrane technology is the flux decline caused by membrane fouling. Implementation of the right pretreatment process is very important to minimize flux decline and hence maintain an efficient membrane separation process. Membrane filtration technology assisted with the physicochemical pretreatment methods such as coagulation, adsorption, sand filtration, membrane processes (MF, UF) is reported to be one of the most promising ones for the reclamation of textile effluents [7,9,10, ,36]. Among these alternatives, MF has been gaining a wider recognition since it is economically competitive alternative. The use of MF to remove colloidal species from the exhausted dye bath effluents before NF has been proposed in the past studies [11,12]. In another study wastewater of a textile plant which manufactures socks and panties was studied for the reuse purpose. Combination of a physicochemical treatment (coagulation with aluminum sulfate and ferric chloride) and membrane technologies had been proposed. The physicochemical treatment applied provided a COD removal efficiency around 50%. UF tests reduced COD of the physicochemically treated water. However, the permeates of NF membranes can be reused in the industry due to their low COD and conductivity [9]. In a similar study focused on the printing, dyeing and finifhing wastewaters physicochemical pretreatment and NF were proposed in order to reuse the wastewater. For the physicochemical treatment two coagulants (one containing Al^{+3} and another containing Fe^{+2}) were compared by coagulation using different chemical concentrations and pH values. Besides pretreated wastewater were given to NF. The results showed that the COD and conductivity of the NF permeates were lower than 100 mg/L and 1000 μS/cm respectively satisfying the reuse criteria given in Table 1.1 [10].

In a recent study textile wastewater was studied for reuse purpose and the proposed treatment scheme was the sequential application of cross flow UF and NF. It can be concluded from the study that UF is an appropriate technique as a pretreatment of a NF/RO process to textile wastewater reuse. In that study membrane selection and operating conditions were considered as important issues to optimize technically and economically the process. Nevertheless, these parameters were accepted as they had minor effects on COD and color removal efficiencies [8].

Recently indigo dyeing wastewater originating from a textile mill processing cotton fiber was studied in order to reuse the wastewater by using membrane technologies. The developed process chain has been proposed as MF+NF and this scheme was tested for dilute indigo dyeing wastewater and it has been accepted as generic for indigo dyeing wastewaters [37]. In essence, selection of the appropriate treatment technology for colored textile effluents is also related with the dye used in dyeing process. An alternative dye classification that refers to color removal technologies places the various classes of dyes (with respect to their application) into three groups depending on their state in solution and on the type of charge the dye acquires [38]. Each group can be associated with potential color-removal methods. Table 2.4 shows the classification of dyes with respect to offered color removal technologies. Coagulation and membrane technologies are recommended for indigo (vat), sulfur and disperse dyeing wastewaters, which are applied in the selected textile mill.

Table 2.4. Dye classification with respect to color removal [38]

Classification	**Dye Class**	**Charge/Solution state**	**Technology**
Group A	Disperse Azoic Vat Sulfur	Negatively charged, Colloidal	Coagulation, Membrane, Oxidation
Group B	Acid Reactive Direct Mordant Metal complex	Anionic, Soluble	Adsorption, Ion exchange, Membrane, Oxidation
Group C	Basic	Cationic, Soluble	Adsorption, Ion exchange, Membrane, Oxidation

CHAPTER 3

THEORETICAL BACKGROUND

In this chapter, brief reviews of the colloidal chemistry and membrane filtration, which are relevant to the present study, are provided. Firstly, the electrical double layer concept and the fundamental principles relating to coagulation (chemical precipitation) are discussed. Then, membrane filtration processes are introduced along with recent published studies.

3.1. Coagulation

The colloidal sized particles in water and wastewater are generally hard to remove since they are very small (about 0.01 to 1 μm) and generally possess negative charges preventing from coming together to form large particles that could be more readily be settled out. The removal of these particles requires charge neutralization and then particles are encouraged to collide with each other to form large particles and settle. Coagulation is the process of destabilizing colloidal particles via charge neutralization so that particle growth can occur as a result of particle collisions.

Coagulation can be also explained by electrical double layer model. Figure 3.1 is a representation of the static electric field surrounding the particle. Since the solid particle is negatively charged, it attracts the positively charged ions surrounding it. Some of the ions are so strongly attracted to the particle that they are virtually attached to the particle and travel with it forming a "shear plane" (slippage plane). These ions are held there through electrostatic and van der Waals forces of attraction. Around this inner layer, an outer layer named as "diffused layer" consisting mostly of positive ions are attached less strongly to the particle. The electrical double-layer consists of a "stern layer" (compact layer) and a "diffused layer". The charge on the particle as it moves through the fluid is the negative charge, diminished by the positive ions in the inner layer. The latter, i.e. electrical potential at the shear surface depending on the distance through which the charge is effective is called the zeta potential.

In addition to the repulsive charges of the particles, all particles carry an attractive electrostatic charge, van der Waals force, which is a function of the molecular structure of the particle. The combination of these forces results in a net repulsive charge, an energy barrier, or "energy hill," that prevents the particles from coming together. The objective of coagulation is to reduce this energy barrier to zero so that the particles no longer repel each other. Adding trivalent cations to the water is one way to reduce the energy barrier. These ions are electrostatically attracted to the negatively charged particle and, because they are more positively charged, they displace the monovalent cations. The net negative charge, and thus the net repulsive force, is thereby reduced. Under this condition, the particles do not repel each other and, on colliding, stick together. A stable colloidal suspension can be destabilized in this way, and the larger particles will not remain suspended. Aluminum sulfate is the usual source of trivalent cations in water treatment. Aluminum sulfate has an advantage in addition to its high positive charge: some fraction of the aluminum ions may form aluminum oxide and hydroxide by the reaction (3.1);

$$Al^{+3} + 30H^{-} + Al(0H)_3 \downarrow \qquad (3.1)$$

These complexes are sticky and heavy and will greatly assist in the clarification of the water in the settling tank if the unstable colloidal particles can be made to come in contact with the floc. This process is enhanced through an operation known as flocculation. As a second step after coagulation, flocculation introduces velocity gradients into the water so that the particles in a fast-moving stream can catch up and collide with slow-moving particles. After flocculation, particles are large enough to settle down and thereby can be removed from the water in the final step, i.e. settling [39,40].

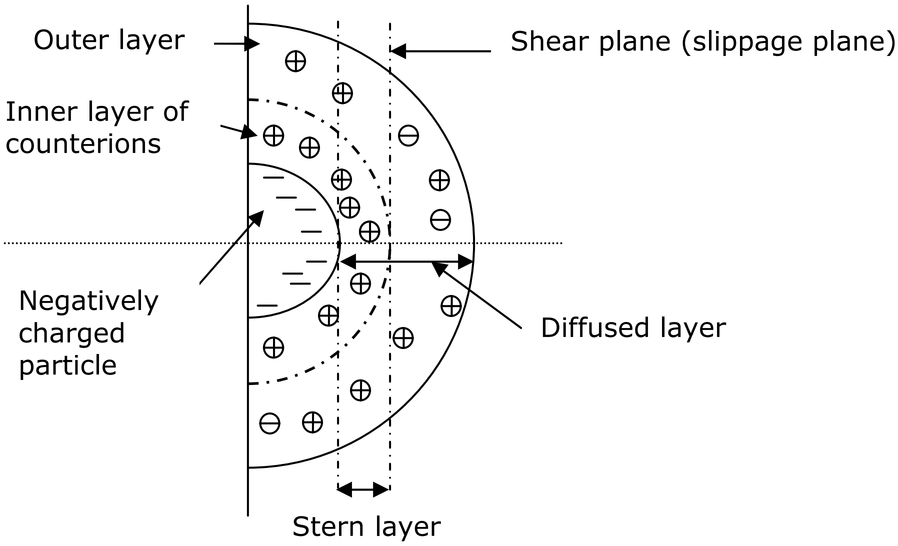


Figure 3.1. Charges on a suspended particle, as explained by the double-layer theory

The nature of an industrial wastewater is often such that conventional physical treatment methods will not provide an adequate level of treatment. Particularly, ordinary settling or flotation processes will not remove colloidal particles and metal ions. In these instances, natural stabilizing forces (such as electrostatic repulsion and physical separation) predominate over the natural aggregating forces and mechanisms, namely, van der Waals forces and Brownian motion, which tend to cause particle contact. Therefore, to adequately treat such particles in industrial wastewaters, coagulation is an important technology in which rapid mixing of coagulants with fluid ensures the chemical dispersion throughout the wastewater and flocculation provides particle contact at a slow mix letting particle agglomeration and settling allows large particle separation from liquid [41].

3.2. Membrane Technologies

A membrane is a permeable and semi-permeable phase, often a thin polymeric solid, which restricts the motion of certain species. Membranes are generally classified in broad categories by their ability to remove particles, ions and other substances in certain size ranges. The type of the driving force applied across the membrane leads to a basic classification of membrane separation processes, as shown in Table 3.1.

There are four commonly accepted pressure-driven membrane separation processes, defined based on the size of the material they will remove from the solvent. Table 3.2 shows the ranges of material sizes retained, the pressures required, the typical fluxes obtained and the separation mechanisms used by each membrane separation process [35].

Table 3.1. Membrane Processes According to Their Driving Forces [42].

Membrane process	Driving force
MF/UF/NF/RO	Pressure difference
Pervaporation Gas separation Dialysis Liquid membranes	Concentration difference
Thermoosmosis Membrane distillation	Temperature difference
Electodialysis Electroosmosis	Electrical potential difference

Table 3.2. Specifications of pressure driven membrane processes [42,43]

Process	Retained particle size	Pressure required, bar	Typical fluxes obtained, L/m^2/h/bar	Separation mechanism
MF	0.05-10 μm (microparticles)	0.1-2	>50	Sieving
UF	1-100 nm (macroparticles)	1-10	10-50	Sieving
NF	0.5-5 nm (molecules)	5-20	1.4-12	Solution-diffusion
RO	<1 nm (molecules)	10-100	0.05-1.4	Solution-diffusion

In water and wastewater treatment, the membranes most widely used are broadly described as pressure driven. Each membrane process is best suited for a particular treatment function. For example, MF and UF, which are very low-pressure processes, most effectively remove particles and microorganisms. The RO process most effectively desalts brackish water and seawater and removes natural organic matter and synthetic organic and inorganic chemicals. The NF process softens water by removing calcium and magnesium ions and used for reuse purposes. These so-called nanofilters are also effective in removing the precursors to disinfection by-products that result from such oxidants as chlorine [44].

Membrane processes offer advantages over conventional treatments. They reduce the number of unit processes in treatment systems for clarification disinfection and increase the potential for process automation and plant compactness. Designers also thought membrane plants could be much smaller than conventional plants of the same capacity and, given their modular configuration, could be easily expanded. Additionally, these plants would produce less sludge than conventional plants because they would not use such chemicals as coagulants or polymers.

One innovative process configuration for surface water and tertiary wastewater treatment involves the use of double-membrane systems, consisting of a low pressure and a high-pressure membrane in series. This treatment is effective for both microbial and chemical contaminant control. The first membrane (MF or UF) is used to help prevent fouling of the second, higher-pressure membrane system (RO or NF).

3.2.1. Basic Definitions and Principles

The performance of a membrane is defined in terms of two factors so called flux and selectivity. Flux or permeation rate is the volumetric flowrate of the fluid passing through the membrane per unit area of the membrane per unit time is shown in Equation (3.2);

$$J = \frac{1}{A} \times \frac{dv}{dt} \tag{3.2}$$

where,

J : flux ($L/m^2/h$)
A : effective membrane area (m^2)
dv/dt : permeate flowrate (L/h)

Selectivity, named as retention for solutes and particles in liquids and gases, the fraction of solute retained in the feed by the membrane [45]. Retention is given by Equation (3.3);

$$R = \frac{C_f - C_p}{C_f} \tag{3.3}$$

where,

R : retention
C_p : solute concentration in the permeate
C_f : solute concentration in the feed

As membranes filter out the impurities from the water, the membranes themselves become fouled (or clogged) and less effective. The *fouling* can be reversible or irreversible. *Concentration polarization* refers to the reversible build-up of solutes near the membrane surface. Concentration polarization can lead to irreversible fouling by altering interactions between the solvent, solutes and membrane. The fouling of membranes has been the main drawback to their more widespread application in water and wastewater treatment. In general, membranes can be fouled by an accumulation of inorganic particles and organic compounds. Bacteria can also adhere to the membranes and create a biofilm. When this is the case water flux decreases when the system is operated at constant pressure [44]. Fouling can be controlled by hydrodynamic and chemical methods, periodic backwashing, and chemical cleaning. A typical cleaning consists of flushing the membrane modules by recirculating the cleaning solution at high speed through the module, followed by a soaking period, followed by a second flush, and so on. The chemical cleaning agents commonly used are acids, alkalis, chelatants, detergents, formulated products, and sterilizers. Other methods include improving pretreatment and changing operating conditions [44,46].

Membrane processes can be operated as:

- Dead-end filtration (in-line filtration)
- Cross-flow filtration [43].

Dead-end filtration refers to filtration at one end. The entire fluid flow is forced through the membrane under pressure. As particles accumulate on the membrane surface or in its interior, the pressure required to maintain the required flow increases, until at some point the membrane must be replaced. A problem with these systems is frequent membrane clogging [46]. Dead-end filtration is generally suitable for concentrated suspensions, and not appropriate for the filtration of very fine and dilute suspensions or production of very pure filtrates [47].

In *cross-flow filtration* the feed solution is circulated across the surface of the filter, producing two streams: a clean particle-free permeate and a concentrated retentate containing the particles. The equipment required for cross-flow filtration is more complex, but overcoming the problem of membrane clogging lets membrane lifetime be longer than with in-line filtration and it is widely used in water and wastewater treatment [44,46]. Figure 3.2 shows the schematic representation of dead-end and cross-flow filtration mode.

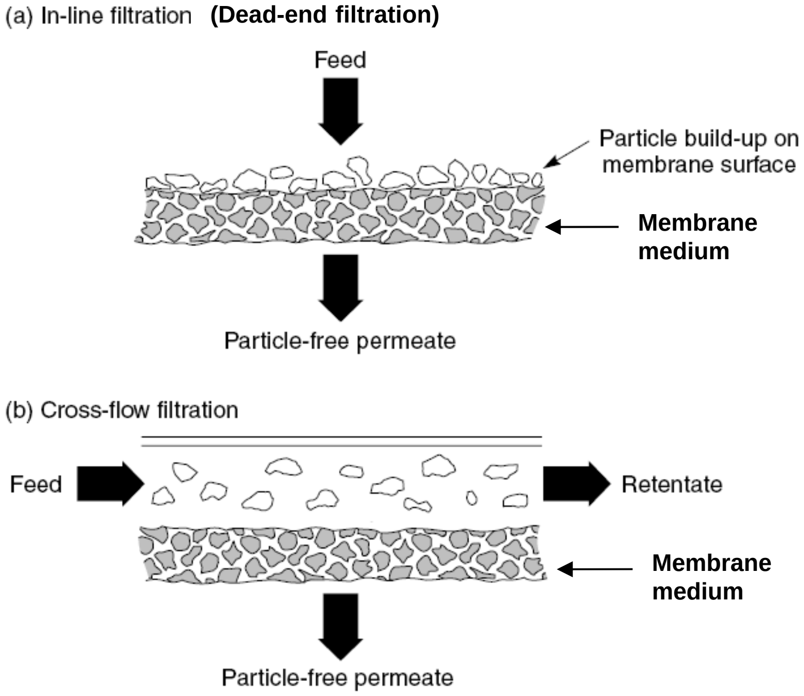


Figure 3.2. Schematic Representation of (a) dead-end and (b) cross-flow filtration [46]

Cross flow velocity (CFV) is calculated in Equation (3.4);

$$CFV = \frac{1}{A} \times \frac{dV}{dt} \tag{3.4}$$

where;

V=the volume of retentate collected during filtration at time t,
A=cross-sectional area of the membrane.

In real applications, build-up of solutes, macromolecules or particles near the membrane surface of a porous inorganic membrane can exert significant influence over the permeate flux. In general the build-up layer becomes lessened with increasing crossflow velocity [48].

Transmembrane pressure (TMP) is the driving force for the pressure-driven membrane processes, and it is defined in Equation (3.5) as the pressure difference across the membrane, i.e. arithmetic average of feed and retentate pressure minus the permeate pressure (in our study P_p=atmospheric pressure).

$$TMP = \frac{P_{in} - P_{out}}{2} - P_p \qquad (3.5)$$

where,

P_{in} : inlet pressure (feed pressure)
P_{out} : outlet pressure (retentate pressure)
P_p : permeate pressure (atmospheric pressure)

Among the pressure-driven membrane processes MF, UF, and NF were applied to indigo dyeing rinsing wastewaters in this study. These processes were discussed in the following sections.

3.2.2. Microfiltration

MF refers to filtration processes that use porous membranes to separate suspended particles with diameters between 0.1 and 10 μm thus yielding a relatively higher flux than the other membrane separation technology. Thus, microfiltration membranes fall between UF membranes and conventional filters [46].

All current MF membranes may be classified as either "tortuous-pore" or "capillary-pore" membranes as shown in Figure 3.3. The "capillary-pore" structure is distinguished by its straight-through cylindrical capillaries, whereas the "tortuous-pore" structure resembles a sponge with a network of interconnecting tortuous pores. The "tortuous-pore" membranes are the most common and include typical cellulosic membranes and virtually all other polymers [49].

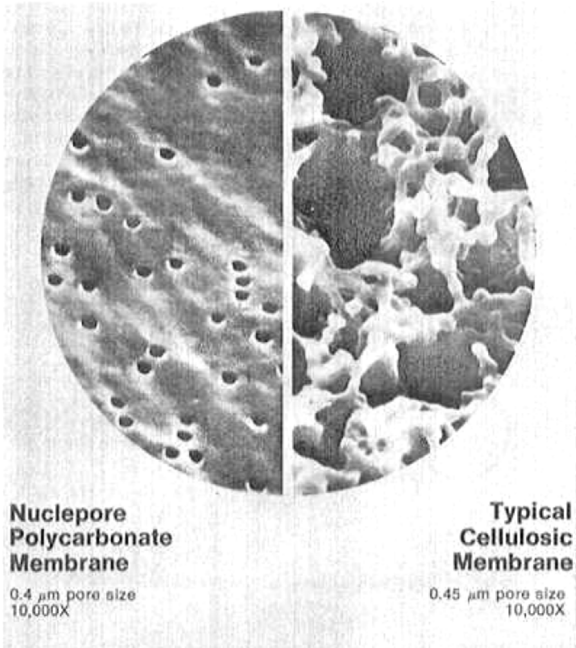


Figure 3.3. Capillary-pore and tortuous-pore membranes [49].

The most widely used process design, illustrated in Figure 3.2 (a), is dead-end or in-line filtration [46].There is not any advantage in running the MF unit in a crossflow mode and there may even be some disadvantages. The permeate quality and evolution of pressure drop obtained from the membrane operated in the dead-end mode is found similar or superior to that obtained under crossflow conditions [44].

MF is applied in both production and analytical applications such as;

- Removal of particles from liquid and gas streams for chemical, biological, pharmaceutical, and food industries,
- Clarification and sterile of heat sensitive solutions and beverages,
- Production of pure water in the electronics industry,
- Product purification, gas filtration, process solvent recovery in the chemical industry
- Wastewater treatment [45].

3.2.2. Ultrafiltration

Suspended materials and macromolecules with diameters between 1 and 100 nm can be separated from a waste stream using UF membranes while only water and some dissolved low molecular weight materials such as solvents and salts pass through the membrane under an applied hydrostatic pressure. UF membranes are often rated by molecular weight cut-off (MWCO) which is a means of determining the size of the largest molecule able to permeate a UF, NF or RO membrane. Solutes above the MWCO are retained and those below the MWCO permeate through the membrane. The pores of UF membranes are much smaller than the particles rejected, and particles cannot enter the membrane structure. As a result, the pores cannot become plugged. The term dynamic membrane describes deposits that benefit the separation process by reducing the membrane's effective MWCO (Molecular Weight cut-off) so that a solute of interest is better retained. Better performances with the low and high MWCO membranes are explained by considering the effects of fouling on the membranes. Higher product rates are sometimes realized with lower MWCO membranes because they exclude more potential foulants and internal pore fouling is reduced. Membranes with higher MWCO's will sometimes effectively separate smaller solutes because solutes aggregate into larger entities or because foulant forms an effective dynamic membrane. The dynamic membrane reduces the effective MWCO of the membrane so that the solute is retained. The larger pores suffer less flow restriction due to adsorption, and the greater hydraulic permeability of the larger pores yields high product rates. Therefore, the effect of MWCO on membrane performance is dependent on the effect of the fouling on the membrane.

This technology is useful for the recovery and recycle of suspended solids and macromolecules. Excellent results have been achieved in textile finishing applications and other situations where neither entrained solids that could clog the filter nor dissolved ions that would pass through are present. The largest industrial use of UF is the recovery of paint from water-soluble coat bases (primers) applied by the wet electrodeposition process (electrocoating) in auto and appliance factories. Many installations of this type are operating around the world. The recovery of proteins in cheese whey (a waste from cheese processing) for dairy applications is the second largest application [44].

3.2.3. Nanofiltration

NF is a term to define membranes, which were already in use, referred to as "loose RO." The typical pore size of NF membranes is 0.5-5 nm, and the applied pressures are typically 5-20 bar as given in Table 3.2. Typical NF membranes pass a higher percentage of monovalent salt ions than divalent and trivalent ions. Most NF membrane polymers carry formal charges that exclude higher valence ions more than monovalents from passing through the membrane with the solvent water. NF membranes span the gap between RO and UF classes. Hundreds of applications have been commercialized, falling in three broad categories: water purification, manufacturing process separations, and waste treatment. Among the widely used application areas of NF process are textile waste recovery for reuse, pulp and paper water recovery for reuse, dye and ink concentration and recovery, water softening, removal of natural organic matter, heavy metals and plating salts concentration etc. [50].

CHAPTER 4

THE TEXTILE PLANT STUDIED

4.1. General View of the Plant

The plant, from which the indigo dyeing wastewater samples used in the present study were collected, was established in 1953. It is located in Central Anatolian Region of Turkey with 900 employees on a 156000 m^2 area. It serves as a fiber manufacturing and weaving factory and produces denim textile starting from raw cotton. It is one of the leading denim cloth producers worldwide. The plant produces 20,000 tons of cotton fiber and 45 million meter of denim fabric per year with a daily water consumption of 3500-5000 tons.

Textile production starts with fiber manufacturing continues with sizing, dyeing, weaving and ends up with finishing as shown in Figure 4.1. Among these, dyeing, sizing and finishing are the wet processes; fiber manufacturing and weaving are the dry processes. The plant extracts water from wells, softens through the processes of an ion exchange and a reverse osmosis, and discharges its treated wastewaters into the sewer line that ends up with a municipal wastewater treatment plant. Figure 4.2 shows the distribution of the totally extracted 3500-5000 tons/day of water within the processes. More than 70% of the total water extracted is used for dyeing and finishing processes; and the rest being used for other purposes such as steam generation, sizing, good housekeeping etc. [26,51].

A general overview of the processes carried on in the plant can be described as follows:

- Cotton as the raw material is physically processed to produce fibers **(fiber preparation)**,

- Yarn is produced by spinning of the fibers **(yarn manufacturing)**,
- Manufactured yarns enter the dyeing process that is composed of 6 sub-processes: pre-processing, pre-rinsing, dyeing, post-rinsing, softening and drying **(dyeing)**,
- Dyed yarns are further processed in the sizing stage **(sizing)**,
- Depending on customer preferences, different weaving types are applied through physical processes to the dyed yarns **(weaving)**,
- Desired end use properties are given to the woven fabric **(finishing).**

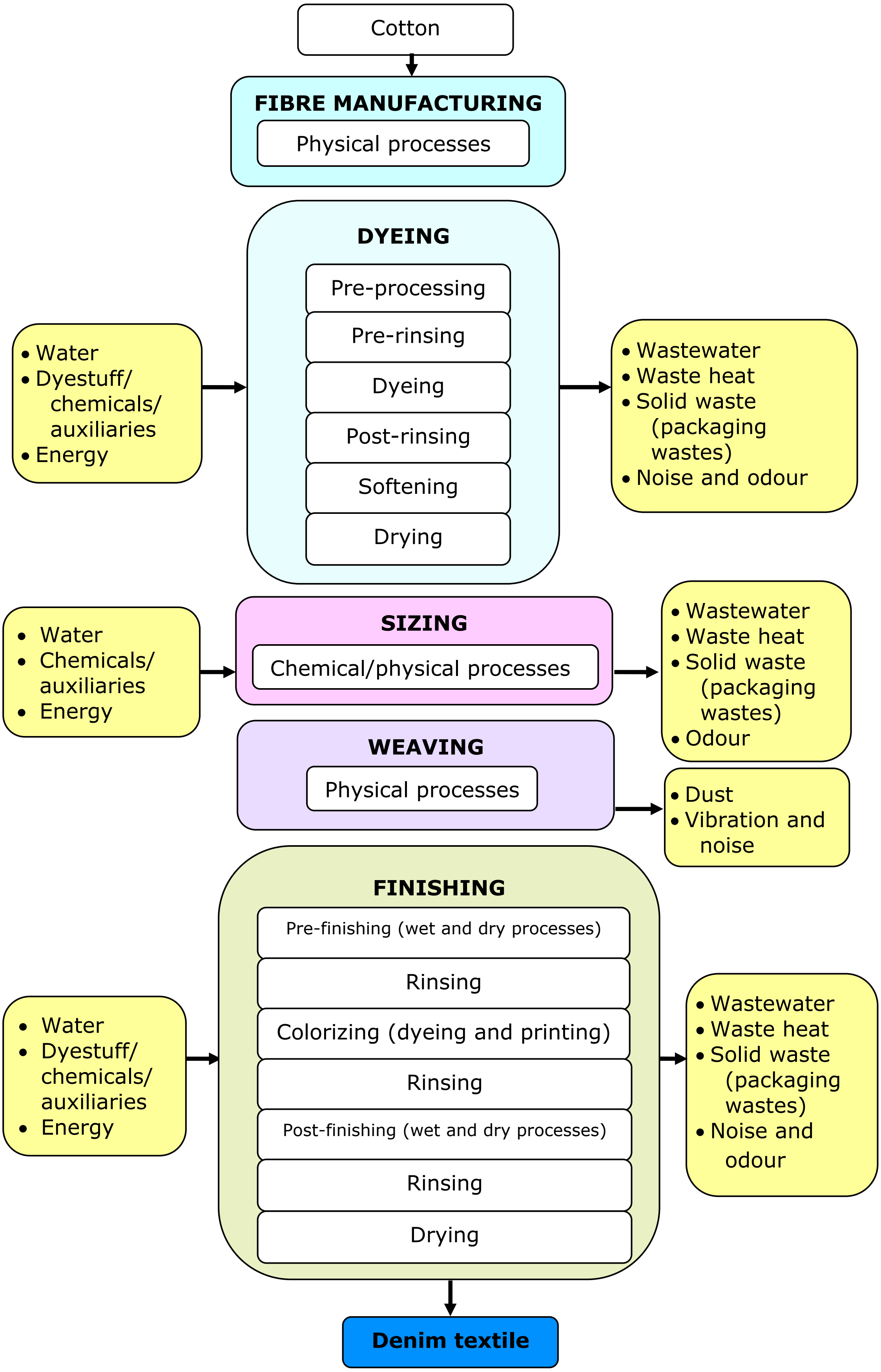


Figure 4.1. Process Flow Diagram of the Pilot Plant

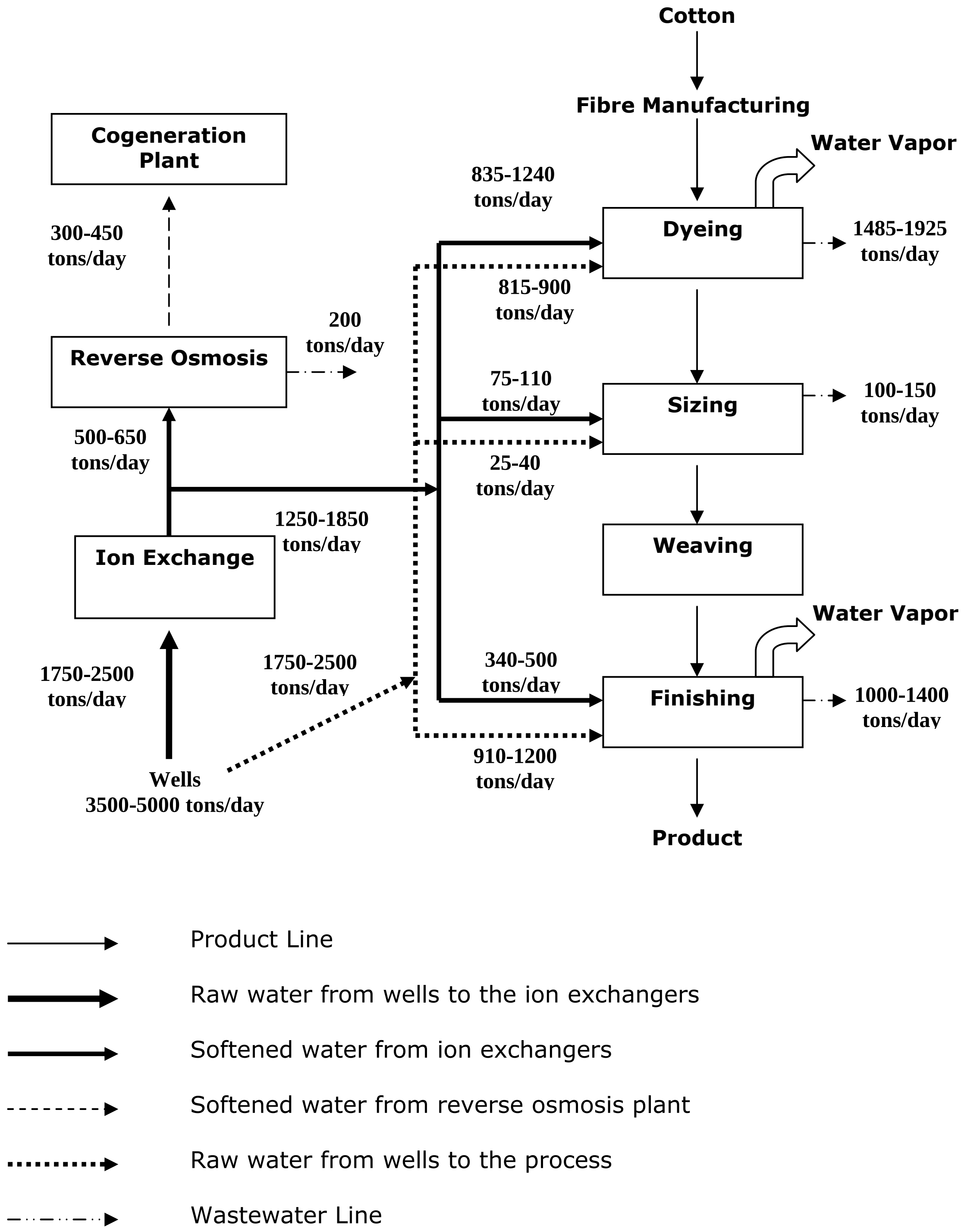


Figure 4.2. Water consumption and wastewater generation of the plant

Section 4.2 provides descriptions of the processes in detail listed above.

4.2. Process Descriptions

4.2.1. Fiber Manufacturing

Fiber Preparation

Fiber preparation is a dry process and it composes of the physical processes applied to the raw cotton. The amount of the cotton processed in the plant is about 65-70 tons/day. As the first step in fiber preparation, cotton screening is done and then the cotton is sent to blending. The purpose of blending is to mix and combine different cottons of different origin to provide homogeneity in the fiber. Besides providing homogeneity, blending also removes the impurities in cotton lumps. After blending, the cotton is ready to yarn production with its homogeneous structure.

Yarn Production

After fiber preparation a series of physical dry processes such as carding, drawing and spinning are applied to the fiber to form yarns. Following blending the fiber is sent to carding in which parallel fiber structures are formed. Each six parallel lines of fiber structure leaving the carding process is led to drawing machine where thick strips are formed (Figure 4.3). These strips are then led to spinning where final thickness of the strips is provided and then rolled onto bobbins that are then stocked in the warehouse (Figure 4.4.). The final step prior to the dyeing process is to form ropes each formed with more than 100 pieces of yarns. In addition to these processes fixation process under a certain pressure and temperature for a certain time is applied to the yarns in order to protect the yarn from mechanical stresses and to impart polish prior to the further processes.

Figure 4.3. Drawing Process in which thick strips are formed

Figure 4.4. Spinning Process in which final thickness of the yarns are provided

4.2.2. Dyeing Process

Ropes manufactured via a series of physical processes applied to cotton enter the dyeing process composing of six basic wet processes . These are;

- Pre-processing
- Pre-rinsing
- Dyeing
- Post-rinsing
- Softening
- Drying

Water, dyestuff, chemicals, auxiliaries and the cotton ropes are the inputs to the dyeing process whereas the wastewater is the major output from the system. Among the sub processes indicated above, the major water consumption takes place in pre- and post-rinsing stages. The majority of dyestuff (indigo, disperse, reactive and sulfur dyes) and chemical consumption (dispersing agents, complexing agents etc.) takes place in the dyeing step. After each chemical application rinsing takes place in all the processes throughout the plant.

Pre-processing of yarns

Pre-processing step is applied to the yarns in order to remove the impurities present in the fiber to make it homogeneous and to make the yarn hydrophilic thereby increasing its affinity to absorb the dissolved dyestuff and the chemicals applied in the dyeing line. In order to remove the impurities in the fiber, particular chemicals such as wetting agents and caustic like chemicals are applied according to the proceeding dyeing recipe to be applied in the dyeing process.

Water is not fed to the pre-processing tank continuously and following the process finalization wastewater is discharged to the main dyeing line channel therefore intermittent discharge occurs from pre-processing stage.

In this process, soft water at 60^{o}C is used. Chemicals used in the process are prepared with the soft water in the chemical agent preparation unit and then send to the pre-processing tank. The rope incoming to the system is dry and absorbs as much pre-treatment liquid as 65% of its weight after the process. The ropes that are pre-treated are squeezed under 100 psi pressure prior to the pre-rinsing process.

Pre-rinsing

Pre-rinsing step is applied to the pre-processed yarn in order to remove the unexhausted chemicals in the pre-processing to prevent their interference with the processes in the subsequent dyeing process. Water is continuously applied to the rope in the pre-rinsing tank and therefore there occurs continuous wastewater discharge, which is directed to the wastewater treatment plant of the mill via main dyeing line channel.

In this process, mainly hard water is used. The temperature of the water in the pre-rinsing tanks varies according to the required dyeing temperatures in dyeing tanks.

Dyeing

The dyeing unit is composed of four major machines that all include pre-processing, pre-rinsing, indigo dyeing, topping, post-rinsing, softening, and drying as the last step. In the present text, these four machines are shortly named as Indigo-1, Indigo-2, Indigo-3 and Indigo-4. A schematic representation of the machines can be seen in Appendix A. 20,000 meters of fiber can be processed in each dyeing machine. As it is seen in Appendix A, these four machines differ in number and volume of dyeing and rinsing tanks existing throughout the dyeing line. With this difference, more than 400 dyeing recipes can be applied in the plant. These recipes differ in dye solution (concentration and species of dyestuff and auxiliary chemicals such as dispersing agents, complexing agents, anti-foaming agents, stabilizing agents etc.), rinse water flowrate and volume/number of the tanks used for rinsing purpose, contact period of the rope with the dye solution etc.

Dyeing is applied to the rope in continuous mode, i.e. a fixed amount of rope specified by the dyeing recipe applied is loaded into the dyeing tanks and passed through a dye solution for a certain period of time and then enters subsequent dyeing tank following the same dyeing scheme. In dyeing tanks, dyestuff is adsorbed onto the surface of the rope initially and then the diffusion of dye solution in to the rope takes place. Auxiliary chemicals, the temperature of the dye solution and the contact time of the rope with the solution affects the fixation rate of the solution onto the rope. All these variables such as temperature, flowrate, concentration of chemicals and dyestuff, contact time differ according to dyeing recipes that differ with respect to the final product requested by the client.

Dye-houses in which dye solution preparation takes place are fully automated. All process parameters (temperature, pH, chemical feeding amount, dye solution preparation ratios, etc) are controlled by an online programme.

The mill mostly applies indigo dyes as all the dyeing machines are named as Indigo machines. Besides indigo dyes; sulfur, and disperse dyes are also applied according to the clients' demand. In the following section general properties of the dyestuffs applied in the plant are described.

- **Vat Dyes**

The major dyestuffs used in the dyeing process are indigo dyes and their derivatives, which are defined as vat dyes. Vat dyes are normally insoluble in water, but they become water-soluble and substantive for the fiber after reduction under alkaline conditions (vatting). They are then converted again to the original insoluble form by oxidation and in this way they remain fixed into the fiber. Indigo dyes are almost exclusively used for dyeing warp yarn in the production of blue denim [1]. These dyestuffs are applied to the fiber individually or sequentially in the selected mill according to the decision of the staff, fashion and demand of the customer.

- **Sulfur Dyes**

Sulfur dyes are used in piece dyeing (cellulose and cellulose-polyester blends), yarn dyeing (sewing thread, warp yarn for denim fabric, yarn for colored woven goods), dyeing of flock, card sliver (wool-man-made fibers blends). Like vat dyes, sulfur dyes are insoluble in water, and, under alkaline conditions, are converted into the leuco-form, which is water-soluble and has a high affinity for the fiber. After adsorption into the fiber, the colorant is oxidized and converted to the original insoluble state. The reducing agent, salts, alkali and unfixed dye are finally removed from the fiber by rinsing and washing [1]. In our study, sulfur dyes are applied separately or sequentially.

- **Disperse dyes**

Disperse dyes are used generally for polyamide fibers. They are applied especially for lighter shades. The material is dyed in acidic conditions (pH 5) by acetic acid. A dispersing agent is always added to the liquor [1]. In our study disperse dyes were used for cotton dyeing in a sequential mode with other dye solutions.

It is reported that more than 90 % of the organic chemicals and auxiliaries in pretreatment and dyeing operations does not stay on the fiber and found in the emissions [1]. The fixation rate of an individual dye varies according to type of fibre, shade and dyeing parameters. Estimated fixation rates for different types of dyes, processes and fibers are given in Table 4.1. They are useful to give an idea of the amount of unfixed dyes that can be found in wastewater indicating the color and other parameters like COD of the wastewater. The fixation rates for vat, sulfur and disperse dyes for the continuous dyeing process applied to the specific fibers given in Table 4.1 are 85%, 70%, and 95% respectively. This indicates that the unfixed ratio of about 15%, 30%, and 5% dyestuff applied remains in the wastewater for vat, sulfur, and disperse dyes respectively.

Table 4.1. Estimated fixation rate for different types of dyes, processes and fibres [52]

Type of Dye	Process*	Type of fibre**	Average fixation rate	Range [%]
Disperse	C	CE, PES	95	88 – 99
Disperse	P		97	91 – 99
Disperse	B	PES	97	95 – 99
Direct	B	CO	88	64 – 96
Reactive	B	WO	95	90 – 97
Reactive	B	CO	75	65 – 90
Reactive	C	CO	80	70 – 95
Reactive	P		75	60 – 90
Vat	C	CO	85	80 – 95
Vat	P		75	70 – 80
Vat		CO	90	85 – 95
Sulfur	C	CO	70	60 – 90
Sulfur	P		70	65 – 95
Acid, 1 SO^{-3} group	B	PA, PAN	90	85 – 93
Acid, >1 SO^{-3} group	B		95	85 – 98
Basic	B	PAN, PES, PA, CO	99	96 – 100
Azoic (naphtol)	C		84	76 – 89
Azoic (naphtol)	P		87	80 – 91
Metal complex	B		94	82 – 98
Pigment	C		100	
Pigment	P		100	98 – 100
Unknown/ hardly soluble	C		97	85 – 99.5
Unknown/acid groups	P		90	85 – 95

* Processes: C = continuous dyeing; P = printing; B = batch dyeing
** Fibres: CO=cotton; WO=wool; CE=cellulose; PES=polyester; PA=polyamide; PAN=Polyacrylonitrile

Post-Rinsing

As it is mentioned, rinsing is applied to the fiber after dyeing step since chemicals, and dyestuffs are used in the dyeing process and thereby interference via dyeing chemicals for the subsequent processes is eliminated. In this process, hard water at 70^{o}C is applied to the dyed rope.

Since a variety of chemicals and dyestuffs are applied in pre-processing and dyeing stages, wastewater resulting from the rinsing tanks is expected to have high color content, COD and dissolved and suspended solids.

Softening

Softening may be considered as a subsequent rinsing after post-rinsing. After dyeing, the rope should be softened in order to make the rope unwrapping process easier, which is applied prior to the weaving. Softening is a batch process; hence intermittent wastewater discharge occurs (approximately 1000 liter of wastewater/week). In this process, softening agent and citric acid for pH adjustment are used.

Drying

The purpose of drying process is to reduce or eliminate the water content of the ropes, yarns or fabrics after wet processes applied in dyeing. In the selected mill, drying process is applied via contact driers at a temperature of 140^{o}C in order to reduce the water content of the rope from 68% to 7-8%.

4.2.3 Sizing

Chemical and physical processes are applied at high temperatures to the dyed fibers in a batch mode in sizing process prior to the weaving. In sizing process, starch as main sizing agent is applied to the ropes in order to lubricate and increase the mechanical strength of the rope in the weaving process. Besides starch, synthetic sizing agents, starch derivatives and vegetable oil are also used in minor There are two machines operated in sizing process, one is for pre-moisturizing and the other is for sizing. Pre-moisturizing is applied with soft water under 90^{o}C in order to make the penetration of sizing agents into the yarns easy. After sizing, ropes are dried via high temperature initially then by reducing temperature with desired moisture content. Dried ropes are then combed in drawing process in which the ropes are prepared for weaving.

4.2.4. Weaving

In the weaving stage, depending on customer preferences, different weaving types are applied through physical processes. Weaving is a dry process like fiber manufacturing therefore neither water is consumed nor wastewater is generated. In order to have efficient weaving, moisture content of the indoor air should be arranged to a specific value and this condition is provided via air conditioners in the plant. Monthly production in weaving process is more than 3.000.000 meters of fabric.

4.2.5. Finishing

Finally, the woven fabric gets its desired end use properties such as visual effects, handle and special characteristics (i.e. non-flammability, water-proofing, and shrink resistance) in the finishing process. For the finishing stage, depending on the desired end product, applied sub processes differ. As in the case of dyeing process, pre-and post-rinsing tanks consume high amounts of water. Pre-finishing, colorizing and post-finishing steps are the major chemical consuming stages.

CHAPTER 5

EXPERIMENTAL

5.1. Determination of the representative effluents of the dyeing plant

Wastewater from the dyeing plant is mainly composed of spent dye baths, rinsing wastewaters, and machinery cleaning wastes. Rinsing wastewater samples are discharged continuously and originate from pre-rinsing and post-rinsing tanks that are located following pre-processing and dyeing tanks respectively. Spent dye baths and machinery cleaning wastes are intermittent and rarely discharged. During sampling period of the study, none of these tanks were sampled; instead, samples were taken from the overall effluent channel of the dyeing line. The parameters to be analyzed in the collected samples were identified in accordance with the BREF-textile document and water reuse criteria for the dyeing processes given in Table 1.1.

During the sampling period; one and a half month, the production scheme in the factory was quite variable and there was production of denim textile with 12 different dyeing recipes. Totally 294 samples were taken from 33 sampling points (pre-rinsing, post-rinsing, mixture of these two rinsing) from the dyeing line and analyzed for the quality parameters determined. Table 5.1 presents the results from wastewater characterization study. Since the production may vary widely not only during a year (because of seasonal changes and fashion) but even over a single day (according to the production programme), the resulting emissions are even more difficult to standardize and compare. As seen, wastewater characteristics change widely when the recipe changes and it is known that there are more than 400 different dyeing recipes in dyeing line, implying a wide variation in terms of wastewater quality.

In the table, the recipes are listed in the order of decreasing application frequency. The most commonly applied recipe (A) is indigo dyeing with a certain dose of indigo dye. On the other hand, the least common recipe (L) is again indigo dyeing but with a different indigo dye concentration in the dye bath. As a consequence of the difference in indigo dye concentration, there is a considerable difference in COD and color of the effluents from these two recipes. The difference in the effluent characteristics becomes more apparent when sulfur dye exists together with the indigo dye (D, E, and J). However, in general, all waste streams are high in color and COD with an alkaline pH that originates from the application of indigo dye. All these results implied for the assessment of water reuse and recycling opportunities in the indigo dyeing line that it is necessary to consider at least the most commonly applied recipes individually or as a whole.

An evaluation of the recipes applied during the sampling period and during the past four months indicated that analyzed dyeing wastewater samples represent typical production in the denim dying line (82% of total production of the plant as meter denim fabric) as given in Table 5.2. After ensuring that the sampled recipes represented the typical production in dyeing line, three mostly applied recipes were decided to study in terms of recovery and reuse. The selected three recipes composes of about 50% of all the dyeing recipes, more than 400, applied in the mill. It is evident that the mixture of the three dyeing recipes will mimic the total dyeing line effluent.

Table 5.1. Characterization results of dyeing recipes applied in dyeing process in the plant[1]

Parameter	Unit	A	B	C	D	E	F	G	H	I	J	K	L
pH	-	9.6	12.3	9.7	8.9	11.4	9.2	10.2	10.4	10.7	11.6	12.7	12.7
Conductivity	(mS/cm)	-	15.7	4.44	2.5	19.7	5.6	3.4	2.7	4.1	5.8	34.4	13.6
COD	(mg/L)	516	3250	1076	598	1563	1902	1203	840	934	1557	1199	779
BOD	(mg/L)	255	-	-	-	506	500	456	-	-	360	25	340
AOX	(mg/L)	0.4	1.1	3.1	0	0.3	7.5	0.5	0.6	2.2	0.3	0.3	0.1
Total Phosphorus	(mg/L)	2.4	4.3	2.9	2.9	2.3	1.9	2.2	1.8	2.5	2.3	4.6	1.3
TSS	(mg/L)	92	348	260	102	294	246	128	112	142	146	146	126
TDS	(mg/L)	2328	9976	6650	2038	9078	3950	2796	2642	2836	4250	10460	5298
Turbidity	(NTU)	93.5	972	190	84.4	56.8	315	86.5	41.4	54.3	190	44.4	24
Alkalinity	(mg/L $CaCO_3$)	240	3230	1110	184	4960	1430	740	488	1030	1250	8440	1800
Color	(Pt-Co)	1260	14250	2340	650	1938	2080	2118	3500	3910	3992	1686	1158
Zn	(mg/L)	0.704	0.012	0.0340	0.042	0.1	0.894	0.0438	0.034	0.0130	0.012	0.021	0.527
Pb	(mg/L)	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL
Mn	(mg/L)	<DL	0.136	0.0280	0.026	<DL	0.721	0.0168	<DL	0.0070	0.142	<DL	<DL
Fe	(mg/L)	<DL	0.052	0.0340	0.085	0.1	<DL	0.2099	0.096	0.0620	0.130	0.024	<DL
Cu	(mg/L)	<DL	<DL	<DL	0.006	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL
Cr	(mg/L)	<DL	0.012	0.0090	<DL	0.0	0.345	0.0103	<DL	<DL	<DL	0.012	<DL
Ni	(mg/L)	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL
Sb	(mg/L)	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL

<DL: under detection limit; A-L: Different dyeing recipes analyzed in the sampling period

[1]Dyeing wastewater characterization study was a team-work and carried out as a part of the project "Adaptation of IPPC Directive to a Textile Mill in Turkey'-105Y088" financially supported by TÜBİTAK.

Table 5.2. Percentage of total denim production with respect to dyeing recipes

Analyzed recipes during sampling period	Produced meter denim fabricX1000	% of total production
A	1142	17.8
I	224	3.5
D	503	7.8
L	44	0.7
H	235	3.7
K	77	1.2
G	278	4.3
E	409	6.4
F	286	4.4
B	957	14.9
C	949	14.8
J	147	2.3
Total (12 recipes)	**5251**	**81.7**
Total (all recipes applied in sampling period)	**6427**	

5.2. Representative effluents

The rinsing wastewaters of Recipe 1, Recipe 2, and Recipe 3 were taken from the main dyeing rinsing stream where the wastewaters resulting from both pre-rinsing and post rinsing tanks are mixed.

Dyeing wastewaters considered in the study will be shortly called as follows from now on:

R1: Rinsing Wastewater of Recipe 1
R2: Rinsing Wastewater of Recipe 2
R3: Rinsing Wastewater of Recipe 3
Mixture: A mixture of the R1 and R2 and R3 at a 1:1:1 volumetric ratio

Table 5.3. shows the characteristics of the effluents of R1, R2, R3 and the Mixture. The values are given with a range since characteristics of the same dyeing recipe may differ due to the operating conditions such as the flowrate of the rinsing water applied in the pre- and post-rinsing tanks, change in the concentration and type of the dyestuff and auxiliary chemicals used in the dyeing process, production capacity, etc. Besides these, water consumption minimization measures were taken in the plant during the study by the plant staff. Therefore the variation in wastewater characterization of the same dyeing recipe was an expected situation. It appeared that wastewaters have very high color and COD values reaching up to 9540 Pt-Co and 1787 mg/L, respectively. They are highly alkaline and include high amounts of dissolved solids owing to the dyes and chemicals used in the dyeing process.

Table 5.3. General characteristics of the effluents used in the study

Parameters	**R1**	**R2**	**R3**	**Mixture**
pH	9.4-10.4	10.0-12.0	9.2-10.2	9.4-11.3
Conductivity, mS/cm	6.8-4.0	8.0-10.1	5.5-3.2	6.6-5.9
TSS, mg/L	254-260	342-348	92-100	218-230
Alkalinity, mg/L $CaCO_3$	964-1100-	1274-1450	706-792	876-1080
COD, mg/L	1096-841	1571-1787	1178-348	1263-929
Color, Pt-Co	6460-5593	10660-8600	5070-1255	6850-5120

During wastewater characterization, the measured parameters were COD, color, conductivity and pH since these are the parameters included in the reuse criteria. In addition, alkalinity was measured in order to check the alkalinity requirement for the coagulation pretreatment tests. Besides these parameters, for a better assessment of the filtration results, particle size distribution (PSD) analysis was done for R1, R2, and R3 (Appendix B).

Wastewater characterization for all recipes was conducted not only at the beginning of the study but also prior to each experiment. Considering the highly variable nature of the wastewaters; all R1, R2 and R3 samples obtained and utilized during the course of the study, were characterized in terms of COD, color, conductivity and pH.

5.3. Study Approach

The study composed of two stages; at the first stage, pretreatment alternatives were evaluated for the indigo dyeing rinsing wastewaters to identify the optimum pretreatment process and the relevant operational conditions. At the second stage, nanofiltration was applied to the pretreated wastewater to be able to obtain reusable water.

While assessing the feasibility of selected pretreatment alternatives, the rinsing wastewaters of R1, R2 and R3 and the Mixture were considered, separately. All pretreatment experiments were repeated for all these wastewaters with the intention of determining the possible effects of the variation in wastewater composition on the performance of the processes. The target in this approach was also to determine the optimum operational conditions for alternative pretreatment processes for all the wastewaters separately and then to determine whether it is necessary or not to vary operational conditions in running pretreatment processes for different recipes.

After deciding on the pretreatment alternatives (MF/MF+UF), NF tests were conducted with the Mixture. The reason why pretreatment tests were conducted with all wastewaters separately and NF tests only with the Mixture is critical and requires explanation. At the start of the experimental studies, it was thought that in case of more intense application of any of the three major recipes in dyeing process, both pretreatment and final treatment processes would be applied as required by that recipe and therefore pretreatment tests were run with all three recipes. However, the findings from this stage has indicated that the treatability of wastewater from different dyeing recipes is not so different therefore NF tests were run with the Mixture. Moreover, majority of the dyeing rinsing wastewater will be handled at the same time if mixture wastewater is decided to study rather than recipes separately and this is more logical and practical for the wastewater management aspect.

5.4. Analytical Methods

COD measurements were done by means of HACH Method No. 8000 certified by USEPA using HACH DR-2000 model spectrophotometer at a wavelength of 620 nm for high range measurements (up to 1500 mg/L) and at a wavelength of 420 nm for low range measurements (up to 150 mg/L). Color was measured by the same method (HACH Method No.8000) at a wavelength of 455 nm. Conductivity and pH determinations were done by means of a HACH Sension 378. Alkalinity measurements were done according to the Standard Methods [53]. In order to have a better understanding about the filtration performances PSD analysis (Appendix-B) were done for all samples (R1, R2, R3) by means of laser diffraction method using Mastersizer 2000 device in the TUBITAK Marmara Research Center Laboratories.

5.5. Experimental Procedure

5.5.1. Experiments conducted on R1, R2, R3, and the Mixture

Within the scope of the study; firstly coagulation and MF tests were conducted with the wastewaters R1, R2, and R3 and the Mixture. Secondly, MF and UF were applied sequentially only to the Mixture, which is the representative of all most common recipes considered in the study. Thirdly, NF tests were run after single stage MF application and also after sequential MF+UF application for the Mixture (Table 5.4).

Table 5.4. Treatment methods applied to indigo dyeing rinsing wastewaters

	Treatment methods	**Applied Wastewater**
Pretreatment methods	Coagulation (Aluminum Sulfate, Ferric Chloride)	R1, R2, R3, The Mixture
	MF (0.45,2.5,8 μm)	R1, R2, R3, The Mixture
	MF (0.45 μm)+UF (5,10,50,100 kDa)	The Mixture
Pretreatment+NF	MF (0.45 μm)+UF (100 kDa) +NF (NF270)	The Mixture
	MF (0.45 μm)+NF (NF270)	The Mixture

5.5.2. Coagulation Experiments

Coagulation process was investigated by running a series of jar tests via Aqua Lytic Jar Test apparatus using the coagulants, aluminum sulfate and ferric chloride. Stock solutions of these coagulants at a concentration of 10 g/L were prepared and added into the jars as needed. The experiments were carried out at room temperature (20±2^{o}C) using 500 mL wastewater samples by applying 11 different coagulant concentrations ranging from 50 mg/L to 1000 mg/L.

During jar testing, following coagulant addition, 2 min rapid mixing at 120 rpm, 30 min slow mixing at 30 rpm and 1 h settling were applied. After settling, supernatant samples were taken for the analyses of residual color and COD (COD was analyzed for only the coagulant dose at which maximum color removal was achieved). The experimental conditions applied during coagulation tests are tabulated in Table 5.5.

Table 5.5. Experimental conditions for coagulation

Experiment phases	Duration, min	Mixing speed, rpm
Rapid mixing	2	120
Slow mixing	30	30
Settlement	60	-

Bearing in mind very high and continuous dyeing wastewater generation (1485-1925 m^3/d) in the mill, all treatability tests were held at the original pH of the wastewaters given in Table 5.3 taking into consideration chemical cost related issues. All coagulation experiments were conducted in duplicates in order to obtain more reliable and reproducible results. The numerical values presented in this thesis, are the arithmetic averages of the measurements resulting from these duplicate experiments.

5.5.3. Microfiltration/Ultrafiltration Experiments

All MF and UF experiments were performed as dead-end experiments at batch mode 0.45, and 8 μm pore sized mixed cellulose ester (MCE) Millipore filter papers, and 2.5 μm pore sized Whatman filter paper at two different pressures (0.7 bar and 3 bar) in order to determine the optimum pore size and the conditions for the filtration.

Low-pressure (0.7 bar) microfiltration tests were carried out for all recipes (R1, R2, and R3) by using 0.45, 2.5, and 8 μm pore sized filter papers via Buchner funnel (BF) filtration test apparatus given in Figure 5.1. The wastewater samples were poured into BF into which filter papers were placed. By means of vacuum applied, the filtrate was collected in a graduated cylinder that was placed on top of a calibrated balance. The mass of the filtrate collected was recorded as a function of filtration time by a computer. Filtrate flux values were evaluated by converting filtrate mass data to filtrate volume data taking the density of the dyeing rinsing wastewater as 1000 kg/m^3.

High-pressure (3 bar) MF tests were conducted only for the Mixture by Amicon Series 8000 Stirred Cells (400 mL) filtration apparatus shown in Figure 5.2. By this device, also stirring the fluid during filtration can be achieved. However, the stirring option was not used to be able to compare the low and high-pressure filtration tests under the same conditions differing in just applicable pressures. The device allows to apply high-pressure values. Filtered wastewater via MF was then filtered by polyethersulphone (PES) UF membranes (100, 50, 10, 5 kDa) in dead-end mode filtration at applicable maximum pressure of 4 bar by the same filtration apparatus. For each UF membrane, 400 mL wastewater was filtered. The effects of sequential application of MF and UF and different pressures on COD and color rejections and permeate fluxes were examined.

Each MF and UF test was repeated several times until reliable filtrate volume vs. time data is gathered. The flux data presented for any test in the present study is therefore the average of these multiple measurements. All raw data (volume vs. time) belonging to the MF and UF experiments for the mixture were given in Appendix D.

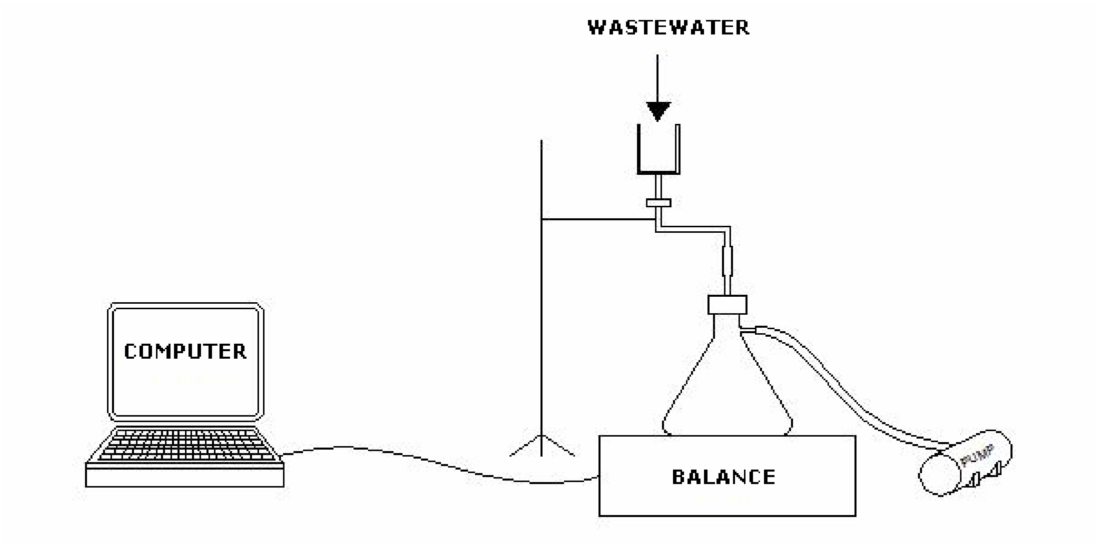


Figure 5.1. BF filtration test apparatus

Figure 5.2. Microfiltration and Ultrafiltration Test Apparatus

5.5.4. Nanofiltration Experiments

NF experiments were carried out by using a flat sheet polyamide thin film composite NF-270 membrane, supplied by Filmtec Membranes-DOW Chemical Company, and DSS Labstak M 20 membrane module (Figure 5.3) with an effective filtration area of 0.036 m^2. Operating conditions were 5.02 bar TMP and 0.62 m/s cross-flow velocity. During the filtration period, sampling was done for permeate and feed streams at 15 minutes intervals. The experiments were carried out until the stable permeate flux values were obtained. Membrane unit was operated in a total-recycle mode meaning all retentate and permeate streams ending in the feed tank. Two sets of experiments were conducted which differed in terms of pretreatment applications. Same pairs of NF membranes were used in both sets. The sets are;

- Set1: NF application to the pretreated wastewater by means of sequential application of MF and UF,
- Set2: NF application to the pretreated wastewater via only MF.

Before and after the filtration process, clean water flux was determined in order to evaluate permeate flux relative to clean water flux and also to find out the flux decline of the membrane after wastewater filtration, which is an indicator of membrane fouling. In case of high flux decline after filtration, acid (HNO_3-pH3) and base (NaOH-pH9) cleaning in a total recycle mode were applied for 30 min to increase flux recovery of the membrane.

Figure 5.3. DSS Labstak M20 membrane module

CHAPTER 6

RESULTS AND DISCUSSIONS

This chapter was divided into two main sections composing of the results of the;

(i) Pretreatment; coagulation and MF/UF,

(ii) NF

applied to the indigo dyeing rinsing wastewater.

6.1. Pretreatment Tests

In the proceeding sections, results of the coagulation (Section 6.1.1.) and filtration (MF, MF+UF) (Section 6.1.2.) tests applied to R1, R2, R3, and the Mixture are given and a comparison of all tests' results are provided towards the selection of the best pretreatment method.

6.1.1. Evaluation of Coagulation as Pretreatment Method

The first part of the experimental series was conducted to assess the feasibility of coagulation in the removal of color and COD from indigo dyeing wastewaters. The determination of optimum dose for aluminum sulfate and ferric chloride was achieved at this stage. In the following sections, the results of the coagulation experiments with both of the coagulants are presented and discussed separately for each indigo dyeing rinsing wastewater. Bearing in mind very high and continuous dyeing wastewater generation (1485-1925 m^3/d) in the mill, all coagulation tests were held at the original pH of the wastewaters given in Table 5.3 taking into consideration chemical cost related issues. However in order to observe the effect of the pH, the pH of the Mixture was adjusted to 7.1 and coagulation was conducted via 500 mg/L aluminum sulfate and ferric chloride additions and the results presented in Section 6.1.1.4 were obtained.

6.1.1.1. Recipe-1

Characterization of the sample of R1 used during coagulation studies is given in Table 6.1. The values are within the range of the characteristics belonging to R1 given in Table 5.3, which presents the general characteristics of the wastewater.

Table 6.1. Characteristics of R1

Parameters	Values
pH	10.4
Conductivity, mS/cm	4.0
Alkalinity, mg/L as $CaCO_3$	1032
COD, mg/L	841
Color, Pt-Co	5593

Part 1: Tests with $Al_2(SO_4)_3.18H_20$

Two parallel sets of coagulation experiments (Set1 and Set2) were conducted for R1 with aluminum sulfate keeping the pH at the original pH of the wastewater. The experimental results presented in Table 6.2 were obtained. As presented, general trend is that as the applied coagulant concentration increases, an increase in the color removal values is seen and the highest color removal is achieved at the maximum coagulant dose applied (1000 mg/L).COD measurement was done for the this coagulant dose since it is thought that the majority of the COD exerting materials in the wastewater originated from the color exerting dyestuff and therefore, the maximum COD removal should be achieved for this coagulant. As can be seen from Table 6.2, COD at a coagulant dose of 1000 mg/L, the residual COD was measured as 370-429 mg/L corresponding to 56%-49% removal efficiency. The concomitant residual color was 2225-2890 Pt-Co corresponding to 60.2-48.3 % color removal. As can be seen from Table 6.2, there was significant improvement in color removal efficiency as the coagulant dose increases from 50 to 1000 mg/L. However, the removals (both COD and color) achieved up to a dose of 900 mg/L were not significant; they were well below even 50 %. Meanwhile, the conductivity of the treated wastewater ranged from 3.6 mS/cm to 3.9 mS/cm indicating very poor removal of dissolved species resulting from the dyes and chemicals used in the process from the R1 wastewater having an original conductivity of 4.0 mS/cm.

Table 6.2. Optimum coagulant ($Al_2(SO_4)_3.18H_20$) dosage determination results for R1

$Al_2(SO_4)_3.18H_20$ addition, mg/L	pH	Conductivity, mS/cm	Color, Pt-Co	%Color Removal
	Set1-Set2	Set1-Set2	Set1-Set2	Set1-Set2
Original wastewater(Blank)*	10.3-10.2	3.9-4.0	5070-5390	9.4-3.6
50	9.7-10.2	3.9-4.0	4900-5438	12.4-2.8
100	9.7-10.1	3.9-4.0	4850-5285	13.3-5.5
200	9.6-9.9	3.9-4.0	4950-5123	11.5-8.4
300	9.3-9.7	3.8-3.9	5060-5390	9.5-3.6
400	9.1-9.6	3.7-3.9	4870-5255	12.9-6.0
500	8.9-9.4	3.7-3.8	4830-4795	13.6-14.3
600	8.5-9.2	3.6-3.8	4470-4590	20.1-17.9
700	8.1-9.0	3.6-3.8	4270-4390	23.7-21.5
800	7.7-8.5	3.6-3.7	3865-4010	30.9-28.3
900	7.5-8.0	3.6-3.7	2870-3720	48.7-33.5
1000	7.3-7.6	3.6-3.7	2225-2890	60.2-48.3
	COD, mg/L		**% COD Removal**	
1000	370-429		56-49	

* No $Al_2(SO_4)_3.18H_20$ addition

Part 2: Tests with $FeCl_3.6H_2O$

Two parallel sets of coagulation experiments (Set1 and Set2) were conducted for R2 with ferric chloride at the original pH of the wastewater as in the case of aluminum sulfate application. The experimental results presented in Table 6.3 were obtained. Regarding the relation between the coagulant dose and the color removals, similar trend as occurred in aluminum sulfate, which was the increase in applied coagulant concentration resulting in increase in the color removals, was seen and the 1000 mg/L coagulant dose was the dose at which the highest color removal was achieved. The residual color was 2190-1960 Pt-Co corresponding to 60.8-65 % color removal. Table 6.3 shows that, COD at a coagulant dose of 1000 mg/L, the residual COD was measured as 362-328 mg/L corresponding to 57%-61% removal efficiency. This finding is similar to the results of the aluminum sulfate case. As can be seen from Table 6.3, there was significant improvement in color removal efficiency as the coagulant dose increases from 50 to 1000 mg/L. However, the removals (both COD and color) achieved up to a dose of 800 mg/L were not significant; they were below even 50% like the results of aluminum sulfate application. Removal of dissolved solids was very poor since the conductivity of the treated wastewater ranging from 3.7 mS/cm to 3.9 mS/cm differed from the original conductivity of 4.0 mS/cm slightly.

Table 6.3. Optimum coagulant ($FeCl_3.6H_20$) dosage determination results for R1

$FeCl_3.6H_20$ addition, mg/L	**pH**	**Conductivity, mS/cm**	**Color, Pt-Co**	**%Color Removal**
	Set1-Set2	Set1-Set2	Set1-Set2	Set1-Set2
Original wastewater(Blank)*	10.3-10.2	3.9-4.0	5070-5390	9.4-3.6
50	10.2-10.2	3.9-4.0	5290-5330	5.4-4.7
100	10.2-10.1	3.9-4.0	5010-5290	10.4-5.4
200	10.0-9.8	3.8-4.0	5190-5170	7.2-7.6
300	9.8-9.7	3.8-3.9	5100-5110	8.8-8.6
400	9.6-9.3	3.8-3.9	5190-5290	7.2-5.4
500	9.3-9.1	3.8-3.9	4790-5000	14.4-10.6
600	8.9-9.0	3.7-3.8	4020-4050	28.1-27.6
700	8.2-8.4	3.8-3.8	3120-2980	44.2-46.7
800	7.7-7.5	3.7-3.7	2750-2640	50.8-52.8
900	7.4-7.3	3.8-3.7	2370-2220	57.6-60.3
1000	7.1-7.2	3.7-3.7	2190-1960	60.8-65.0
	COD,mg/L		**% COD Removal**	
1000	362-328		57-61	

* No $FeCl_3.6H_20$ addition

6.1.1.2. Recipe-2

Characterization of the sample of R2 used during coagulation studies is given in Table 6.4. The values are within the range of the characteristics belonging to R2 given in Table 6.4, which presents the general characteristics of the wastewater.

Table 6.4. Characteristics of R2

Parameters	Values
pH	12.0
Conductivity, mS/cm	10.1
Alkalinity, mg/L as $CaCO_3$	1450
COD, mg/L	1787
Color, Pt-Co	10660

Part 1: Tests with $Al_2(SO_4)_3.18H_20$

Two parallel sets of coagulation experiments (Set1 and Set2) were conducted for R2 with aluminum sulfate at the original pH of the wastewater. The experimental results presented in Table 6.5 were obtained. As presented, general trend is that as the applied coagulant concentration increases, an increase in the color removal values was seen and the highest color removal was achieved at the maximum coagulant dose applied (1000 mg/L). However there was not a significant improvement in color removal efficiency as the coagulant dose increases from 50 to 1000 mg/L. They were well below even 20%. The residual color was 8820-8520 Pt Co corresponding to 17.3-20.1 % color removal. COD measurement was done for 1000 mg/L coagulant dose at which maximum color removal was achieved. As can be seen from Table 6.5, COD at a coagulant dose of 1000 mg/L, the residual COD was measured as 1465-1447 mg/L corresponding to 18%-19% removal efficiency. Meanwhile, the conductivity of the treated wastewater ranged from 8.0 mS/cm to 9.7 mS/cm. As compared to the original conductivity of 10.1 mS/cm very poor removal of dissolved solids was provided via coagulation.

Table 6.5. Optimum coagulant ($Al_2(SO_4)_3.18H_20$) dosage determination results for R2

$Al_2(SO_4)_3.18H_20$ addition, mg/L	pH	Conductivity, mS/cm	Color, Pt-Co	%Color Removal
	Set1-Set2	Set1-Set2	Set1-Set2	Set1-Set2
Original wastewater(Blank)*	11.7-11.7	10.0-10.0	9740-9770	8.6-8.3
50	11.7-11.7	9.7-9.7	9540-9680	10.5-9.2
100	11.7-11.7	9.7-9.7	9400-9640	11.8-9.6
200	11.6-11.6	9.5-9.4	9400-9700	11.8-9.0
300	11.6-11.6	9.2-9.3	9460-9220	11.3-13.5
400	11.5-11.5	9.1-9.0	9680-9740	9.2-8.6
500	11.5-11.46	8.8-8.7	9320-9280	12.6-13.0
600	11.4-11.4	8.8-8.5	9180-9000	13.9-15.6
700	11.3-11.2	8.4-8.4	9260-8940	13.1-16.1
800	11.2-11.2	8.3-8.3	9500-8900	10.9-16.5
900	11.0-11.0	8.1-8.2	8860-8700	16.9-18.4
1000	10.9-10.8	8.0-8.0	8820-8520	17.3-20.1

	COD,mg/L	% COD Removal
1000	1465-1447	18-19

* No $Al_2(SO_4)_3.18H_20$ addition

Part 2: Tests with $FeCl_3.6H_2O$

Two parallel sets of coagulation experiments (Set1 and Set2) were conducted for R2 with ferric chloride keeping the pH at the original pH of the wastewater. The experimental results presented in Table 6.6 were obtained. As presented, an increase in the color removal values was seen as the applied coagulant concentration increases, and the highest color removal was achieved at the maximum coagulant dose applied (1000 mg/L). Comparing to the aluminum sulfate application ferric chloride is more effective on R2 in terms of color and COD removals. The maximum COD removal was 31%-33% corresponding to 1233-1197 Pt-Co at a 1000 mg/L coagulant dose. The residual color was 4700-4680 Pt-Co corresponding to 55.9 - 56.1 % color removal. As can be seen from

Table 6.6, there was significant improvement in color removal efficiency as the coagulant dose increases from 50 to 1000 mg/L. However, the removals (both COD and color) achieved up to a dose of 900 mg/L were not significant; they were well below even 50%. Meanwhile, the conductivity of the treated wastewater ranged from 8.3 mS/cm to 9.7 mS/cm.

Table 6.6. Optimum coagulant ($FeCl_3.6H_20$) dosage determination results for R2

$FeCl_3.6H_20$ addition, mg/L	**pH**	**Conductivity, mS/cm**	**Color, Pt-Co**	**%Color Removal**
	Set1-Set2	Set1-Set2	Set1-Set2	Set1-Set2
Original wastewater(Blank)*	11.7-11.7	10.0-10.0	9740-9770	8.6-8.3
50	11.8-11.8	9.8-9.7	9760-9560	8.4-10.3
100	11.8-11.7	9.6-9.6	9700-9960	9.0-6.6
200	11.8-11.6	9.4-9.4	9660-9800	9.4-8.1
300	11.4-11.6	9.3-9.3	10140-10160	4.9-4.7
400	11.6-11.5	9.0-9.0	10320-10000	3.3-6.2
500	11.5-11.5	8.9-8.8	10340-9800	3.0-8.1
600	11.4-11.4	8.7-8.6	8240-7320	22.7-31.3
700	11.3-11.3	8.5-8.5	6980-6400	34.5—40.0
800	11.2-11.2	8.3-8.3	5920-5680	44.5-46.7
900	11.0-11.1	8.3-8.3	5420-5400	49.2-49.3
1000	10.9-10.9	8.3-8.3	4700-4680	55.9-56.1
	COD,mg/L		**% COD Removal**	
1000	1233-1197		31-33	

* No $FeCl_3.6H_20$ addition

6.1.1.3. Recipe-3

Characterization of the sample of R3 used during coagulation studies is given in Table 6.7. The values are within the range of the characteristics belonging to R3 given in Table 5.3, which presents the general characteristics of the wastewater.

Table 6.7. Characteristics of R3

Parameters	Values
pH	10.2
Conductivity, mS/cm	3.2
Alkalinity, mg/L as $CaCO_3$	792
COD, mg/L	348
Color, Pt-Co	1255

Part 1: Tests with $Al_2(SO_4)_3.18H_20$

Two parallel sets of coagulation experiments (Set1 and Set2) were conducted for R3 with aluminum sulfate at the original pH of the wastewater. The experimental results presented in Table 6.8 were obtained. As presented, an increase in the color removal values was seen as the applied coagulant concentration increases, and the highest color removal was achieved at the maximum coagulant dose applied (1000 mg/L). Comparing to the R1 and R2 aluminum sulfate application is much more effective on R3 in terms of color removals and also the original color and COD values are much more lower than the other two recipes. The maximum color removal was 94.9%-96.6% corresponding to 64-43 Pt-Co at a 1000 mg/L coagulant dose. The residual COD was 202-198 mg/L corresponding to 42-43 % color removal. As can be seen from Table 6.8, there was significant improvement in color removal efficiency as the coagulant dose increases from 50 to 1000 mg/L. Even at low coagulant doses almost 50% color removal was achieved. Besides the blank, which is subject to same operational conditions of the coagulation (rapid-slow mixing and the settling) without addition of the coagulant also, showed almost 45% color removal. This means just mixing and letting the sample settle is enough to remove color up to 45% for R3. The conductivity of the treated wastewater ranged from 3.0 mS/cm to 3.2 mS/cm and did not differ so much as compared to the conductivity (3.2 mS/cm) of the original wastewater.

Table 6.8. Optimum coagulant ($Al_2(SO_4)_3.18H_20$) dosage determination results for R3

$Al_2(SO_4)_3.18H_20$ addition, mg/L	**pH**	**Conductivity, mS/cm**	**Color, Pt-Co**	**%Color Removal**
	Set1-Set2	Set1-Set2	Set1-Set2	Set1-Set2
Original wastewater(Blank)*	10.1-10.1	3.2-3.2	709-700	43.5-44.2
50	10.0-10.0	3.2-3.2	642-698	48.8-52.4
100	9.9-9.8	3.1-3.1	626-632	50.1-49.6
200	9.5-9.5	3.1-3.1	616-620	50.9-50.6
300	9.1-9.2	3.1-3.1	564-578	55.1-53.9
400	8.6-8.5	3.1-3.1	718-678	42.8-46.0
500	8.2-8.2	3.1-3.1	717-594	42.9-52.7
600	8.0-8.0	3.1-3.1	347-255	72.4-79.7
700	7.7-7.6	3.1-3.1	143-100	88.6-92.0
800	7.4-7.5	3.1-3.1	57-60	95.5-95.2
900	7.3-7.3	3.0-3.1	53-47	95.8-96.3
1000	7.1-7.2	3.0-3.0	64-43	94.9-96.6
	COD,mg/L		**% COD Removal**	
1000	202-198		42-43	

* No $Al_2(SO_4)_3.18H_20$ addition

Part 2: Tests with $FeCl_3.6H_2O$

Two parallel sets of coagulation experiments (Set1 and Set2) were conducted for R3 with ferric chloride at the original pH of the wastewater as in the case of aluminum sulfate application. The experimental results presented in Table 6.9 were obtained. Regarding the relation between the coagulant dose and the color removals, similar trend as occurred in aluminum sulfate, which was the increase in applied coagulant concentration resulting in increase in the color removals, was seen and the 500 mg/L coagulant dose was the dose at which the highest color removal was achieved. The color removal efficiency was similar and around 70% at doses higher than 300 mg/L. The residual color was 271-254 Pt-Co corresponding to 78.4-79.8 % color removal. Like the results of the aluminum sulfate application blank sample showed almost 45% color removal. As presented, COD at a coagulant dose of 500 mg/L, the residual COD was measured as 205-198 mg/L corresponding to 41%-43% removal efficiency, which is similar to the aluminum sulfate case. As can be seen from Table 6.9, there was significant improvement in color removal efficiency as the coagulant dose increases from 50 to 1000 mg/L. The conductivity of the treated wastewater ranged from 3.1 mS/cm to 3.2 mS/cm and did not differ so much as compared to the conductivity (3.2 mS/cm) of the original wastewater.

Table 6.9. Optimum coagulant ($FeCl_3.6H_20$) dosage determination results for R3

$FeCl_3.6H_20$ addition, mg/L	**pH**	**Conductivity, mS/cm**	**Color, Pt-Co**	**%Color Removal**
	Set1-Set2	Set1-Set2	Set1-Set2	Set1-Set2
Original wastewater(Blank)*	10.1-10.1	3.2-3.2	709-700	43.5-44.2
50	9.9-10.0	3.2-3.2	535-528	57.4-58.0
100	9.8-9.8	3.2-3.2	485-467	61.4-62.8
200	9.5-9.6	3.1-3.2	414-399	67.0-68.2
300	9.1-9.0	3.1-3.1	373-342	70.3-72.8
400	8.2-8.1	3.2-3.1	355-317	71.7-74.7
500	7.8-7.6	3.1-3.2	271-254	78.4-79.8
600	7.6-7.5	3.2-3.2	254-280	79.8-77.7
700	7.4-7.2	3.2-3.2	280-286	77.7-77.0
800	7.2-7.1	3.2-3.2	343-338	72.7-73.1
900	7.0-6.9	3.2-3.2	354-305	71.8-75.7
1000	6.8-6.9	3.2-3.1	316-363	74.8-71.1
	COD,mg/L		**% COD Removal**	
500	205-198		41-43	

* No $FeCl_3.6H_20$ addition

6.1.1.4. The Mixture

Characterization of the sample of mixture of the three recipes used during coagulation studies are given in Table 6.10. The values are within the range of the characteristics belonging to mixture given in Table 5.3. As it is expected, the values of the parameters analyzed were close to the arithmetic average of the ones of the three samples namely R1, R2, and R3 since the Mixture composed of mixture of the three recipes in equal volumes in laboratory conditions.

Table 6.10 Characteristics of the Mixture

Parameters	Values
pH	11.3
Conductivity, mS/cm	5.9
Alkalinity, mg/L CaCO3	1080
COD, mg/L	929
Color, Pt-Co	5120

Part 1: Tests with $Al_2(SO_4)_3.18H_20$

Two parallel sets of coagulation experiments (Set1 and Set2) were conducted for the Mixture with aluminum sulfate at the original pH of the wastewater and at pH 7.1 for the dose of 500 mg/L. The experimental results presented in Table 6.11 were obtained. As presented, an increase in the color removal values was seen as the applied coagulant concentration increases, and the highest color removal was achieved at the maximum coagulant dose applied (1000 mg/L). There was a significant improvement in color removal efficiency as the coagulant dose increases from 50 to 1000 mg/L. However, the removals (both COD and color) achieved up to a dose of 1000 mg/L were not significant; they were well below even 50%. The residual color was 2790-2880 Pt Co corresponding to 45.5-43.8 % color removal. COD measurement was done for 1000 mg/L coagulant dose at which maximum color removal was achieved. As can be seen from Table 6.11, COD at a coagulant dose of 1000 mg/L, the residual COD was measured as 520-539 mg/L corresponding to 44%-42% removal efficiency. Meanwhile, the conductivity of the treated wastewater ranged from 4.9 mS/cm to 5.3 mS/cm. As compared to the original conductivity of 5.9 mS/cm poor removal of dissolved solids was provided via coagulation. Decreasing the pH to 7.1 at a dose of 500 mg/L coagulant did not provide a considerable change in removals.

Table 6.11. Optimum coagulant ($Al_2(SO_4)_3 18H_2 0$) dosage determination results for the Mixture

$Al_2(SO_4)_3.18H_20$ addition, mg/L	pH	Conductivity, mS/cm	Color, Pt-Co	%Color Removal
	Set1-Set2	Set1-Set2	Set1-Set2	Set1-Set2
Original wastewater(Blank)*	10.3-10.2	5.3-5.3	3980-3950	22.3-22.9
50	10.1-10.2	5.3-5.3	3870-3770	24.4-26.4
100	10.2-10.1	5.3-5.3	3800-3730	25.8-27.2
200	10.0-10.1	5.2-5.2	3710-3720	27.5-27.3
300	9.9-10.0	5.2-5.2	3630-3640	29.1-28.9
400	9.8-9.7	5.1-5.1	3530-3550	31.1-30.7
500**	9.6-9.5	5.0-5.0	3420-3440	33.2-32.8
500***	7.01-7.06	4.9-5.0	3760-3680	26.6-28.1
600	9.5-9.4	5.0-5.0	3310-3260	35.4-36.3
700	9.4-9.3	5.0-4.9	3270-3130	36.1-38.9
800	9.2-9.2	4.9-4.9	3190-3170	37.7-38.1
900	9.0-9.1	4.9-4.9	2800-2960	45.3-42.2
1000	8.8-8.8	4.9-4.9	2790-2880	45.5-43.8
	COD,mg/L		**% COD Removal**	
1000	520-539		44-42	

* No $Al_2(SO_4)_3.18H_20$ addition

** Experiments were conducted at original pH of the Mixture

*** Experiments were conducted at pH=7.1

Part 2: Tests with $FeCl_3.6H_2O$

Two parallel sets of coagulation experiments (Set1 and Set2) were conducted for the Mixture with ferric chloride keeping the pH at the original pH of the wastewater and at pH 7.1 for the dose of 500 mg/L. The experimental results presented in Table 6.12 were obtained. As presented, color removal efficiency increases with the applied coagulant dose, and the highest color removal was achieved at the maximum coagulant dose applied (1000 mg/L). Both aluminum sulfate and ferric chloride provided similar color and COD removal efficiencies. The maximum COD removal was 50%-48% corresponding to 465-483 Pt-Co at a

1000 mg/L coagulant dose. The residual color was 2458-2540 Pt-Co corresponding to 52.0-50.4% color removal. As can be seen from Table 6.12, there was significant improvement in color removal efficiency as the coagulant dose increases from 50 to 1000 mg/L. However, the removals (both COD and color) achieved up to a dose of 900 mg/L were not significant; they were well below even 50%. Meanwhile, the conductivity of the treated wastewater ranged from 5.0 mS/cm to 5.3 mS/cm and did not differ so much as compared to the initial conductivity of the Mixture. As in the case of aluminum sulfate decreasing the pH to 7.1 at a dose of 500 mg/L coagulant did not provide a considerable change in removals.

Table 6.12. Optimum coagulant ($FeCl_3.6H_20$) dosage determination results for the Mixture

$FeCl_3.6H_20$ addition, mg/L	**pH**	**Conductivity, mS/cm**	**Color, Pt-Co**	**%Color Removal**
	Set1-Set2	Set1-Set2	Set1-Set2	Set1-Set2
Original wastewater(Blank)*	10.3-10.2	5.3-5.3	3980-3950	22.3-22.9
50	10.3-10.3	5.3-5.3	3830-3723	25.2-27.0
100	10.3-10.3	5.3-5.3	3922-3912	23.4-23.6
200	10.2-10.2	5.3-5.3	3937-4019	23.1-21.5
300	10.1-10.0	5.3-5.2	3809-3676	25.6-28.2
400	9.9-9.9	5.2-5.2	3466-3523	32.3-31.2
500**	9.7-9.7	5.2-5.2	3446-3267	32.7-36.2
500***	7.07-7.09	5.1-5.0	3700-3534	27.7-31.0
600	9.6-9.6	5.1-5.1	3523-3543	31.2-30.8
700	9.4-9.3	5.1-5.1	3036-3256	40.7-36.4
800	9.2-9.2	5.1-5.0	2575-2785	49.7-45.6
900	8.7-8.6	5.0-5.0	2642-2831	48.4-44.7
1000	8.4-8.5	5.0-5.0	2458-2540	52.0-50.4
	COD,mg/L		**% COD Removal**	
1000	465-483		50-48	

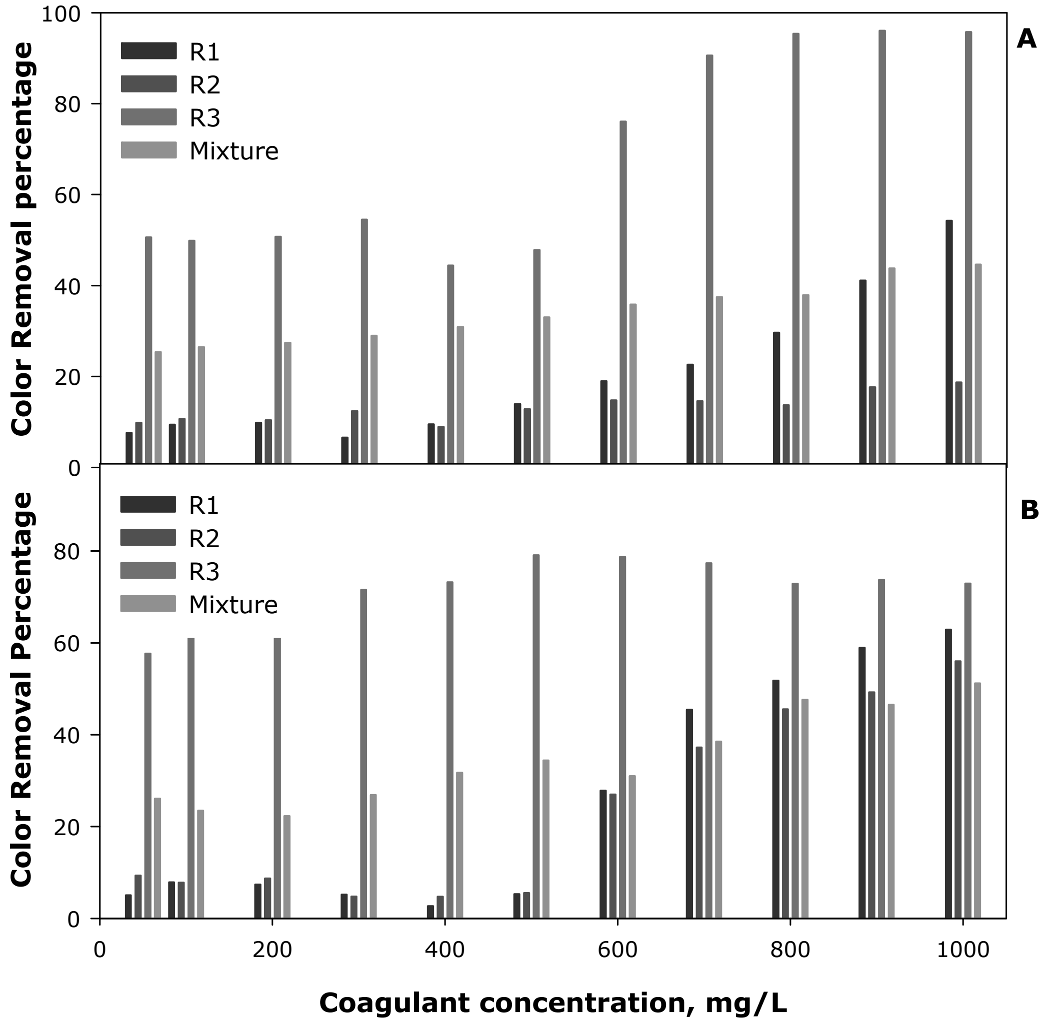
* No $FeCl_3.6H_20$ addition

** Experiments were conducted at original pH of the Mixture

*** Experiments were conducted at pH=7.1

6.1.2. Assessment of the Results from Coagulation Pretreatment Tests

Figure 6.1 was plotted by taking the average of the color values of the supernatants obtained in parallel sets at all doses for both coagulants and in all recipes. As can be depicted from Figure 6.1., for R1 and R2 effluents, color removals were comparable with both coagulants and there was an increase in color removal with an increase in coagulant concentration. Furthermore, percentage color removals obtained with aluminum sulfate and ferric chloride were similar and maximum at a coagulant dose of 1000 mg/L for both R1 and R2. Maximum color removals were observed via coagulation for R3 in both coagulant case. This may be explained by considering the dyestuff type applied and therefore the change of the auxiliary chemicals in the dye solution. This results in the different response of R3 to the coagulation. Unlike R1 and R2 cases in which both coagulants provided similar results, the color removal was much better with aluminum sulfate than with ferric chloride for R3 case. Aluminum sulfate was effective at a dose of 1000 mg/L with 97 % efficiency while ferric chloride provided 80 % color removal at a much lower dose of 500 mg/L for R3. When the Mixture was subjected to coagulation, it was found that the response to the coagulation in terms of color reduction was as expected considering its composition (mixture of R1, R2, and R3, 1:1:1 by volume).



A: Aluminum Sulfate, B: Ferric Chloride

Figure 6.1. Color removal by using aluminum sulfate and ferric chloride

Table 6.13 shows the highest COD removals achieved along with color removals by coagulation process. As shown, COD removals were in parallel with color removals for R1, R2 and the Mixture indicating that the color causing substances exert most of the COD in the wastewater. However, color removals were almost twice as COD removals for R3, possibly due to the presence of some chemicals specific to this dyeing recipe exerting COD but not color. Similar to R1, R2, and R3 coagulation provided similar COD and color removals in the treatment of the Mixture.

Table 6.13. COD and Color Removal Values (Values in parenthesis represent the coagulant dose as mg/L)

Recipes		Coagulants	
		Aluminum Sulfate	Ferric Chloride
R1	COD Removal (%)	49-56 (1000)	57-61 (1000)
	Color Removal (%)	48-60 (1000)	61-65 (1000)
R2	COD Removal (%)	18-19 (1000)	31-33 (1000)
	Color Removal (%)	17-20 (1000)	56-56 (1000)
R3	COD Removal (%)	42-43 (1000)	41-43 (500)
	Color Removal (%)	95-97 (1000)	78-80 (500)
Mixture	COD Removal (%)	42-44 (1000)	48-50 (1000)
	Color Removal (%)	44-46 (1000)	50-52 (1000)

All the findings from coagulation tests reveal that coagulation is not an effective and efficient pretreatment method for the denim textile dyeing wastewaters due to high dose of coagulant requirement. A recent study focused on indigo dyeing wastewater recovery revealed the same result for the coagulation as pretreatment [37]. As can be depicted from Table 6.13, for all the recipes and the Mixture, the coagulant requirements are very high with both aluminum sulfate and ferric chloride. As it is well known, high coagulant dose leads to high treatment costs and large volumes of chemical sludge to be handled. Very brief estimations for the denim textile mill considered indicates that if coagulation is adopted as the pretreatment process using aluminum sulfate as the coagulant, the relevant chemical cost should be about 12795 TL/month with about 9.8 tons/month sludge generation. The calculations are given in Appendix C. In parallel with this finding, in a past study it has been reported that the chemical coagulation treatment is not an economical solution for decolorization and detoxification of the cotton textile mill wastewater due to high coagulant requirements (aluminum sulfate and ferrous sulfate were tested as coagulants) [32].

6.1.3. Evaluation of Filtration as Pretreatment Method

In this part of the experimental studies, the applicability of membrane filtration as pretreatment was investigated to control flux decline in post NF or to reduce suspended solids load to NF that is the major cause of membrane fouling. Two different alternatives were considered; single MF and sequential application of MF and UF.

MF tests were carried out at two different pressures. At low pressure of 0.7 bar, MF was tested for the rinsing wastewaters of all the recipes studied. Based on the poor performance observed in these low pressure tests, a high pressure of 3 bar was selected and tested with the Mixture only.

Sequential application of MF and UF was then considered by using UF membranes (100, 50, 10, 5 kDa) in dead-end mode filtration at applicable maximum pressure of 4 bar by the same filtration apparatus as in single MF tests. For each UF membrane, 400 mL wastewater was filtered.

The effects of different pressures applied for single MF tests were evaluated in terms of color, COD rejections and the permeate fluxes. Besides the additional effects of sequential application of MF and UF on COD and color rejections and permeate fluxes were also examined.

6.1.3.1. Microfiltration Studies

In the proceeding sections, the results obtained at low and high pressure MF studies are given separately specific to the rinsing wastewaters of the recipes studied.

Part 1: Low Pressure MF

Recipe-1

In this series of tests, three different pore sized filter papers (0.45, 2.5 and 8 µm) were used and the time dependent flux data presented in Figure 6.2 were obtained. As the 0.45 µm filter paper was clogged immediately right after the start of the filtration run, it was not possible to monitor permeate flux from this filter. Therefore, Figure 6.2 only presents the data for 2.5 and 8 µm membranes. As one can immediately see, 2.5 and 8 µm membranes also clogged rapidly. This rapid clogging indicated high solids load of the dyeing wastewater, which has complex characteristics due to the presence of cotton fibers, unfixed dyes as well as other constituents of the dye bath solution. As one can depict from Figure 6.2, throughout the filtration process 8 μm membrane provided a higher permeate flux than 2.5 μm membrane. As expected, the flux from 8 μm membrane during the first few minutes was comparably higher than that from 2.5 μm membrane. However, with the progressive deposition of solids on the 8 μm membrane, a dynamic membrane formed and possibly, the pore size of the 8 μm membrane become approximately equal to that of 2.5 membrane. Consequently, at the end of the filtration test, the permeate flux from 8 μm membrane was almost identical to that of 2.5 μm membrane.

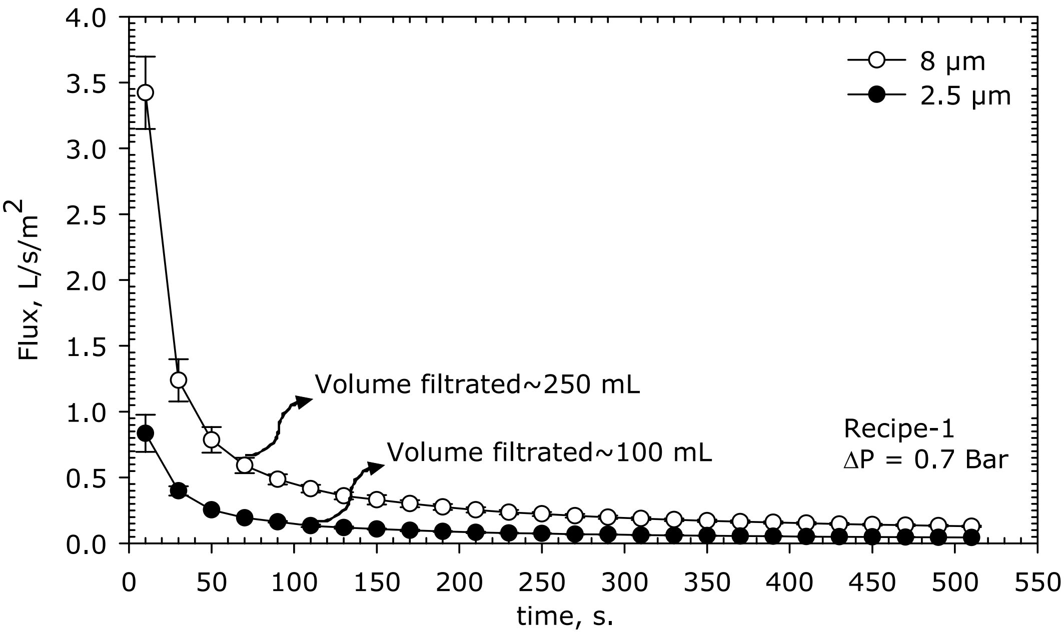


Figure 6.2. Flux values of MF membrane filters for R1

Considering that the filtrate quality observed at the end of a batch filtration test will correspond to the typical filtrate or permeate quality from a continuous flow filtration test with the same membrane, the characteristics of the filtrate at the end of the filtration test was analyzed, and the results given in Table 6.14 were obtained. As expected, there was no change in the conductivity and pH of the prefiltered wastewater as compared to the original wastewater. Microfiltration is not expected to reduce conductivity as it removes coarse suspended particles with diameters between 0.1 and 10 μm but not dissolved solids [46]. However, both 2.5 μm and 8 μm membranes were effective in the removal of color and COD. They provided similar color and COD reductions of approximately 50% and

30%, respectively; indicating the association of some part of color and COD in the wastewater with particulate matter removed by the tested membranes. Dyestuff that is not fixed to the fabric during dyeing process remains partly in the wastewater as coarse particles. MF removes these particles but not dissolved dyestuff in the wastewater.

An interesting finding from the comparison of the membranes is that COD removal by 8 μm membrane is slightly better than that by 2.5 μm membrane. This finding was speculated to originate from the pore size of the dynamic membrane formed on the surface of 8 μm membrane.

Table 6.14. Characteristics of the R1 pretreated via MF

Filter size	Conductivity, mS/cm	pH	COD, mg/L	%COD Removal	Color, Pt-Co	%Color Removal
Feed water	4.0	10.4	841		5593	
0.45 μ	-	-	-	-	-	-
2.5 μ	3.5	9.8	637	24	2710	52
8 μ	3.5	9.7	565	33	2633	53

Recipe-2

When MF membranes of 0.45 μm, 2.5 μm and 8 μm pore size were used for the filtration of R2, flux development presented in Figure 6.3 was obtained. As seen, all these filter media were clogged rapidly within almost 2 min. Throughout the whole filtration cycle, 8 μm membrane was superior to the other filter papers in terms of permeate flux. Both initial flux and also flux at later times during filtration cycle were higher with this membrane. On the other side, 2.5 μm membrane was the membrane that had the lowest flux values although it did not have the smallest pore size. The reason for that can be the structure and the composition of the membranes. The membranes of the pore sizes 0.45 and 8 μm were Millipore filter papers whereas 2.5 μm filter was the Whatman filter paper.

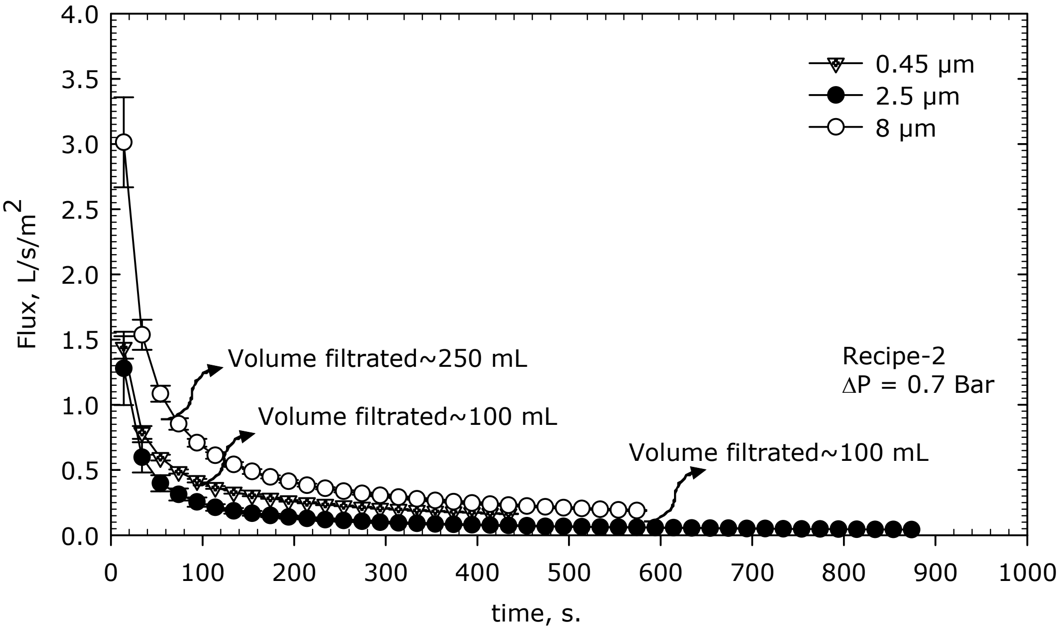


Figure 6.3. Flux values of MF membrane filters for R2

When the characteristics of the filtrate samples collected at the end of the filtration cycle were analyzed, the results given in Table 6.15 were obtained. As can be depicted, a high color removal efficiency of 76% was achieved with the finest micro filtration membrane (0.45 µm). The color removal efficiencies reached with 2.5 µm and 8 µm filters were also high; 71%. Much lower but comparable COD reductions of about 22 to 29 % were observed for all the membranes, indicating the presence of organic matter not causing color in this recipe too. Similar to the results for R1, conductivity and pH of the pretreated wastewater did not change so much comparing to the original wastewater.

Table 6.15. Characteristics of the R2 pretreated via MF

Filter size	Conductivity, mS/cm	pH	COD, mg/L	%COD Removal	Color, Pt-Co	%Color Removal
Feed water	10.1	12.0	1787		10660	
0.45 µm	9.3	11.7	1344	25	2540	76
2.5 µm	8.0	11.5	1271	29	3070	71
8 µm	9.4	11.7	1397	22	3110	71

Recipe-3

As if the filtration tests conducted on R1 and R2, MF membranes of 0.45 µm, 2.5 µm and 8 µm pore size were used for the filtration of R3 and time dependent flux developments presented in Figure 6.4 were obtained. As one can immediately see, all these filter media were clogged rapidly within almost 2 min. As can be seen from Figure 6.4, throughout the filtration process 8 and 0.45 µm membranes provided similar and higher permeate fluxes than 2.5 µm membrane. On the other side, 2.5 µm membrane was the membrane that had the lowest flux values. However, with the progressive deposition of solids on the membranes, a dynamic membrane formed and possibly, the pore sizes of all membranes become approximately equal. Therefore, at the end of the filtration test, all membranes provided similar fluxes. Dynamic membrane formation affected the fluxes provided via all membranes during the filtration cycle and all three membranes provided almost the same filtrate rate as they are all clogged at the end of the filtration cycle.

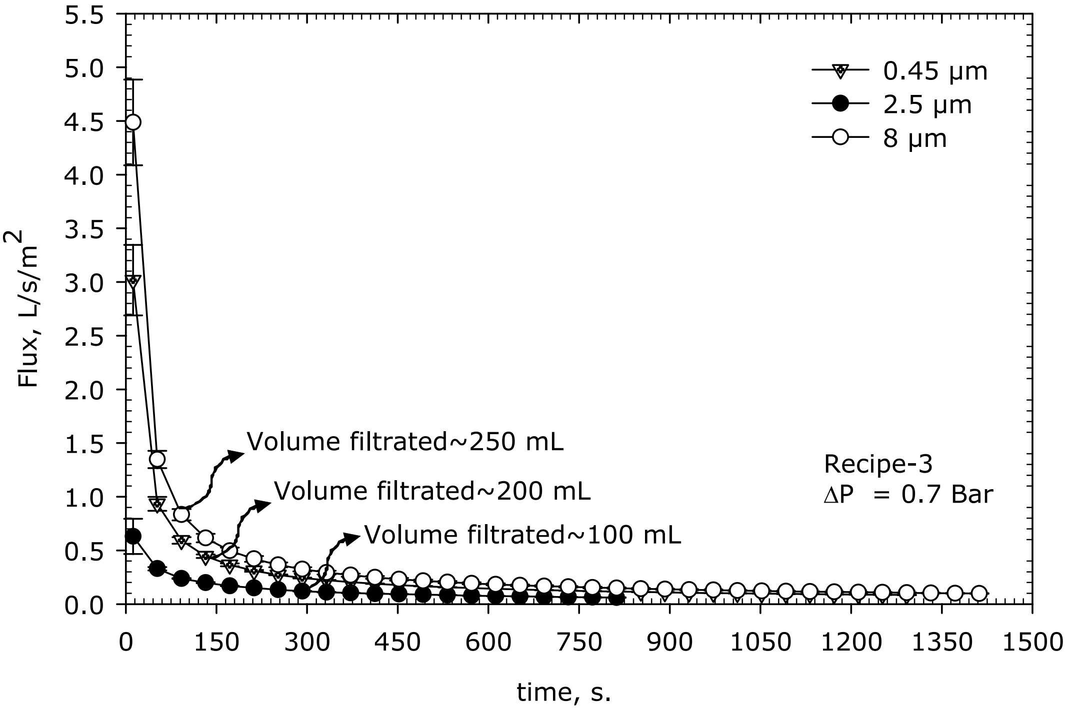


Figure 6.4. Flux values of MF membrane filters for R3

Characteristics of the filtrate at the end of the process were analyzed, and the results given in Table 6.16 were obtained. Similar to the results for R1 and R2, conductivity and pH of the pretreated wastewater did not change at all compared to the original wastewater's conductivity. As can be seen from Table 6.16, a high color removal efficiency of 74% was achieved with the finest micro filter (0.45 µm) similar to the results of R2. The color removal efficiencies reached with 2.5 µm and 8 µm filters were also high; up to 68% as is the case with R2. Yet, COD removals for this recipe by all the membranes were much higher than for R1. COD reductions of about 47 to 50 % were observed for this recipe.

Table 6.16. Characteristics of the R3 pretreated via MF

Filter size	Conductivity, mS/cm	pH	COD, mg/L	%COD Removal	Color, Pt-Co	%Color Removal
Feed water	3.2	10.2	348		1255	
0.45 µm	3.2	9.8	174	50	321	74
2.5 µm	3.0	9.7	184	47	419	67
8 µm	3.1	9.8	180	48	405	68

The Mixture

The Mixture wastewater was also subjected to MF with 0.45 µm, 2.5 µm and 8 µm filter papers and the time dependent flux variation presented in Figure 6.5 were obtained. As it is clear from the figure, the highest flux was provided by 8 µm membrane and the lowest by the 2.5 µm membrane. This finding was an agreement with the findings for individual recipes. Since the mixture includes all three recipes in the same volume ratio, this is an expected result. As regards the decrease in the filtrate flux during the initial stage of filtration, the poorest performance was with 2.5 µm membrane. Initial flux provided with this membrane was so low compared to the others and there was a drastic decrease in filtrate rate during the first 60 sec. reaching to a value of almost 0.1 L/sec/m^2. Corresponding filtrate rate of 8 µm membrane was approximately 0.6 L/sec/m^2 (50% decrease in filtrate rate) after 60 sec. of filtration. At the end of the filtration cycle, all three membranes provided almost the same filtrate rate as they are all clogged at that time.

When the characteristics of the filtrates collected at the end of the process were analyzed, the results given in Table 6.17 were obtained. As can be depicted from Table 6.17, a high color removal efficiency of 72% was achieved with the finest MF membrane (0.45 μm). This result was in line with the findings for individual recipes. The color removal results obtained with the membranes of the pore size 2.5 μm and 8 μm filters were similar and relatively low (61%) as compared to that achieved by 0.45 μm membrane. However, with these three MF membranes, similar COD reductions of about 30 to 32 % were observed. Such low COD removals along with relatively high color removals indicated the presence of non-color causing, dissolved organics in the wastewater. On the other side, the permeates from all three MF membranes contained almost same conductivity and pH as the pretreated wastewater.

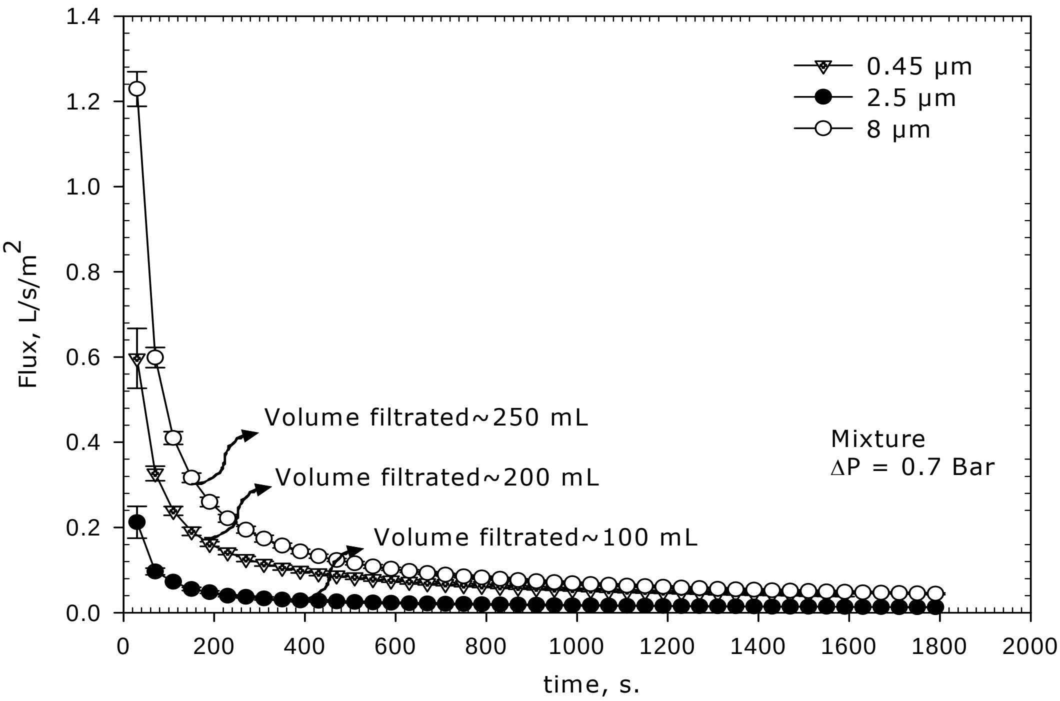


Figure 6.5. Flux values of MF membrane filters for the mixture

Table 6.17. Characteristics of the Mixture pretreated via MF*

Filter size	Conductivity, mS/cm	pH	COD, mg/L	%COD Removal	Color, Pt-Co	%Color Removal
Feed water	5.9	11.3	929		5120	
0.45 μm	5.1	10.1	630	32	1446	72
2.5 μm	5.2	10.1	648	30	1983	61
8 μm	5.2	10.1	650	30	2020	61

*P=0.7 bar

Part 2: High Pressure MF

As presented above in detail, low pressure MF tests with all the membranes tested provided low filtrate flowrate due to immediate clogging of the membranes by the accumulation of the suspended solids. This is the case in batch tests, when the filtration system is operated at a constant pressure of 0.7 bar. One of the ways of increasing flux and letting the filtration continue is to increase the trans-membrane pressure during the filtration [44]. Thus, at this phase of the experimental studies, applicability of MF at a high pressure was tested. High pressure tests were only held with the Mixture, as the low pressure MF tests with the individual recipes provided very similar results.

When 0.45 μm, 2.5 μm and 8 μm MF membranes were tested for the Mixture at a pressure of 3 bars, flux variation presented in Figure 6.6 was obtained. As the 8 μm membrane was torn immediately after the start of the filtration test, no permeate flux was measured for 8 μm. Therefore no data is presented in Figure 6.6 for this membrane. This finding is in fact a clear indication of low resistance of this membrane to a pressure of 3 atm. Although the membrane material of 0.45 μm membrane was same as that of 8 μm membrane (mixed cellulose ester, MCE) only 8 μm membrane was torn. The reason for this can be explained by the tortuous structure not having unique homogeneous pore size of the membrane. Typical MF cellulosic membranes generally have tortuous structures as shown in Figure 3.3 [49].

From Figure 6.6 it can clearly be seen that 0.45 μm membrane was superior to 2.5 μm membrane in terms of initial flux and also the time to produce 400 mL of filtrate. Comparing the performance of 0.45 μm membrane at 0.7 bar pressure to its performance at 3 bars, it can evidently be seen that 3 bar pressure provided a flux increase from 0.6 $L/s/m^2$ to 1.5 $L/s/m^2$. In low pressure case, 250 mL wastewater was filtrated in a much longer period than in the high pressure case in which 400 mL filtrate was collected in 1200 s. Increasing the pressure increased the initial flux or filtration rate for 0.45 μm membrane.

Characteristics of the filtrates collected at the end of the process from 0.45 and 2.5 μm membranes were analyzed, and the results given in Table 6.18 were obtained. Both MF membranes were similarly satisfactory in color and COD removals, i.e. 71-74 Both MF membranes were similarly successful in color and turbidity rejection, i.e. 71–74% color rejection and 27 to 29 % COD reduction was observed.

Conductivity and pH of the pretreated wastewater did not differ so much in comparison to the original wastewater as in the case of all other three recipes. Pressure effect on conductivity and pH change was negligible. When the color and COD removals for high pressure MF tests were compared with low pressure removals, it is evident that the removals did not differ considerably upon increase of pressure.

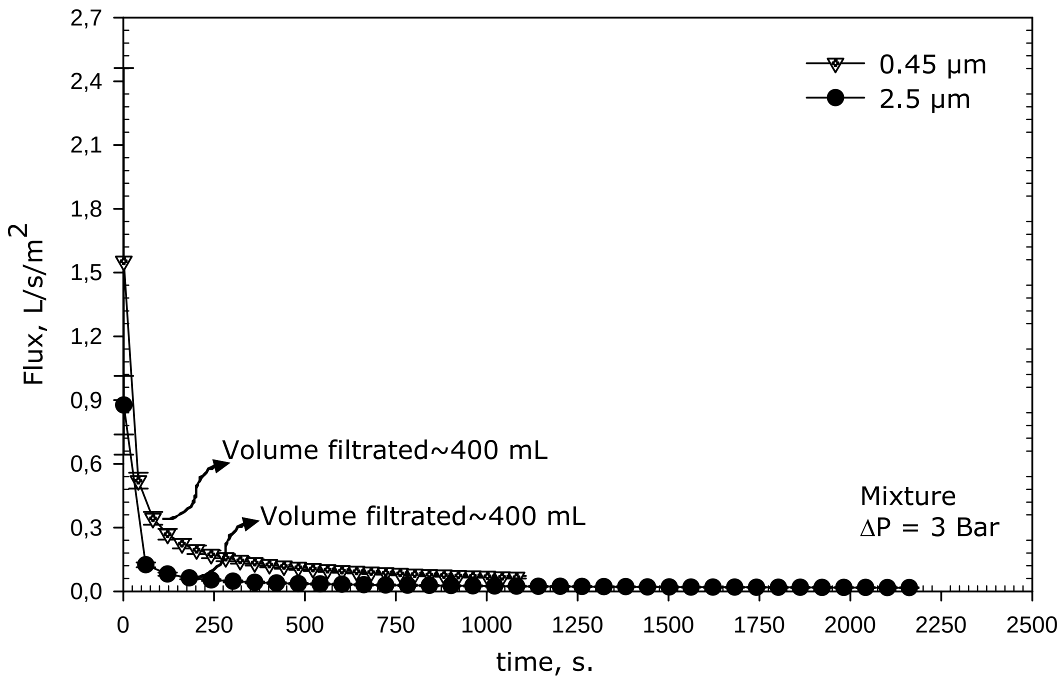


Figure 6.6. Flux values of MF membrane filters for the mixture

Table 6.18. Characteristics of the Mixture pretreated via MF**

Filter size	Conductivity, mS/cm	pH	COD, mg/L	%COD Removal	Color, Pt-Co	%Color Removal
Feed water	5.9	11.3	929		5120	
0.45 µ	5.2	10.3	660	29	1331	74
2.5 µ	5.1	10.1	678	27	1485	71
8 µ	-	-	-	-	-	-

**P=3 bar

Considering the flux and the removal rates, 0.45 µm membrane seemed to have better performance than the others did at 3 bar pressure.

6.1.3.2. Microfiltration+Ultrafiltration Studies

Results of the Mixture

Following MF tests, a series of UF tests was carried out using four different membranes (100, 50, 10, 5 kDa). Influent to UF membranes was the filtrate provided by 0.45 µm MF at 3 bar pressure with the characteristics given in Table 6.18. As can be depicted from Table 6.19, additional COD and color removals of 4-19 % and 69-81%, respectively were achieved by UF after MF. The finest UF membrane provided the highest additional COD and color removals of 81 and 19 %, respectively. On the other hand, the coarsest UF membrane; 100 kDa, removed an additional 4 % of COD and 69 % of color from the permeate from 0.45 µm MF. The resulting permeate COD and color values provided by UF membranes were 535-634 mg/L and 256-410 Pt-Co, respectively indicating further treatment requirement by NF for reuse. A comparison of this quality with the reuse quality criteria presented in Table 1.1. indicates that this effluent can not be used without further removal of color, COD, and conductivity. Needless to say that further treatment by NF is expected to provide effective COD, color and also conductivity removals.

As can be depicted from Figure 6.7, among all the UF membranes 100 kDa showed the highest and 5 kDa showed the lowest flux values. Among them 10 and 50 kDa showed similar fluxes. In a recent study which applied cross flow UF experiments on indigo dyeing wastewaters as pretreatment, higher steady state fluxes of up to 60 $L/m^2/h/bar$ by 100 kDa membrane [37] were achieved compared to a steady state flux of 27 $L/m^2/h/bar$ (corresponds to 0.03 $L/m^2/s$ at 4 bar-given in Figure 6.7) achieved by 100 kDa UF at dead-end in the present study. Therefore crossflow UF experiments may be recommended as pretreatment to NF for indigo dyeing wastewaters for future studies.

While choosing the optimum UF membrane both effluent quality and fluxes were considered. Color removals achieved by all UF membranes were in the range of 70% to 80% and can be considered as almost the same. Although the COD removal efficiency provided by 100 kDa UF membrane was lower than those of other UF membranes; in general, COD removal efficiencies provided by all the tested UF membranes were low. Therefore it was argued that COD rejection should not be of primary importance in comparing the UF membranes' effectiveness. Therefore, in the selection of best UF membrane, both effluent quality and the fluxes achieved were considered and 100 kDa UF membrane that provided a high flux but relatively a low COD was selected. With this selection, optimum pretreatment scheme for the dyeing wastewater (mixture) may be sequential application of MF (0.45 µm) at 3 bar and UF (100 kDa) at 4 bar or single stage MF (0.45 µm) at 3 bar prior to NF.

Table 6.19. Characteristics of the pretreated wastewater after UF

Pore size (kDa)	pH	Conductivity (mS/cm)	Color (Pt-Co)	COD (mg/L)	Color removal (%)	COD removal (%)
Feed to UF	10.30	5.2	1331	660		
5	10.25	5.1	256	535	81	19
10	10.29	5.1	307	601	77	9
50	10.38	5.2	358	620	73	6
100	10.49	5.2	410	634	69	4

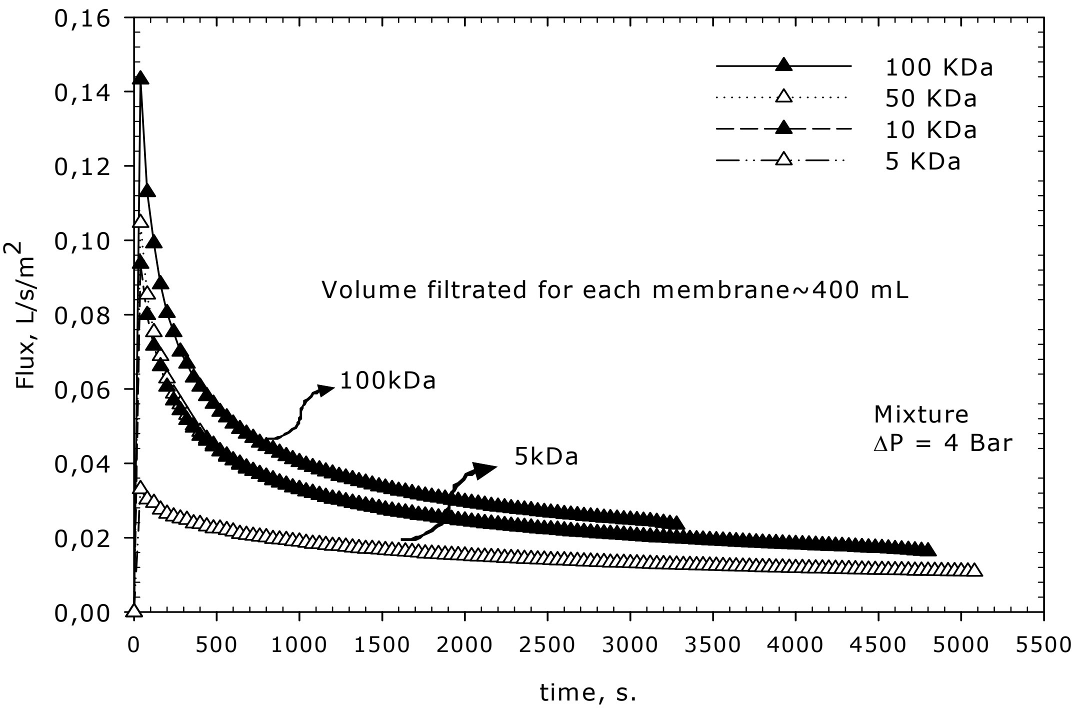


Figure 6.7. Flux values of UF membrane filters

6.1.4. Assessment of the Results from Filtration Pretreatment Studies

As an alternative method to coagulation for the pretreatment of indigo dyeing rinsing wastewaters, MF was tested for three different recipes and also for their Mixture and the results presented in Table 6.20 were obtained. As presented, regardless of the size of the filter, MF provided similar color and COD removals for each recipe or feed wastewater. Color removal from R1 was about 50 % via both 2.5 and 8 μm MF membranes. Similarly, all three membranes provided 70-75 % color removal for R2 and 67-74 % for R3. With the Mixture, on the other hand, color removals were in the range 61 to 74 % that are a bit lower than those for R2 and R3 are. Evidently, this was due to the presence of R1 wastewater in the Mixture, which contains smaller size color causing materials in it. This was a clear indication of the influence of the variation in wastewater composition with different recipes applied in indigo dyeing. This observation was in fact further supported by the variation in COD removal from different recipes' wastewaters. For R1 and R2, COD removal was at around 25 to 30 % while that for R3 was 50 %. Consequently, for the Mixture, COD rejection was 30 to 32 %.

Table 6.20. Color and COD removals via MF (P_1 = 0.7 bar, P_2 = 3 bar)

	Color Removal (%)					**COD Removal (%)**				
Filter pore size (μm)	R_1	R_2	R_3	Mixture		R_1	R_2	R_3	Mixture	
	P_1	P_1	P_1	P_1	P_2	P_1	P_1	P_1	P_1	P_2
0.45	-	76	74	72	74	-	25	50	32	29
2.5	52	71	67	61	71	24	29	47	30	27
8	53	71	68	61	-	33	22	48	30	-

In assessing the influence of the change in wastewater composition on the prefiltration of indigo dyeing wastewater, obviously, not only color and COD removals but also flux values are to be considered. As can be depicted from Table 6.21, throughout the filtration process 8 μm membrane provided a higher initial flux of 3.4 L/s/m^2 compared to 0.8 L/s/m^2 provided by 2.5 μm membrane for R1. Similarly throughout the whole filtration cycle higher initial fluxes were obtained by 8 μm membrane and the lowest initial fluxes via 2.5 μm membrane for all recipes. However with the progressive deposition of solids on the membranes at the end of the filtration cycle and the formation of the dynamic membrane, all three membranes provided almost the same filtrate rate and they are all clogged at that time for all recipes. Another reason for the similar fluxes at the end of the filtration cycles for all MF and UF membranes may be the similar PSD (given in Appendix B) of all dyeing rinsing wastewaters tested. Because of the similarity in the PSD of the wastewaters it can be considered that the pore sizes of the dynamic membranes formed for all membranes were approximately equal to each other. Therefore similar steady state fluxes were achieved. For the Mixture the highest flux was provided by 8 μm membrane and the lowest by the 2.5 μm membrane. This finding was an agreement with the findings for individual recipes. Comparing the performance of 0.45 μm membrane at 0.7 bar pressure to its performance at 3 bars, it can evidently be seen that 3 bar pressure provided a flux increase from 0.6 L/s/m^2 to 1.5 L/s/m^2 for 0.45 μm membrane. Increasing the pressure increased the initial flux or filtration rate for 0.45 μm membrane.

Table 6.21. Initial and steady state fluxes provided via MF
(P_1 = 0.7 bar, P_2 = 3 bar)

	Initial flux (L/s/m^2)					**Steady state flux (L/s/m^2)**				
Filter pore size (μm)	R_1	R_2	R_3	Mixture		R_1	R_2	R_3	Mixture	
	P_1	P_1	P_1	P_1	P_2	P_1	P_1	P_1	P_1	P_2
0.45	-	1.4	3.0	0.6	1.5	-	0.2	0.1	0.1	0.1
2.5	0.8	1.3	0.7	0.2	0.9	0.1	0.1	0.1	0.1	0.1
8	3.4	3.0	4.5	1.2	-	0.2	0.3	0.1	0.1	-

In order to minimize flux decline and hence maintain an efficient membrane separation process for the further NF experiments, UF experiments were conducted with the pretreated wastewater via MF to increase the quality of the pretreated wastewater. Among all the UF membranes tested, as expected 100 kDa showed the highest flux value as shown in Figure 6.7. However, color and COD removals were similar for all the UF membranes. Although the MWCO of the UF membranes tested were significantly different, their COD removal performances were surprisingly very close to each other. This is probably due to the wide range of molecular weights of the organic compounds in the feed, i.e. dyes have relatively small molecular weights whereas surfactants have much bigger.

6.2. Nanofiltration Tests

6.2.1. Set1-NF application to the wastewater pretreated by the sequential MF and UF application

The wastewater from the sequential MF and UF applications were subjected to NF in total recycle mode of filtration and the permeate characteristics (in terms of reuse criteria parameters) and the removal efficiencies given in Table 6.22 were achieved. As seen, very high (96 to 97 %) retentions were achieved for color and COD at steady-state. The permeate color decreased to 15 Pt-Co where COD and conductivity values were stabilized at around 20 mg/L and 1700 μS/cm, respectively. When this permeate quality is compared to the reuse quality criteria given in Table 1.1, it is seen that the permeate from NF after sequential MF plus NF application can be satisfactorily reused in the wet processes of the textile industry. The effluent from NF is of perfect quality with a very low COD and color and also a low conductivity.

Table 6.22. Permeate characteristics
from the sequential MF (0.45 μm)+UF (100 kDa) + NF application

time (min)	Flux, L/m^2/h	pH	Color (Pt-Co)	COD (mg/L)	Conductivity (μS/cm)	Color Retention (%)	COD Retention (%)	Conductivity Retention (%)
15	12.99	10.10	22	14	1627	95	98	69
30	13.22	10.12	20	13	1621	95	98	69
45	13.39	10.23	18	28	1639	96	96	68
60	13.22	9.98	17	22	1656	96	97	68
75	13.39	10.20	17	30	1662	96	95	68
90	13.27	10.23	16	28	1691	96	96	67
105	13.27	10.18	16	35	1677	96	94	68
120	13.27	10.20	15	25	1711	96	96	67
135	13.27	10.22	15	21	1730	96	97	67

As can be depicted from Figure 6.8, clean water flux through the membrane was very high at the start of the filtration cycle, but after about 50 min it stabilized at around 81.97 L/m^2/h. When this membrane was subjected to the permeate from the sequential application of 0.45 μm MF and 100 kDa UF, a steady permeate flux of 43.86 L/m^2/h-clean water flux, i.e. 53.5% clean water flux recovery was obtained indicating severe fouling of the membrane. Moreover, this fouling was immediate and all through the filtration cycle, a steady permeate flux was monitored. This finding clearly indicated that there occurs in fact no change in membrane retention characteristics during filtration, therefore the fouling could be reversible. In an effort to test the validity of this supposition, the membrane subjected to chemical cleaning after wastewater filtration. Acid (HNO_3-pH3)-base (NaOH-pH9) cleaning was applied in total recycle mode for 30 minutes to recover flux or to find out the reversible portion of the fouling. A clean water flux recovery of about 85.92% (70.42 L/m^2/h) was measured indicating that the flux decline is mostly reversible. A further analysis of the flux decline revealed that concentration polarization was the major cause of flux decline, since 69.7 % of flux decline was due to concentration polarization whereas fouling was responsible for up to 46.5 % of flux decline (Table 6.23).

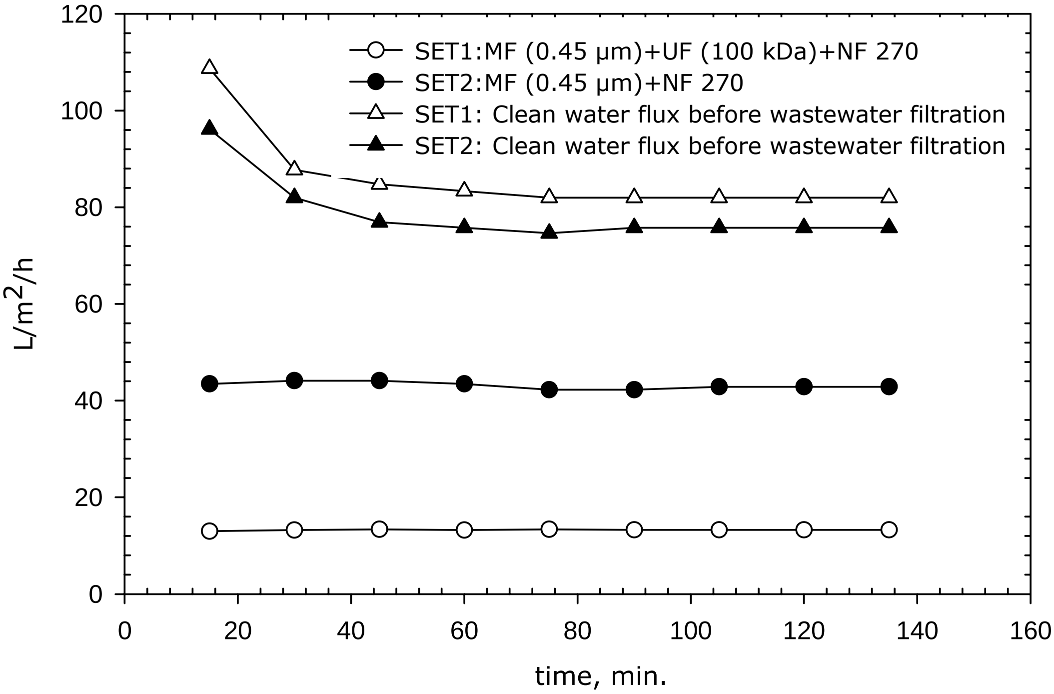


Figure 6.8. Flux values provided by two sets of NF tests

Table 6.23 Flux decline analysis for Set1 NF

Permeate Flux ($L/m^2/h$)				**Flux decline (%)**				
Clean water			WW	Total (%)	Concentration Polarization (%)	Fouling (%)		
Initial J_{cwi}	Final J_{cwf}	Cleaned J_{cwc}	J_{ww}	$(J_{cwi}-J_{ww})/J_{cwi}$	$(J_{cwf}-J_{ww})/J_{cwf}$	Total $(J_{cwi}-J_{cwf})/J_{cwi}$	Reversible $(J_{cwc}-J_{cwf})/J_{cwc}$	Irreversible $(J_{cwi}-J_{cwc})/J_{cwi}$
81.97	43.86	70.42	13.27	83.8	69.7	46.5	37.7	14.1

J_{cwi}= Initial clean water flux,

J_{cwf}= Final clean water flux,

J_{cwc}= Clean water flux after cleaning of the membrane,

J_{ww}= Steady state wastewater flux.

6.2.2. Set2-NF application to the pretreated wastewater via only MF

Table 6.24 shows the permeate characteristics from this NF test in terms of reuse criteria parameters. Color values were decreased to 15 Pt-Co at the end of the filtration period from its earlier value of 1331 Pt-Co. As seen, COD and conductivity values were stabilized around 20 mg/L and 1070 μS/cm, respectively. Thus, high retentions were observed for all parameters.

On the other side, as can be seen from Figure 6.8, clean water flux through the membrane was very high at the start of the filtration cycle as in Set1, but after about 50 min it stabilized at around 75.76 L/m^2/h. When this membrane was subjected to the permeate from 0.45 μm MF only, a steady permeate flux of 83.33 L/m^2/h which is above initial clean water flux was observed. This finding indicated that after filtration with wastewater, there occurred an increase in the pore size of the membrane used. Same pairs of NF membranes were used in both sets. Therefore this increase in the pore size may be the result of cleaning of the membrane by means of acid and base solution in Set1. Moreover, it also indicated that there is no fouling occurred due to wastewater filtration.

When permeate from MF (0.45 μm)+ NF application was filtered, as can be depicted from Table 6.25, a steady state permeate flux of 42.86 L/m2/h was measured. This value was corresponding to 43.4 % flux decline. This decline in permeate flux as compared to clean water flux was partly by concentration polarization as presented in Table 6.25.

Table 6.24. Permeate characteristics
from the sequential MF (0.45 μm)+ NF application

time (min)	**Flux, $L/m^2/h$**	**pH**	**Color (Pt-Co)**	**COD (mg/L)**	**Conductivity (μS/cm)**	**Color Retention (%)**	**COD Retention (%)**	**Conductivity Retention (%)**
15	43.48	10.20	17	23	961	99	97	82
30	44.12	10.23	14	23	1023	99	97	80
45	44.12	10.23	13	24	1026	99	96	80
60	43.48	10.18	16	19	1030	99	97	80
75	42.25	10.22	18	31	1031	99	95	80
90	42.25	10.20	14	26	1041	99	96	80
105	42.86	10.21	15	18	1048	99	97	80
120	42.86	10.16	15	19	1072	99	97	79
135	42.86	10.19	15	24	1080	99	96	79

Table 6.25 Flux decline analysis for Set2 NF

Permeate Flux ($L/m^2/h$)				**Flux decline (%)**				
Clean water			WW	Total (%)	Concentration Polarization(%)	Fouling (%)		
Initial J_{cwi}	Final J_{cwf}	Cleaned J_{cwc}	J_{ww}	$(J_{cwi}-J_{ww})/J_{cwi}$	$(J_{cwf}-J_{ww})/J_{cwf}$	Total $(J_{cwi}-J_{cwf})/J_{cwi}$	Reversible $(J_{cwc}-J_{cwf})/J_{cwc}$	Irreversible $(J_{cwi}-J_{cwc})/J_{cwi}$
75.76	83.33	83.33	42.86	43.4	48.6	-	-	-

Considering the results from the two sets NF application, "single stage MF pretreatment option" was chosen since clean water flux recovery and the permeate flux provided throughout the filtration process were higher for this alternative; with concomitant high color, COD and conductivity removal rates. Single stage application of MF+NF was found superior to the MF+UF+NF treatment scheme in terms of both wastewater flux and the flux recovery. The reason for that may be the structure of the NF membranes. Most NF membrane polymers carry formal charges that exclude higher valence ions more than monovalents from passing through the membrane with the solvent water [50]. Because of the rejected solutes by means of UF applied in Set1, charge of the solution may be changed and the charge interaction between the wastewater and the NF membrane did not allow the passage of monovalent ions. Therefore fluxes achieved via Set1 was lower than the ones obtained in Set2. Regarding the permeate characteristics from NF there was not considerable benefit of adding one additional step pretreatment (UF) after MF. This finding was in agreement with the past literature. In a recent study dealing with the indigo dyeing wastewater recovery, MF and MF+UF were applied as pretreatment alternatives before NF and the results of the study revealed that using an additional 100 kDa UF membrane as a second stage after 5 μm MF membrane did not result in a significant improvement in color and COD retentions and also in permeate flux in NF parallel to the results obtained in our study [37]. In another study about the pretreatment of acid-dye bath wastewaters showed similar results. The little improvement in color and turbidity removal efficiencies were achieved by the implementation of MF+UF compared to the removals obtained by single stage UF. Single stage processes were as effective as the sequential ones; hence there was no advantage in implementing sequential filtration as pretreatment [54]. The use of double-membrane systems, consisting of a low pressure and a high-pressure membrane in series is accepted as an innovative process configuration for wastewater treatment and reuse. The first membrane (MF or UF) application helps preventing the fouling of the second, higher-pressure membrane system (RO or NF) [44]. A recent study focusing on textile wastewater management in which the proposed treatment scheme was the sequential application of cross flow UF and NF, supports the use of double-membrane systems [8]. Double membrane system is promising for the textile wastewater reuse and there is a variety of study in the literature supporting this treatment scheme

CHAPTER 7

CONCLUSIONS

This work presents operational data on the suitable pretreatment (coagulation and MF/UF) and membrane filtration (NF) of indigo dyeing process rinsing wastewaters originating from a denim textile mill located in Kayseri Turkey

The study is composed of two stages. In the first stage, pretreatment alternatives were evaluated for the indigo dyeing rinsing wastewaters to identify the optimum pretreatment type and the conditions. In the second stage, NF was applied to the pretreated wastewater to be able to obtain reusable water. The optimum operating conditions and the best pretreatment alternative applicable to indigo dyeing wastewaters were found. Moreover, the possibility to upgrade the Mixture quality for the reuse purpose was assessed.

While determining the pretreatment options, the rinsing wastewaters of dyeing recipes and the Mixture were considered separately; in order to determine process conditions to apply in case of the dominance of one of the most common applied recipes in the production. In order to assess the NF performance after pretreatment, NF tests were run with the Mixture only instead of conducting the tests on each recipe, as the effluent quality from MF is independent of recipe.

Based on the results obtained the following conclusion can be made:

- Coagulation tests using alum and ferric chloride as coagulants provided the maximum color and COD removals of 52% and 50% respectively, via ferric chloride application at a very high dose of 1000 mg/L. This finding indicated that due to high dose of coagulant requirement, coagulation is not an effective and efficient pretreatment method for the denim textile indigo dyeing wastewaters.

- Single MF test carried out at 0.7 bar and 3 bar pressures using three different pore sized filters (0.45, 2.5, and 8 μm) revealed that the best overall performance was achieved via 0.45 μm MF membrane at 3 bar. With this MF membrane increasing the transmembrane pressure from 0.7 to 3 bar increased the permeate flux by 25 % (from 1.2 $L/s/m^2$ to 1.5 $L/s/m^2$) and as a result, 74% color and 29% COD removals were achieved.

- UF tests for the permeate from 0.45 μm MF membrane (at 3 bar) indicated that, among all the UF membranes tested (5, 10, 50, and 100 kDa) 100 kDa (at a transmembrane pressure of 4 bar) provided the best performance with the highest initial and steady state fluxes. This sequential application of MF and UF provided cumulative color and COD removals of 69% and 4%, respectively; yielding a color value of 410 Pt-Co and a COD of 634 mg/L.

- The sequential application of MF and UF was found to be superior to both coagulation and single MF processes in terms of color and COD reductions.

- Two sets of NF tests were run using NF 270 membrane in a total recycle mode. The first NF test was applied to the wastewater from MF (0.45 μm at 3 bar) only; while the second was to the permeate from the sequential MF (0.45 μm at 3 bar) and UF (100 kDa, at 4 bar) applications. Among these alternatives, MF + NF alternative provided very high (99 to 97 %) retentions of color and COD at steady-state yielding a color of 15 Pt-Co 20 mg/L COD along with a higher permeate flux. Conductivity retention by this treatment scheme was also very high and eventually an effluent conductivity of 1070 mS/cm was attained. Thus, the quality of the permeate was satisfactory in meeting the reuse criteria.

- Although it is highly variable in characteristics, indigo dyeing wastewater from the denim textile mill considered in the present study can be treated for reuse; the optimum scheme being MF plus NF.

- The treatment scheme developed is applicable for the indigo dyeing wastewater from the mill considered as the pretreatment process was found to be almost independent of variation in wastewater composition.

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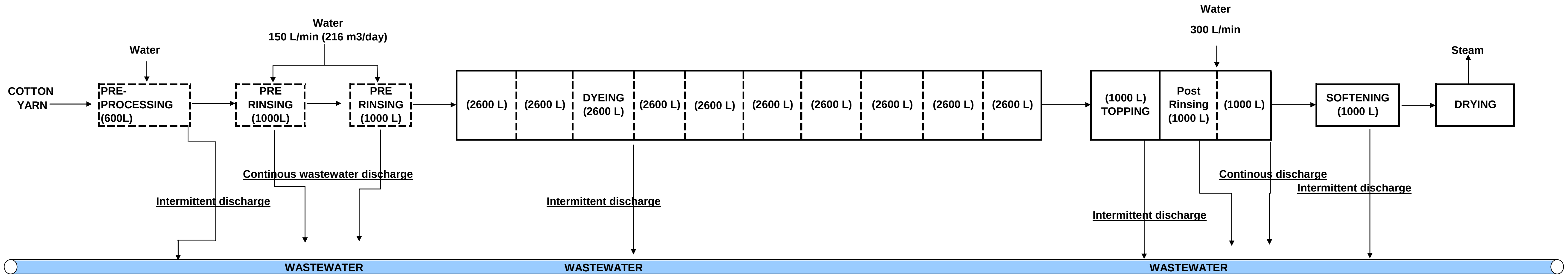
APPENDIX A

SCHEMATIC REPRESENTATION OF INDIGO DYEING MACHINES-4 LINES AS ; INDIGO-1, INDIGO-2, INDIGO-3, INDIGO-4.

In Figure A1, in each line, number and volume of preprocessing, pre-rinsing, dyeing, post-rinsing, softening, and drying tanks with the representation of intermittent and continuous wastewater discharges and average influent process water flowrates are given.

INDIGO 1



INDIGO 2

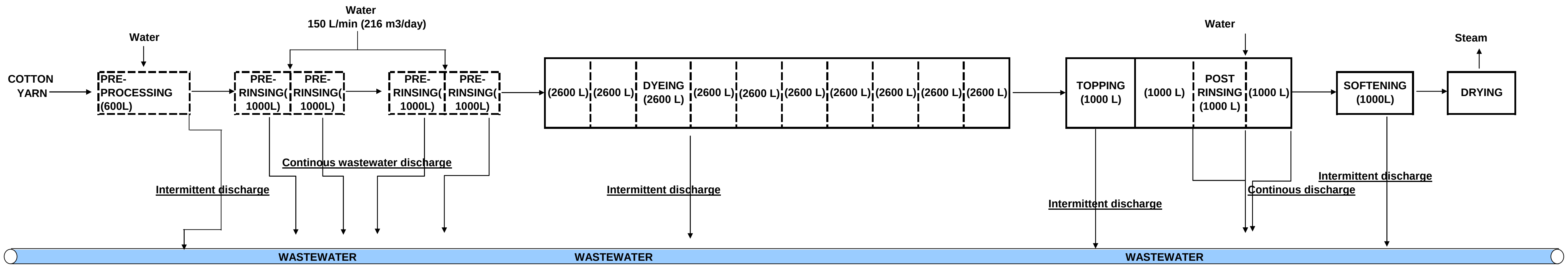
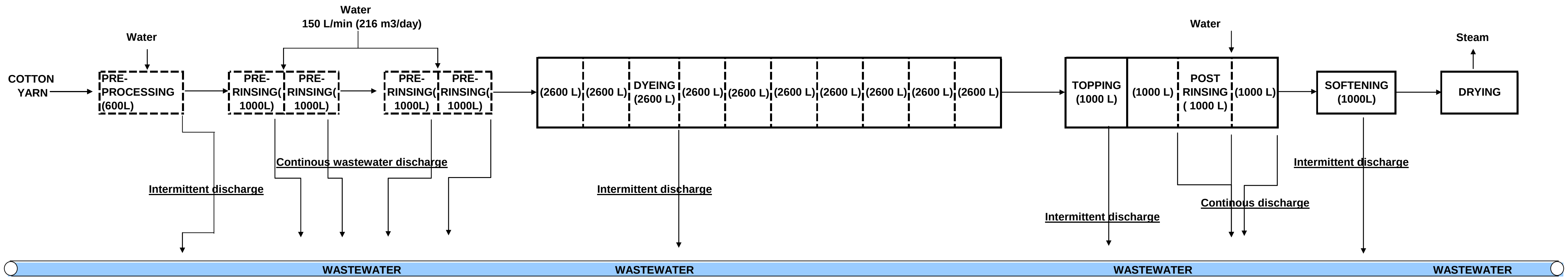


Figure A1. Schematic Representation of Indigo Dyeing Machines-4 lines

INDIGO 3



INDIGO 4

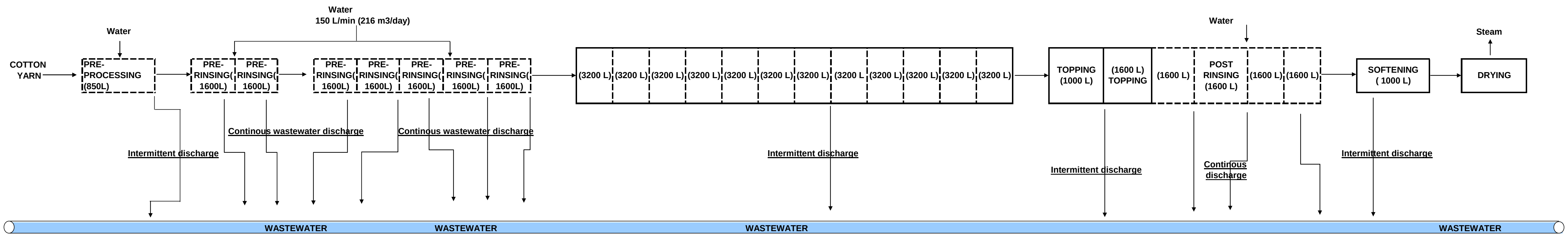


Figure A1 (continued)

APPENDIX B

PARTICLE SIZE DISTRIBUTION ANALYSIS RESULTS

This appendix provides the supplementary data for the particle size distribution (PSD) in order to have a better understanding about the filtration performances of all indigo dyeing rinsing wastewaters.

R1

The PSD of the R1 is given via Figure B.1.1 and Figure B.1.2 in detail. The size of the most of the particles are in the range of 5 (d0.1)-80 (d0.9) μm. Almost 5% of the particles (volume based) are smaller than 0.45 μm and 95% of the particles are captured via 0.45 μm membrane.

d0.1: Particle size of which 10% of the particles in the solution are smaller than that value

d0.9: Particle size of which 90% of the particles in the solution are smaller than that value

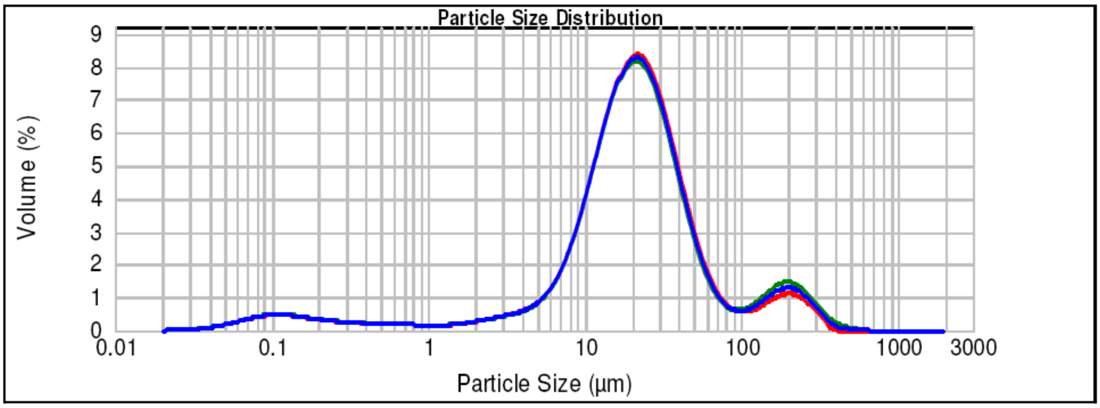


Figure B.1.1 PSD of R1

Size (μm)	Vol Under %	Size (μm)	Vol Under %	Size (μm)	Vol Under %	Size (μm)	Vol Under %	Size (μm)	Vol Under %	Size (μm)	Vol Under %
0.010	0.00	0.105	2.02	1.096	6.28	11.482	23.22	120.226	92.70	1258.925	100.00
0.011	0.00	0.120	2.45	1.259	6.42	13.183	28.25	138.038	93.44	1445.440	100.00
0.013	0.00	0.138	2.86	1.445	6.57	15.136	34.23	158.489	94.37	1659.587	100.00
0.015	0.00	0.158	3.25	1.660	6.74	17.378	41.00	181.970	95.47	1905.461	100.00
0.017	0.00	0.182	3.61	1.905	6.95	19.953	48.30	208.930	96.64	2187.762	100.00
0.020	0.00	0.209	3.93	2.188	7.20	22.909	55.76	239.883	97.76	2511.886	100.00
0.023	0.00	0.240	4.22	2.512	7.51	26.303	63.01	275.423	98.69	2884.032	100.00
0.026	0.00	0.275	4.47	2.884	7.86	30.200	69.70	316.228	99.36	3311.311	100.00
0.030	0.02	0.316	4.70	3.311	8.28	34.674	75.53	363.078	99.74	3801.894	100.00
0.035	0.06	0.363	4.91	3.802	8.75	39.811	80.35	416.869	99.89	4365.158	100.00
0.040	0.13	0.417	5.12	4.365	9.31	45.709	84.10	478.630	99.95	5011.872	100.00
0.046	0.24	0.479	5.31	5.012	9.99	52.481	86.86	549.541	99.99	5754.399	100.00
0.052	0.39	0.550	5.50	5.754	10.88	60.256	88.78	630.957	100.00	6606.934	100.00
0.060	0.59	0.631	5.68	6.607	12.09	69.183	90.07	724.436	100.00	7585.776	100.00
0.069	0.86	0.724	5.84	7.586	13.76	79.433	90.94	831.764	100.00	8709.636	100.00
0.079	1.21	0.832	6.00	8.710	16.07	91.201	91.56	954.993	100.00	10000.000	100.00
0.091	1.60	0.955	6.14	10.000	19.17	104.713	92.11	1096.478	100.00		

Figure B.1.2 Size of the particles wrt. volume percentages in the solution

R2

The PSD of the R2 is given via Figure B.2.1 and Figure B.2.2 in detail. The size of the most of the particles are in the range of 0.1-26 μm. Almost 25% of the particles (volume based) are smaller than 0.45 μm and 75% of the particles are captured via 0.45 μm membrane.

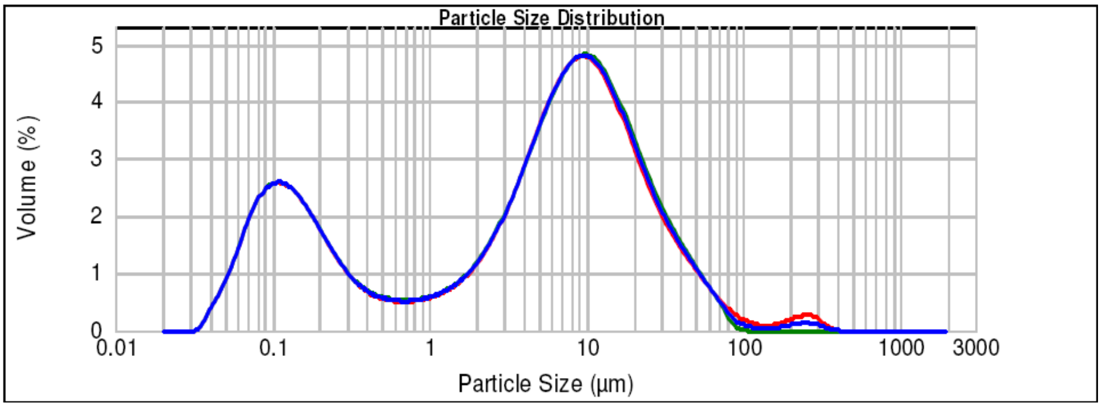


Figure B.2.1 PSD of R2

Size (μm)	Vol Under %	Size (μm)	Vol Under %	Size (μm)	Vol Under %	Size (μm)	Vol Under %	Size (μm)	Vol Under %	Size (μm)	Vol Under %
0.010	0.00	0.105	10.21	1.096	28.94	11.482	69.79	120.226	99.39	1258.925	100.00
0.011	0.00	0.120	12.55	1.259	29.53	13.183	73.95	138.038	99.44	1445.440	100.00
0.013	0.00	0.138	14.81	1.445	30.20	15.136	77.85	158.489	99.47	1659.587	100.00
0.015	0.00	0.158	16.92	1.660	30.97	17.378	81.40	181.970	99.53	1905.461	100.00
0.017	0.00	0.182	18.82	1.905	31.88	19.953	84.56	208.930	99.62	2187.762	100.00
0.020	0.00	0.209	20.48	2.188	32.95	22.909	87.32	239.883	99.73	2511.886	100.00
0.023	0.00	0.240	21.88	2.512	34.26	26.303	89.70	275.423	99.85	2884.032	100.00
0.026	0.00	0.275	23.04	2.884	35.83	30.200	91.73	316.228	99.95	3311.311	100.00
0.030	0.00	0.316	23.99	3.311	37.72	34.674	93.47	363.078	100.00	3801.894	100.00
0.035	0.00	0.363	24.77	3.802	39.98	39.811	94.94	416.869	100.00	4365.158	100.00
0.040	0.19	0.417	25.43	4.365	42.63	45.709	96.18	478.630	100.00	5011.872	100.00
0.046	0.63	0.479	25.99	5.012	45.67	52.481	97.19	549.541	100.00	5754.399	100.00
0.052	1.36	0.550	26.50	5.754	49.09	60.256	98.00	630.957	100.00	6606.934	100.00
0.060	2.42	0.631	26.98	6.607	52.86	69.183	98.60	724.436	100.00	7585.776	100.00
0.069	3.88	0.724	27.44	7.586	56.90	79.433	99.01	831.764	100.00	8709.636	100.00
0.079	5.75	0.832	27.92	8.710	61.14	91.201	99.23	954.993	100.00	10000.000	100.00
0.091	7.90	0.955	28.41	10.000	65.48	104.713	99.34	1096.478	100.00		

Figure B.2.2 Size of the particles wrt. volume percentages in the solution

R3

The PSD of the R3 is given via Figure B.3.1 and Figure B.3.2 in detail. The PSD of R1 is so variable that three peaks were observed at different particle sizes. However the size of the most of the particles are in the range of 2.5 (d0.1)-240 (d0.9) µm. Almost 8% of the particles (volume based) are smaller than 0.45 µm and 92% of the particles are captured via 0.45 µm membrane.

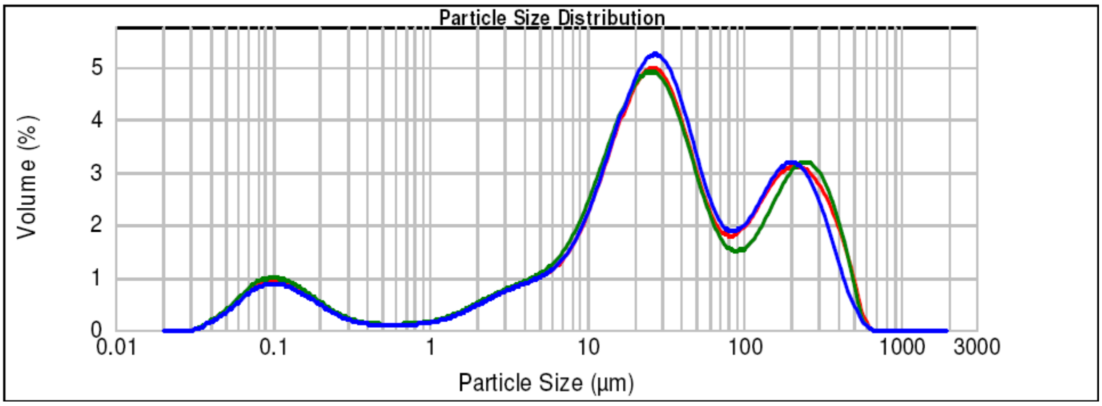


Figure B.3.1 PSD of R3

Size (µm)	Vol Under %	Size (µm)	Vol Under %	Size (µm)	Vol Under %	Size (µm)	Vol Under %	Size (µm)	Vol Under %	Size (µm)	Vol Under %
0.010	0.00	0.105	3.66	1.096	8.51	11.482	22.72	120.226	77.39	1258.925	100.00
0.011	0.00	0.120	4.43	1.259	8.67	13.183	25.33	138.038	79.66	1445.440	100.00
0.013	0.00	0.138	5.16	1.445	8.88	15.136	28.43	158.489	82.23	1659.587	100.00
0.015	0.00	0.158	5.81	1.660	9.15	17.378	32.05	181.970	85.00	1905.461	100.00
0.017	0.00	0.182	6.37	1.905	9.50	19.953	36.13	208.930	87.88	2187.762	100.00
0.020	0.00	0.209	6.82	2.188	9.93	22.909	40.59	239.883	90.71	2511.886	100.00
0.023	0.00	0.240	7.17	2.512	10.44	26.303	45.27	275.423	93.33	2884.032	100.00
0.026	0.00	0.275	7.43	2.884	11.04	30.200	49.99	316.228	95.62	3311.311	100.00
0.030	0.00	0.316	7.63	3.311	11.72	34.674	54.54	363.078	97.44	3801.894	100.00
0.035	0.00	0.363	7.77	3.802	12.46	39.811	58.74	416.869	98.74	4365.158	100.00
0.040	0.08	0.417	7.87	4.365	13.27	45.709	62.42	478.630	99.51	5011.872	100.00
0.046	0.25	0.479	7.96	5.012	14.14	52.481	65.53	549.541	99.91	5754.399	100.00
0.052	0.52	0.550	8.04	5.754	15.08	60.256	68.07	630.957	100.00	6606.934	100.00
0.060	0.91	0.631	8.11	6.607	16.14	69.183	70.16	724.436	100.00	7585.776	100.00
0.069	1.44	0.724	8.19	7.586	17.36	79.433	71.94	831.764	100.00	8709.636	100.00
0.079	2.11	0.832	8.28	8.710	18.81	91.201	73.63	954.993	100.00	10000.000	100.00
0.091	2.86	0.955	8.38	10.000	20.57	104.713	75.40	1096.478	100.00		

Figure B.3.2 Size of the particles wrt. volume percentages in the solution

APPENDIX C

CALLATIONS OF SLUDGE PRODUCTION IN COAGULATION AND CHEMICAL COST ESTIMATION

i. Sludge Production Estimation Calculations

When aluminum sulfate is added to wastewater containing bicarbonate alkalinity the following reaction (C.1) takes place and a precipitate of aluminum hydroxide forms.

$$3Ca(HCO_3)_2 + \underbrace{\mathbf{Al_2(SO_4)_3.18H_2O}}_{\text{666.5 g/mole}} \Leftrightarrow \mathbf{2Al(OH)_3} + 3CaSO_4 + 6CO_2 + 18H_2O \qquad (C.1)$$

Calcium Bicarbonate (soluble); Aluminum sulfate (soluble); **2x78 g/mole** Aluminum Hydroxide **(insoluble)**; Calcium sulfate (soluble); Carbon dioxide (soluble)

The maximum color and COD removal for the mixture wastewater were provided at a dose of 1000 mg/L aluminum sulfate (1000 mg/L chemical dosage: 1000 mg chemical per 1 L of wastewater). In order to determine the sludge production in case of 1000 mg/L aluminum sulfate addition one should use Equation (C.1). When 665 g aluminum sulfate is added 156 g aluminum hydroxide precipitates as sludge. According to this ratio 1000 mg/L aluminum hydroxide produces;

$$\frac{156\,g/mole\,Al(OH)_3 \times 1000\,mg/L\,Al_2(SO_4)_3.18H_2O}{666.5\,g/mole\,Al_2(SO_4)_3.18H_2O} = 234\,mg/L\,Al(OH)_3\text{ sludge} \qquad (C.2)$$

When chemical dosage rate is 1000 mg/L then we have 234 mg aluminum hydroxide precipitated per 1 L of wastewater treated. Total suspended solids (TSS) in the mixture is 224 mg/L on average as given in Table 5.3 (This means TSS in 1 L of wastewater is 224 mg). It is assumed that all TSS precipitates as a result of coagulation. Therefore total sludge produced at the end of the coagulation process can be estimated by summing up aluminum hydroxide sludge formed and TSS in the Mixture.

Total sludge=234 mg+224 mg=458 mg solids precipitate/L wastewater (C.3)

In order to estimate monthly sludge production one should know dyeing wastewater flowrate. 1485-1925 tons/day wastewater generates from dyeing process as given in Figure 4.2. The selected three recipes correspond to about 50% of the total production (as of the year 2005) of the mill that actually applies more than 400 different dyeing recipes and this indicates that the Mixture wastewater composes of 50% of total dyeing wastewater generation resulting in 743-963 m^3/d (853 m^3/day on average).

Daily solid production=853 m^3/day wastewaterx458 mg solids/L wastewater

$\approx$ 391 kg solids produced/day (C.4)

Normally there is no production on Sundays so it is accepted as 25 working days/month and according to this monthly sludge production if coagulation is considered as pretreatment for the selected three recipes will be approximately **9.8 tons/month.**

ii. Chemical Cost Estimation Calculations

In order to estimate the cost of aluminum sulfate required for the coagulation of dyeing wastewaters one should know the amount of aluminum sulfate required to provide a concentration of 1000 mg/L aluminum sulfate and the unit price. The calculations are shown in Equation (C.5);

1000 mg/L $Al_2(SO_4)_3.18H_2O$x853 m^3/day wastewater

=853 kg $Al_2(SO_4)_3.18H_2O$/day required (C.5)

Unit price of $Al_2(SO_4)_3.18H_2O$ is approximately 0.6 TL/kg [55]. Accordingly,

Chemical cost of coagulants/month=

=853 kg $Al_2(SO_4)_3.18H_2O$/dayx0.6 TL/kg $Al_2(SO_4)_3.18H_2O$x25 days/month

=12795 TL/month (C.6)

APPENDIX D

RAW DATA OF MF PRETREATMENT EXPERIMENTS

MF experiments were done and volume vs. time data were recorded throughout the filtration process. Each filtration experiment conducted by means of a specific pore size membrane and for the specific recipe experiment was carried on until providing at least 2 similar experimental sets in terms of volume vs. time plots. Flux vs. time graphs also showing the standard deviation of fluxes between filtration sets were plotted via the data obtained throughout the filtration and these data for the Mixture are given in Appendix D.

D.1 MF

MF tests were carried on at two different pressures via three different pore sized membranes.

D.1.1. Low Pressure MF

Low pressure MF tests were carried on at a pressure of 0.7 Bar. The data belonging to the Mixture are given in Table D1.

Table D1. Raw Data (volume vs. time) of MF for the Mixture (P=0.7 Bar)

	0.45 µm						2.5 µm				8 µm				
	Flux (L/sec/m²)						Flux (L/sec/m²)				Flux (L/sec/m²)				
time,s.	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**	**Set1**	**Set2**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Average**	**Std.**
2	1.592	5.173	5.968	2.785	3.879	2.039	0.918	0.428	0.673	0.346	0.418	0.188	0.138	0.248	0.149
4	1.989	3.382	4.178	2.984	3.133	0.910	0.983	0.702	0.843	0.199	0.231	0.250	0.214	0.232	0.018
6	1.724	2.387	3.050	2.122	2.321	0.557	1.017	0.707	0.862	0.219	0.191	0.349	0.296	0.278	0.080
8	1.393	1.790	2.288	1.592	1.766	0.384	1.017	0.707	0.862	0.219	0.173	0.458	0.389	0.340	0.149
10	1.194	1.512	1.830	1.273	1.452	0.286	0.963	0.670	0.817	0.207	0.157	0.528	0.448	0.377	0.195
12	1.061	1.260	1.592	0.995	1.227	0.268	1.005	0.628	0.817	0.267	0.174	0.652	0.530	0.452	0.248
14	0.909	1.137	1.364	0.853	1.066	0.234	0.955	0.597	0.776	0.253	0.175	0.713	0.579	0.489	0.280
16	0.846	0.995	1.194	0.796	0.957	0.179	0.955	0.637	0.796	0.225	0.149	0.794	0.661	0.535	0.341
18	0.796	0.928	1.061	0.707	0.873	0.155	0.909	0.606	0.758	0.214	0.141	0.829	0.691	0.554	0.364
20	0.716	0.836	0.995	0.676	0.806	0.143	0.947	0.644	0.796	0.214	0.141	0.936	0.786	0.621	0.422
22	0.687	0.760	0.904	0.651	0.751	0.112	0.947	0.682	0.815	0.188	0.119	1.004	0.864	0.662	0.476
24	0.630	0.729	0.829	0.597	0.696	0.105	0.904	0.651	0.778	0.179	0.120	1.033	0.889	0.681	0.491
26	0.612	0.673	0.765	0.582	0.658	0.081	0.904	0.687	0.796	0.153	0.098	1.094	0.962	0.718	0.541
30	0.557	0.610	0.690	0.531	0.597	0.070	0.900	0.692	0.796	0.147	0.094	1.199	1.061	0.785	0.603
32	0.522	0.572	0.647	0.522	0.566	0.059	0.900	0.727	0.813	0.122	0.083	1.265	1.144	0.831	0.651
34	0.515	0.538	0.632	0.492	0.544	0.062	0.934	0.727	0.830	0.147	0.090	1.366	1.214	0.890	0.697
36	0.486	0.508	0.597	0.486	0.519	0.053	0.934	0.761	0.848	0.122	0.081	1.431	1.299	0.937	0.744

Table D1 (continued)

	0.45 μm						2.5 μm				8 μm				
	Flux (L/sec/m^2)						Flux (L/sec/m^2)				Flux (L/sec/m^2)				
time,s.	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**	**Set1**	**Set2**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Average**	**Std.**
38	0.461	0.503	0.565	0.482	0.503	0.045	0.895	0.763	0.829	0.094	0.072	1.417	1.312	0.934	0.749
40	0.458	0.477	0.537	0.458	0.482	0.038	0.895	0.763	0.829	0.094	0.062	1.477	1.367	0.969	0.787
42	0.436	0.455	0.531	0.455	0.469	0.042	0.928	0.796	0.862	0.094	0.071	1.575	1.463	1.037	0.838
44	0.416	0.434	0.506	0.452	0.452	0.039	0.928	0.829	0.879	0.070	0.069	1.634	1.546	1.083	0.880
46	0.415	0.415	0.484	0.432	0.437	0.033	0.928	0.829	0.879	0.070	0.060	1.691	1.601	1.117	0.917
48	0.398	0.398	0.464	0.414	0.419	0.031	0.928	0.829	0.879	0.070	0.060	1.765	1.670	1.165	0.958
50	0.382	0.398	0.446	0.414	0.410	0.027	0.891	0.828	0.859	0.045	0.053	1.731	1.669	1.151	0.951
52	0.383	0.383	0.428	0.398	0.398	0.022	0.891	0.828	0.859	0.045	0.043	1.783	1.719	1.182	0.986
54	0.368	0.368	0.427	0.398	0.391	0.028	0.923	0.859	0.891	0.045	0.058	1.881	1.816	1.252	1.035
58	0.343	0.357	0.398	0.384	0.370	0.025	0.888	0.857	0.872	0.022	0.054	1.907	1.874	1.278	1.060
60	0.345	0.345	0.385	0.371	0.361	0.020	0.888	0.857	0.872	0.022	0.044	1.954	1.921	1.306	1.093
62	0.334	0.334	0.372	0.359	0.350	0.019	0.888	0.857	0.872	0.022	0.044	2.019	1.985	1.349	1.131
64	0.323	0.336	0.361	0.361	0.345	0.019	0.855	0.855	0.855	0.000	0.043	1.971	1.971	1.329	1.113
66	0.313	0.326	0.362	0.350	0.338	0.022	0.884	0.855	0.869	0.021	0.052	2.084	2.049	1.395	1.163
68	0.316	0.328	0.351	0.339	0.334	0.015	0.853	0.824	0.838	0.020	0.036	2.034	2.000	1.357	1.144
70	0.307	0.318	0.341	0.341	0.327	0.017	0.853	0.853	0.853	0.000	0.042	2.076	2.076	1.398	1.175
72	0.298	0.321	0.332	0.332	0.321	0.016	0.823	0.823	0.823	0.000	0.039	2.044	2.044	1.375	1.158
74	0.290	0.312	0.323	0.323	0.312	0.015	0.823	0.823	0.823	0.000	0.039	2.101	2.101	1.413	1.190
76	0.293	0.304	0.314	0.314	0.306	0.010	0.823	0.823	0.823	0.000	0.026	2.139	2.139	1.435	1.220

Table D1 (continued)

	0.45 μm						2.5 μm				8 μm				
	Flux (L/sec/m^2)						Flux (L/sec/m^2)				Flux (L/sec/m^2)				
time,s.	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**	**Set1**	**Set2**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Average**	**Std.**
78	0.286	0.306	0.316	0.316	0.306	0.014	0.822	0.822	0.822	0.000	0.038	2.138	2.138	1.438	1.213
80	0.279	0.298	0.308	0.308	0.298	0.014	0.822	0.822	0.822	0.000	0.038	2.193	2.193	1.474	1.244
82	0.272	0.291	0.301	0.301	0.291	0.014	0.822	0.822	0.822	0.000	0.038	2.248	2.248	1.511	1.276
84	0.275	0.294	0.294	0.294	0.289	0.009	0.796	0.796	0.796	0.000	0.026	2.192	2.192	1.470	1.250
86	0.268	0.287	0.287	0.296	0.285	0.012	0.796	0.821	0.809	0.018	0.033	2.226	2.261	1.507	1.277
88	0.262	0.280	0.280	0.289	0.278	0.011	0.796	0.821	0.809	0.018	0.033	2.277	2.314	1.541	1.307
90	0.256	0.274	0.274	0.283	0.272	0.011	0.796	0.821	0.809	0.018	0.033	2.329	2.367	1.576	1.337
92	0.251	0.277	0.268	0.277	0.268	0.012	0.771	0.796	0.783	0.018	0.036	2.288	2.325	1.550	1.311
94	0.254	0.271	0.271	0.279	0.269	0.011	0.796	0.821	0.808	0.018	0.032	2.356	2.393	1.593	1.353
96	0.249	0.265	0.265	0.274	0.263	0.010	0.796	0.821	0.808	0.018	0.032	2.406	2.444	1.627	1.382
98	0.244	0.260	0.260	0.268	0.258	0.010	0.796	0.821	0.808	0.018	0.032	2.456	2.495	1.661	1.411
100	0.239	0.263	0.255	0.263	0.255	0.011	0.772	0.796	0.784	0.017	0.035	2.411	2.449	1.632	1.383
102	0.234	0.257	0.250	0.257	0.250	0.011	0.772	0.796	0.784	0.017	0.035	2.460	2.498	1.664	1.411
104	0.237	0.253	0.245	0.260	0.249	0.010	0.772	0.820	0.796	0.034	0.032	2.469	2.546	1.682	1.430
106	0.233	0.248	0.240	0.255	0.244	0.010	0.772	0.820	0.796	0.034	0.032	2.517	2.595	1.715	1.458
110	0.224	0.246	0.239	0.246	0.239	0.010	0.772	0.796	0.784	0.017	0.034	2.575	2.614	1.741	1.478
112	0.220	0.242	0.234	0.242	0.234	0.010	0.772	0.796	0.784	0.017	0.034	2.621	2.661	1.772	1.505
114	0.216	0.237	0.230	0.244	0.232	0.012	0.772	0.819	0.796	0.033	0.041	2.648	2.728	1.806	1.529
116	0.220	0.233	0.226	0.240	0.230	0.009	0.772	0.819	0.796	0.033	0.031	2.674	2.756	1.820	1.550

Table D1 (continued)

	0.45 μm						2.5 μm				8 μm				
	Flux (L/sec/m^2)						Flux (L/sec/m^2)				Flux (L/sec/m^2)				
time,s.	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**	**Set1**	**Set2**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Average**	**Std.**
118	0.216	0.229	0.223	0.236	0.226	0.009	0.772	0.819	0.796	0.033	0.031	2.721	2.803	1.851	1.577
120	0.212	0.225	0.219	0.232	0.222	0.009	0.772	0.819	0.796	0.033	0.031	2.767	2.851	1.883	1.604
122	0.209	0.228	0.215	0.228	0.220	0.010	0.750	0.796	0.773	0.032	0.035	2.712	2.794	1.847	1.570
124	0.205	0.225	0.218	0.225	0.218	0.009	0.773	0.796	0.784	0.016	0.033	2.819	2.861	1.904	1.621
126	0.202	0.221	0.215	0.227	0.216	0.011	0.773	0.819	0.796	0.032	0.040	2.844	2.928	1.937	1.644
128	0.205	0.218	0.211	0.224	0.214	0.008	0.773	0.819	0.796	0.032	0.030	2.868	2.952	1.950	1.664
130	0.202	0.214	0.208	0.220	0.211	0.008	0.773	0.819	0.796	0.032	0.030	2.913	2.999	1.980	1.690
132	0.199	0.211	0.205	0.217	0.208	0.008	0.773	0.819	0.796	0.032	0.030	2.958	3.045	2.011	1.716
134	0.196	0.214	0.202	0.214	0.206	0.009	0.752	0.796	0.774	0.031	0.034	2.898	2.983	1.972	1.679
136	0.193	0.211	0.199	0.216	0.205	0.011	0.752	0.818	0.785	0.047	0.042	2.920	3.049	2.004	1.701
138	0.190	0.208	0.196	0.213	0.202	0.011	0.752	0.818	0.785	0.047	0.042	2.963	3.094	2.033	1.726
140	0.193	0.205	0.193	0.210	0.200	0.009	0.752	0.818	0.785	0.047	0.034	2.985	3.117	2.045	1.743
142	0.191	0.202	0.196	0.207	0.199	0.007	0.774	0.818	0.796	0.031	0.029	3.095	3.183	2.102	1.796
144	0.188	0.199	0.193	0.204	0.196	0.007	0.774	0.818	0.796	0.031	0.029	3.138	3.228	2.132	1.822
146	0.185	0.196	0.191	0.207	0.195	0.009	0.774	0.840	0.807	0.047	0.038	3.160	3.295	2.164	1.843
148	0.183	0.199	0.188	0.204	0.194	0.010	0.753	0.817	0.785	0.046	0.040	3.095	3.227	2.121	1.803
150	0.180	0.196	0.186	0.202	0.191	0.010	0.753	0.817	0.785	0.046	0.040	3.136	3.271	2.149	1.828
152	0.183	0.194	0.183	0.199	0.190	0.008	0.753	0.817	0.785	0.046	0.033	3.156	3.292	2.160	1.844
154	0.181	0.191	0.181	0.196	0.187	0.008	0.753	0.817	0.785	0.046	0.033	3.198	3.335	2.189	1.868

Table D1 (continued)

	0.45 µm						2.5 µm				8 µm				
	Flux (L/sec/m^2)						Flux (L/sec/m^2)				Flux (L/sec/m^2)				
time,s.	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**	**Set1**	**Set2**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Average**	**Std.**
158	0.176	0.186	0.176	0.191	0.183	0.008	0.753	0.817	0.785	0.046	0.033	3.281	3.422	2.245	1.917
160	0.174	0.184	0.179	0.194	0.183	0.008	0.774	0.839	0.807	0.046	0.037	3.371	3.511	2.306	1.967
162	0.172	0.182	0.177	0.192	0.181	0.008	0.774	0.839	0.807	0.046	0.037	3.413	3.555	2.335	1.992
164	0.175	0.180	0.175	0.189	0.180	0.007	0.774	0.839	0.807	0.046	0.030	3.432	3.575	2.346	2.006
166	0.173	0.182	0.173	0.187	0.179	0.007	0.754	0.817	0.785	0.044	0.032	3.360	3.500	2.297	1.963
168	0.171	0.180	0.171	0.185	0.176	0.007	0.754	0.817	0.785	0.044	0.032	3.400	3.542	2.325	1.987
170	0.169	0.178	0.169	0.183	0.174	0.007	0.754	0.817	0.785	0.044	0.032	3.441	3.584	2.352	2.011
172	0.167	0.176	0.167	0.180	0.172	0.007	0.754	0.817	0.785	0.044	0.032	3.481	3.626	2.380	2.034
174	0.165	0.174	0.165	0.183	0.172	0.009	0.754	0.838	0.796	0.059	0.041	3.498	3.692	2.410	2.055
176	0.163	0.172	0.163	0.181	0.170	0.009	0.754	0.838	0.796	0.059	0.041	3.538	3.735	2.438	2.078
178	0.165	0.170	0.165	0.179	0.170	0.006	0.775	0.838	0.806	0.044	0.030	3.629	3.777	2.479	2.122
180	0.164	0.168	0.164	0.177	0.168	0.006	0.775	0.838	0.806	0.044	0.030	3.670	3.819	2.506	2.146
182	0.162	0.171	0.162	0.175	0.167	0.007	0.755	0.816	0.786	0.043	0.031	3.592	3.738	2.454	2.099
184	0.160	0.169	0.160	0.173	0.165	0.006	0.755	0.816	0.786	0.043	0.031	3.632	3.779	2.481	2.123
186	0.158	0.167	0.158	0.171	0.164	0.006	0.755	0.816	0.786	0.043	0.031	3.671	3.820	2.507	2.146
188	0.157	0.165	0.157	0.169	0.162	0.006	0.755	0.816	0.786	0.043	0.031	3.711	3.861	2.534	2.169
190	0.159	0.163	0.155	0.168	0.161	0.005	0.755	0.816	0.786	0.043	0.027	3.726	3.877	2.543	2.181
192	0.157	0.162	0.153	0.170	0.161	0.007	0.755	0.837	0.796	0.058	0.035	3.741	3.943	2.573	2.200
194	0.156	0.160	0.152	0.168	0.159	0.007	0.755	0.837	0.796	0.058	0.035	3.780	3.984	2.600	2.223

Table D1 (continued)

	0.45 μm						2.5 μm				8 μm				
	Flux (L/sec/m^2)						Flux (L/sec/m^2)				Flux (L/sec/m^2)				
time,s.	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**	**Set1**	**Set2**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Average**	**Std.**
198	0.153	0.157	0.149	0.165	0.156	0.007	0.755	0.837	0.796	0.058	0.035	3.858	4.066	2.653	2.270
200	0.151	0.159	0.147	0.163	0.155	0.007	0.736	0.816	0.776	0.056	0.037	3.775	3.979	2.597	2.219
202	0.154	0.158	0.146	0.162	0.155	0.007	0.736	0.816	0.776	0.056	0.035	3.788	3.993	2.605	2.229
204	0.152	0.156	0.148	0.160	0.154	0.005	0.756	0.816	0.786	0.042	0.026	3.904	4.058	2.663	2.285
206	0.151	0.155	0.147	0.162	0.154	0.007	0.756	0.836	0.796	0.056	0.034	3.918	4.124	2.692	2.304
208	0.149	0.153	0.145	0.161	0.152	0.007	0.756	0.836	0.796	0.056	0.034	3.956	4.164	2.718	2.327
210	0.148	0.152	0.144	0.159	0.151	0.006	0.756	0.836	0.796	0.056	0.034	3.994	4.204	2.744	2.349
212	0.146	0.150	0.143	0.158	0.149	0.006	0.756	0.836	0.796	0.056	0.034	4.032	4.244	2.770	2.372
214	0.145	0.149	0.141	0.156	0.148	0.006	0.756	0.836	0.796	0.056	0.034	4.070	4.284	2.796	2.394
216	0.147	0.147	0.140	0.155	0.147	0.006	0.756	0.836	0.796	0.056	0.032	4.082	4.297	2.804	2.403
218	0.146	0.146	0.139	0.153	0.146	0.006	0.756	0.836	0.796	0.056	0.032	4.120	4.337	2.830	2.425
220	0.145	0.148	0.137	0.152	0.146	0.006	0.738	0.815	0.776	0.055	0.034	4.031	4.243	2.770	2.372
222	0.143	0.147	0.136	0.151	0.144	0.006	0.738	0.815	0.776	0.055	0.034	4.068	4.282	2.795	2.393
224	0.142	0.146	0.135	0.153	0.144	0.007	0.738	0.835	0.786	0.069	0.041	4.079	4.348	2.823	2.413
226	0.141	0.144	0.134	0.151	0.143	0.007	0.738	0.835	0.786	0.069	0.041	4.116	4.386	2.848	2.435
228	0.140	0.143	0.136	0.150	0.142	0.006	0.757	0.835	0.796	0.055	0.033	4.235	4.452	2.907	2.491
230	0.142	0.142	0.135	0.149	0.142	0.006	0.757	0.835	0.796	0.055	0.032	4.246	4.464	2.914	2.499
232	0.141	0.141	0.134	0.147	0.141	0.006	0.757	0.835	0.796	0.055	0.032	4.283	4.503	2.939	2.520
234	0.139	0.139	0.133	0.146	0.139	0.006	0.757	0.835	0.796	0.055	0.032	4.320	4.542	2.965	2.542

Table D1 (continued)

	0.45 µm						2.5 µm				8 µm				
	Flux (L/sec/m^2)						Flux (L/sec/m^2)				Flux (L/sec/m^2)				
time,s.	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**	**Set1**	**Set2**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Average**	**Std.**
238	0.137	0.140	0.130	0.147	0.139	0.007	0.739	0.834	0.786	0.067	0.040	4.238	4.509	2.929	2.506
240	0.136	0.139	0.129	0.146	0.138	0.007	0.739	0.834	0.786	0.067	0.040	4.273	4.547	2.954	2.527
242	0.135	0.138	0.128	0.145	0.136	0.007	0.739	0.834	0.786	0.067	0.040	4.309	4.585	2.978	2.548
244	0.134	0.137	0.127	0.144	0.135	0.007	0.739	0.834	0.786	0.067	0.040	4.345	4.623	3.003	2.569
246	0.136	0.136	0.126	0.142	0.135	0.007	0.739	0.834	0.786	0.067	0.039	4.354	4.633	3.009	2.575
248	0.135	0.135	0.125	0.141	0.134	0.007	0.739	0.834	0.786	0.067	0.039	4.389	4.671	3.033	2.597
250	0.134	0.134	0.124	0.140	0.133	0.007	0.739	0.834	0.786	0.067	0.039	4.425	4.708	3.057	2.618
252	0.133	0.133	0.126	0.139	0.133	0.005	0.758	0.834	0.796	0.054	0.031	4.547	4.775	3.118	2.676
254	0.132	0.132	0.125	0.141	0.132	0.006	0.758	0.853	0.805	0.067	0.039	4.556	4.841	3.145	2.694
256	0.131	0.131	0.124	0.140	0.131	0.006	0.758	0.853	0.805	0.067	0.039	4.592	4.879	3.170	2.715
258	0.130	0.130	0.123	0.139	0.130	0.006	0.758	0.853	0.805	0.067	0.039	4.628	4.917	3.195	2.737
260	0.129	0.132	0.122	0.138	0.130	0.006	0.740	0.833	0.787	0.065	0.039	4.529	4.812	3.126	2.678
262	0.128	0.131	0.121	0.137	0.129	0.006	0.740	0.833	0.787	0.065	0.039	4.563	4.849	3.150	2.698
264	0.130	0.130	0.121	0.136	0.129	0.006	0.740	0.833	0.787	0.065	0.038	4.571	4.857	3.156	2.703
266	0.129	0.129	0.120	0.135	0.128	0.006	0.740	0.833	0.787	0.065	0.038	4.606	4.894	3.179	2.724
268	0.128	0.128	0.119	0.134	0.127	0.006	0.740	0.833	0.787	0.065	0.038	4.641	4.931	3.203	2.745
270	0.127	0.127	0.118	0.133	0.126	0.006	0.740	0.833	0.787	0.065	0.038	4.675	4.968	3.227	2.765
272	0.126	0.126	0.117	0.132	0.125	0.006	0.740	0.833	0.787	0.065	0.038	4.710	5.004	3.251	2.786
274	0.125	0.125	0.116	0.131	0.124	0.006	0.740	0.833	0.787	0.065	0.038	4.745	5.041	3.275	2.807

Table D1 (continued)

	0.45 μm Flux (L/sec/m^2)						2.5 μm Flux (L/sec/m^2)				8 μm Flux (L/sec/m^2)				
time,s.	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**	**Set1**	**Set2**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Average**	**Std.**
276	0.124	0.124	0.118	0.133	0.125	0.006	0.759	0.851	0.805	0.065	0.038	4.842	5.137	3.339	2.863
278	0.123	0.123	0.117	0.132	0.124	0.006	0.759	0.851	0.805	0.065	0.038	4.877	5.175	3.363	2.884
280	0.125	0.125	0.117	0.131	0.124	0.006	0.742	0.832	0.787	0.064	0.037	4.746	5.035	3.273	2.806
282	0.124	0.124	0.116	0.130	0.123	0.006	0.742	0.832	0.787	0.064	0.037	4.780	5.071	3.296	2.826
284	0.123	0.123	0.115	0.129	0.123	0.006	0.742	0.832	0.787	0.064	0.037	4.814	5.107	3.319	2.846
286	0.122	0.122	0.114	0.128	0.122	0.006	0.742	0.832	0.787	0.064	0.037	4.847	5.143	3.343	2.866
288	0.122	0.122	0.113	0.127	0.121	0.006	0.742	0.832	0.787	0.064	0.037	4.881	5.179	3.366	2.886
290	0.121	0.121	0.113	0.126	0.120	0.006	0.742	0.832	0.787	0.064	0.037	4.915	5.215	3.389	2.907
292	0.120	0.120	0.112	0.125	0.119	0.006	0.742	0.832	0.787	0.064	0.037	4.949	5.251	3.412	2.927
294	0.119	0.119	0.111	0.125	0.118	0.006	0.742	0.832	0.787	0.064	0.037	4.983	5.287	3.436	2.947
296	0.121	0.118	0.110	0.126	0.119	0.007	0.742	0.850	0.796	0.077	0.045	4.960	5.323	3.443	2.948
298	0.120	0.117	0.109	0.126	0.118	0.007	0.742	0.850	0.796	0.077	0.045	4.994	5.359	3.466	2.968
300	0.119	0.117	0.109	0.125	0.117	0.007	0.742	0.850	0.796	0.077	0.045	5.027	5.395	3.489	2.988
302	0.119	0.119	0.111	0.124	0.118	0.005	0.743	0.831	0.787	0.063	0.037	5.012	5.311	3.453	2.963
304	0.118	0.118	0.110	0.123	0.117	0.005	0.743	0.831	0.787	0.063	0.037	5.046	5.346	3.476	2.982
306	0.117	0.117	0.109	0.122	0.116	0.005	0.743	0.831	0.787	0.063	0.037	5.079	5.381	3.499	3.002
308	0.116	0.116	0.109	0.121	0.116	0.005	0.743	0.831	0.787	0.063	0.037	5.112	5.416	3.522	3.022
310	0.116	0.116	0.108	0.121	0.115	0.005	0.743	0.831	0.787	0.063	0.037	5.145	5.451	3.544	3.042
312	0.115	0.115	0.107	0.120	0.114	0.005	0.743	0.831	0.787	0.063	0.037	5.178	5.487	3.567	3.061

Table D1 (continued)

	0.45 µm Flux (L/sec/m^2)						2.5 µm Flux (L/sec/m^2)				8 µm Flux (L/sec/m^2)				
time,s.	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**	**Set1**	**Set2**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Average**	**Std.**
316	0.116	0.113	0.106	0.121	0.114	0.006	0.743	0.849	0.796	0.075	0.044	5.187	5.557	3.596	3.082
318	0.115	0.113	0.105	0.120	0.113	0.006	0.743	0.849	0.796	0.075	0.044	5.220	5.592	3.619	3.101
320	0.114	0.112	0.104	0.119	0.113	0.006	0.743	0.849	0.796	0.075	0.044	5.252	5.628	3.641	3.121
322	0.114	0.111	0.104	0.119	0.112	0.006	0.743	0.849	0.796	0.075	0.044	5.285	5.663	3.664	3.141
324	0.113	0.113	0.106	0.118	0.112	0.005	0.744	0.830	0.787	0.061	0.036	5.268	5.574	3.626	3.113
326	0.112	0.112	0.105	0.117	0.112	0.005	0.744	0.830	0.787	0.061	0.036	5.301	5.609	3.648	3.132
328	0.112	0.112	0.104	0.116	0.111	0.005	0.744	0.830	0.787	0.061	0.036	5.333	5.643	3.671	3.152
330	0.111	0.111	0.104	0.116	0.110	0.005	0.744	0.830	0.787	0.061	0.036	5.366	5.678	3.693	3.171
332	0.113	0.110	0.103	0.115	0.110	0.005	0.744	0.830	0.787	0.061	0.037	5.369	5.681	3.696	3.172
334	0.112	0.110	0.102	0.117	0.110	0.006	0.744	0.848	0.796	0.073	0.043	5.372	5.747	3.721	3.190
336	0.111	0.109	0.102	0.116	0.110	0.006	0.744	0.848	0.796	0.073	0.043	5.404	5.781	3.743	3.210
338	0.111	0.108	0.101	0.115	0.109	0.006	0.744	0.848	0.796	0.073	0.043	5.436	5.816	3.765	3.229
340	0.110	0.108	0.101	0.115	0.108	0.006	0.744	0.848	0.796	0.073	0.043	5.468	5.850	3.787	3.248
342	0.109	0.107	0.100	0.114	0.108	0.006	0.744	0.848	0.796	0.073	0.043	5.501	5.884	3.809	3.267
344	0.109	0.106	0.099	0.113	0.107	0.006	0.744	0.848	0.796	0.073	0.043	5.533	5.919	3.832	3.287
346	0.108	0.108	0.099	0.113	0.107	0.006	0.728	0.830	0.779	0.072	0.043	5.417	5.795	3.752	3.217
348	0.107	0.107	0.098	0.112	0.106	0.006	0.728	0.830	0.779	0.072	0.043	5.449	5.829	3.773	3.236
350	0.107	0.107	0.098	0.111	0.106	0.006	0.728	0.830	0.779	0.072	0.043	5.480	5.862	3.795	3.255
352	0.109	0.106	0.099	0.111	0.106	0.005	0.745	0.830	0.787	0.060	0.037	5.579	5.896	3.837	3.295

Table D1 (continued)

	0.45 µm						2.5 µm				8 µm				
	Flux (L/sec/m^2)						Flux (L/sec/m^2)				Flux (L/sec/m^2)				
time,s.	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**	**Set1**	**Set2**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Average**	**Std.**
354	0.108	0.106	0.099	0.110	0.106	0.005	0.745	0.830	0.787	0.060	0.037	5.611	5.930	3.859	3.314
356	0.107	0.105	0.098	0.110	0.105	0.005	0.745	0.830	0.787	0.060	0.037	5.643	5.963	3.881	3.333
358	0.107	0.104	0.098	0.111	0.105	0.006	0.745	0.847	0.796	0.072	0.042	5.645	6.029	3.905	3.351
360	0.106	0.104	0.097	0.111	0.104	0.006	0.745	0.847	0.796	0.072	0.042	5.676	6.063	3.927	3.370
362	0.106	0.103	0.097	0.110	0.104	0.005	0.745	0.847	0.796	0.072	0.042	5.708	6.097	3.949	3.389
364	0.105	0.103	0.096	0.109	0.103	0.005	0.745	0.847	0.796	0.072	0.042	5.739	6.130	3.971	3.408
366	0.104	0.102	0.096	0.109	0.103	0.005	0.745	0.847	0.796	0.072	0.042	5.771	6.164	3.992	3.427
368	0.104	0.102	0.095	0.108	0.102	0.005	0.745	0.847	0.796	0.072	0.042	5.802	6.198	4.014	3.445
370	0.103	0.103	0.095	0.108	0.102	0.005	0.729	0.829	0.779	0.070	0.042	5.682	6.070	3.931	3.374
372	0.105	0.103	0.094	0.107	0.102	0.006	0.729	0.829	0.779	0.070	0.044	5.683	6.070	3.932	3.373
374	0.104	0.102	0.094	0.106	0.102	0.006	0.729	0.829	0.779	0.070	0.044	5.713	6.103	3.953	3.391
376	0.104	0.102	0.093	0.106	0.101	0.006	0.729	0.829	0.779	0.070	0.044	5.744	6.136	3.975	3.410
378	0.103	0.101	0.093	0.105	0.101	0.006	0.729	0.829	0.779	0.070	0.044	5.775	6.168	3.996	3.428
380	0.103	0.101	0.092	0.107	0.101	0.006	0.729	0.846	0.787	0.082	0.049	5.775	6.234	4.019	3.446
384	0.102	0.099	0.093	0.106	0.100	0.005	0.746	0.846	0.796	0.070	0.041	5.937	6.333	4.104	3.524
386	0.101	0.099	0.093	0.105	0.099	0.005	0.746	0.846	0.796	0.070	0.041	5.968	6.366	4.125	3.542
388	0.100	0.098	0.092	0.105	0.099	0.005	0.746	0.846	0.796	0.070	0.041	5.999	6.399	4.147	3.561
390	0.100	0.098	0.092	0.104	0.098	0.005	0.746	0.846	0.796	0.070	0.041	6.030	6.432	4.168	3.579
392	0.102	0.097	0.091	0.104	0.098	0.005	0.746	0.846	0.796	0.070	0.043	6.030	6.432	4.168	3.578

Table D1 (continued)

	0.45 µm						2.5 µm				8 µm				
	Flux (L/sec/m^2)						Flux (L/sec/m^2)				Flux (L/sec/m^2)				
time,s.	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**	**Set1**	**Set2**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Average**	**Std.**
394	0.101	0.099	0.091	0.103	0.098	0.005	0.731	0.828	0.780	0.069	0.043	5.906	6.300	4.083	3.505
396	0.100	0.098	0.090	0.102	0.098	0.005	0.731	0.828	0.780	0.069	0.043	5.936	6.332	4.104	3.522
398	0.100	0.098	0.090	0.102	0.097	0.005	0.731	0.828	0.780	0.069	0.043	5.966	6.364	4.125	3.540
400	0.099	0.097	0.090	0.101	0.097	0.005	0.731	0.828	0.780	0.069	0.043	5.996	6.396	4.145	3.558
402	0.099	0.097	0.089	0.101	0.097	0.005	0.731	0.828	0.780	0.069	0.043	6.026	6.428	4.166	3.576
404	0.098	0.097	0.089	0.102	0.097	0.006	0.731	0.844	0.788	0.080	0.048	6.025	6.494	4.189	3.594
406	0.098	0.096	0.088	0.102	0.096	0.006	0.731	0.844	0.788	0.080	0.048	6.055	6.526	4.210	3.612
408	0.098	0.096	0.090	0.101	0.096	0.005	0.747	0.844	0.796	0.069	0.040	6.189	6.592	4.274	3.672
410	0.097	0.095	0.089	0.101	0.096	0.005	0.747	0.844	0.796	0.069	0.040	6.219	6.625	4.295	3.690
412	0.099	0.095	0.089	0.100	0.096	0.005	0.747	0.844	0.796	0.069	0.043	6.218	6.623	4.295	3.688
414	0.098	0.094	0.088	0.100	0.095	0.005	0.747	0.844	0.796	0.069	0.043	6.248	6.656	4.315	3.706
416	0.098	0.096	0.088	0.099	0.095	0.005	0.732	0.828	0.780	0.068	0.042	6.122	6.521	4.228	3.631
418	0.097	0.095	0.088	0.099	0.095	0.005	0.732	0.828	0.780	0.068	0.042	6.151	6.552	4.249	3.648
420	0.097	0.095	0.087	0.099	0.094	0.005	0.732	0.828	0.780	0.068	0.042	6.181	6.584	4.269	3.666
422	0.096	0.094	0.087	0.098	0.094	0.005	0.732	0.828	0.780	0.068	0.042	6.210	6.615	4.289	3.684
424	0.096	0.094	0.086	0.098	0.093	0.005	0.732	0.828	0.780	0.068	0.042	6.240	6.646	4.309	3.701
428	0.095	0.093	0.086	0.099	0.093	0.005	0.732	0.844	0.788	0.079	0.047	6.267	6.744	4.352	3.736
430	0.094	0.093	0.085	0.098	0.093	0.005	0.732	0.844	0.788	0.079	0.047	6.296	6.775	4.373	3.754
432	0.096	0.092	0.085	0.098	0.093	0.006	0.732	0.844	0.788	0.079	0.049	6.294	6.773	4.372	3.751

Table D1 (continued)

	0.45 μm						2.5 μm				8 μm				
	Flux (L/sec/m^2)						Flux (L/sec/m^2)				Flux (L/sec/m^2)				
time,s.	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**	**Set1**	**Set2**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Average**	**Std.**
438	0.094	0.091	0.085	0.096	0.092	0.005	0.748	0.844	0.796	0.068	0.042	6.488	6.902	4.477	3.847
440	0.094	0.090	0.085	0.096	0.091	0.005	0.748	0.844	0.796	0.068	0.042	6.517	6.933	4.498	3.864
442	0.094	0.090	0.085	0.095	0.091	0.005	0.748	0.844	0.796	0.068	0.042	6.547	6.965	4.518	3.882
444	0.093	0.091	0.084	0.095	0.091	0.005	0.733	0.827	0.780	0.066	0.041	6.416	6.826	4.428	3.804
446	0.093	0.091	0.084	0.095	0.091	0.005	0.733	0.827	0.780	0.066	0.041	6.445	6.856	4.447	3.821
448	0.092	0.091	0.083	0.094	0.090	0.005	0.733	0.827	0.780	0.066	0.041	6.474	6.887	4.467	3.839
452	0.092	0.090	0.083	0.095	0.090	0.005	0.733	0.843	0.788	0.077	0.046	6.500	6.984	4.510	3.873
454	0.093	0.089	0.082	0.095	0.090	0.005	0.733	0.843	0.788	0.077	0.048	6.497	6.980	4.508	3.870
456	0.092	0.089	0.082	0.094	0.089	0.005	0.733	0.843	0.788	0.077	0.048	6.525	7.011	4.528	3.887
458	0.092	0.089	0.082	0.094	0.089	0.005	0.733	0.843	0.788	0.077	0.048	6.554	7.042	4.548	3.905
460	0.092	0.088	0.081	0.093	0.089	0.005	0.733	0.843	0.788	0.077	0.048	6.582	7.073	4.568	3.922
462	0.091	0.088	0.081	0.093	0.088	0.005	0.733	0.843	0.788	0.077	0.048	6.611	7.103	4.587	3.939
464	0.091	0.087	0.081	0.093	0.088	0.005	0.733	0.843	0.788	0.077	0.048	6.640	7.134	4.607	3.956
466	0.091	0.087	0.080	0.092	0.088	0.005	0.733	0.843	0.788	0.077	0.048	6.668	7.165	4.627	3.973
468	0.090	0.088	0.082	0.092	0.088	0.004	0.735	0.826	0.780	0.065	0.040	6.643	7.058	4.581	3.937
470	0.090	0.088	0.081	0.091	0.088	0.004	0.735	0.826	0.780	0.065	0.040	6.671	7.088	4.600	3.954
472	0.089	0.088	0.081	0.091	0.087	0.004	0.735	0.826	0.780	0.065	0.040	6.700	7.119	4.620	3.971
474	0.091	0.087	0.081	0.091	0.087	0.005	0.735	0.826	0.780	0.065	0.043	6.696	7.114	4.618	3.967
476	0.090	0.087	0.080	0.090	0.087	0.005	0.735	0.826	0.780	0.065	0.043	6.724	7.144	4.637	3.984

Table D1 (continued)

	0.45 μm						2.5 μm				8 μm				
	Flux (L/sec/m^2)						Flux (L/sec/m^2)				Flux (L/sec/m^2)				
time,s.	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**	**Set1**	**Set2**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Average**	**Std.**
478	0.090	0.087	0.080	0.092	0.087	0.005	0.735	0.842	0.788	0.076	0.047	6.720	7.210	4.659	4.002
480	0.090	0.086	0.080	0.091	0.087	0.005	0.735	0.842	0.788	0.076	0.047	6.748	7.240	4.678	4.018
482	0.089	0.086	0.079	0.091	0.086	0.005	0.735	0.842	0.788	0.076	0.047	6.776	7.270	4.698	4.035
484	0.089	0.085	0.079	0.090	0.086	0.005	0.735	0.842	0.788	0.076	0.047	6.804	7.301	4.717	4.052
486	0.088	0.085	0.079	0.090	0.086	0.005	0.735	0.842	0.788	0.076	0.047	6.832	7.331	4.737	4.069
488	0.088	0.085	0.078	0.090	0.085	0.005	0.735	0.842	0.788	0.076	0.047	6.861	7.361	4.756	4.086
490	0.088	0.084	0.078	0.089	0.085	0.005	0.735	0.842	0.788	0.076	0.047	6.889	7.391	4.776	4.103
492	0.087	0.084	0.078	0.089	0.085	0.005	0.735	0.842	0.788	0.076	0.047	6.917	7.421	4.795	4.120
496	0.088	0.085	0.077	0.088	0.085	0.005	0.721	0.826	0.773	0.074	0.050	6.777	7.271	4.699	4.034
498	0.088	0.085	0.077	0.088	0.084	0.005	0.721	0.826	0.773	0.074	0.050	6.804	7.300	4.718	4.050
500	0.088	0.084	0.078	0.088	0.084	0.005	0.736	0.826	0.781	0.064	0.042	6.941	7.366	4.783	4.111
502	0.087	0.084	0.078	0.087	0.084	0.004	0.736	0.826	0.781	0.064	0.042	6.968	7.395	4.802	4.127
504	0.087	0.084	0.077	0.087	0.084	0.004	0.736	0.826	0.781	0.064	0.042	6.996	7.425	4.821	4.144
506	0.086	0.083	0.077	0.088	0.084	0.005	0.736	0.841	0.788	0.074	0.046	6.991	7.490	4.843	4.161
508	0.086	0.083	0.077	0.088	0.083	0.005	0.736	0.841	0.788	0.074	0.046	7.019	7.520	4.862	4.178
510	0.086	0.083	0.076	0.087	0.083	0.005	0.736	0.841	0.788	0.074	0.046	7.046	7.550	4.881	4.194
512	0.085	0.082	0.076	0.087	0.083	0.005	0.736	0.841	0.788	0.074	0.046	7.074	7.579	4.900	4.211
514	0.085	0.082	0.076	0.087	0.082	0.005	0.736	0.841	0.788	0.074	0.046	7.102	7.609	4.919	4.227
516	0.085	0.082	0.076	0.086	0.082	0.005	0.736	0.841	0.788	0.074	0.046	7.129	7.638	4.938	4.244

Table D1 (continued)

	0.45 μm						2.5 μm				8 μm				
	Flux ($L/sec/m^2$)						Flux ($L/sec/m^2$)				Flux ($L/sec/m^2$)				
time,s.	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**	**Set1**	**Set2**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Average**	**Std.**
518	0.084	0.081	0.075	0.086	0.082	0.005	0.736	0.841	0.788	0.074	0.046	7.157	7.668	4.957	4.261
520	0.086	0.081	0.075	0.086	0.082	0.005	0.736	0.841	0.788	0.074	0.049	7.151	7.662	4.954	4.255
522	0.085	0.081	0.075	0.085	0.082	0.005	0.736	0.841	0.788	0.074	0.049	7.178	7.691	4.973	4.272
524	0.085	0.082	0.074	0.085	0.082	0.005	0.722	0.825	0.774	0.073	0.049	7.040	7.542	4.877	4.189
526	0.085	0.082	0.076	0.085	0.082	0.004	0.737	0.825	0.781	0.063	0.042	7.177	7.608	4.942	4.249
528	0.084	0.081	0.075	0.084	0.081	0.004	0.737	0.825	0.781	0.063	0.042	7.205	7.637	4.961	4.266
530	0.084	0.081	0.075	0.084	0.081	0.004	0.737	0.825	0.781	0.063	0.042	7.232	7.666	4.980	4.282
532	0.084	0.081	0.075	0.084	0.081	0.004	0.737	0.825	0.781	0.063	0.042	7.259	7.695	4.998	4.298
534	0.083	0.080	0.075	0.083	0.080	0.004	0.737	0.825	0.781	0.063	0.042	7.286	7.724	5.017	4.314
536	0.083	0.080	0.074	0.083	0.080	0.004	0.737	0.825	0.781	0.063	0.042	7.314	7.753	5.036	4.331
538	0.083	0.080	0.074	0.083	0.080	0.004	0.737	0.825	0.781	0.063	0.042	7.341	7.781	5.055	4.347
540	0.083	0.080	0.074	0.083	0.080	0.004	0.737	0.825	0.781	0.063	0.042	7.368	7.810	5.073	4.363
542	0.082	0.079	0.073	0.084	0.080	0.005	0.737	0.840	0.788	0.073	0.045	7.361	7.877	5.095	4.380
544	0.082	0.079	0.073	0.083	0.079	0.005	0.737	0.840	0.788	0.073	0.045	7.389	7.906	5.113	4.397
546	0.083	0.079	0.073	0.083	0.079	0.005	0.737	0.840	0.788	0.073	0.048	7.382	7.899	5.110	4.391
550	0.082	0.078	0.072	0.082	0.079	0.005	0.737	0.840	0.788	0.073	0.048	7.436	7.956	5.147	4.423
552	0.082	0.078	0.072	0.082	0.079	0.005	0.737	0.840	0.788	0.073	0.048	7.463	7.985	5.166	4.439
554	0.082	0.079	0.072	0.082	0.079	0.005	0.723	0.825	0.774	0.072	0.048	7.320	7.833	5.067	4.354
556	0.082	0.079	0.073	0.082	0.079	0.004	0.738	0.825	0.781	0.061	0.041	7.460	7.898	5.133	4.415

Table D1 (continued)

	0.45 µm						2.5 µm				8 µm				
	Flux (L/sec/m^2)						Flux (L/sec/m^2)				Flux (L/sec/m^2)				
time,s.	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**	**Set1**	**Set2**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Average**	**Std.**
558	0.081	0.078	0.073	0.081	0.078	0.004	0.738	0.825	0.781	0.061	0.041	7.486	7.927	5.151	4.431
560	0.081	0.078	0.072	0.081	0.078	0.004	0.738	0.825	0.781	0.061	0.041	7.513	7.955	5.170	4.447
562	0.081	0.078	0.072	0.081	0.078	0.004	0.738	0.825	0.781	0.061	0.041	7.540	7.984	5.188	4.463
564	0.080	0.078	0.072	0.080	0.078	0.004	0.738	0.825	0.781	0.061	0.041	7.567	8.012	5.207	4.479
568	0.080	0.077	0.071	0.081	0.077	0.004	0.738	0.839	0.789	0.072	0.045	7.586	8.107	5.246	4.512
570	0.081	0.077	0.071	0.081	0.077	0.005	0.738	0.839	0.789	0.072	0.048	7.578	8.099	5.242	4.506
572	0.081	0.077	0.071	0.081	0.077	0.005	0.738	0.839	0.789	0.072	0.048	7.605	8.127	5.260	4.522
574	0.080	0.076	0.071	0.080	0.077	0.005	0.738	0.839	0.789	0.072	0.048	7.632	8.155	5.278	4.537
576	0.080	0.076	0.070	0.080	0.077	0.005	0.738	0.839	0.789	0.072	0.048	7.658	8.184	5.297	4.553
578	0.080	0.076	0.070	0.080	0.076	0.005	0.738	0.839	0.789	0.072	0.048	7.685	8.212	5.315	4.569
580	0.080	0.075	0.070	0.080	0.076	0.005	0.738	0.839	0.789	0.072	0.048	7.711	8.241	5.333	4.585
582	0.079	0.075	0.070	0.079	0.076	0.005	0.738	0.839	0.789	0.072	0.048	7.738	8.269	5.352	4.601
584	0.079	0.076	0.069	0.079	0.076	0.005	0.725	0.824	0.774	0.070	0.047	7.592	8.113	5.251	4.514
586	0.079	0.076	0.069	0.079	0.076	0.004	0.725	0.824	0.774	0.070	0.047	7.618	8.141	5.268	4.529
588	0.078	0.076	0.069	0.078	0.075	0.004	0.725	0.824	0.774	0.070	0.047	7.644	8.168	5.286	4.545
590	0.078	0.076	0.070	0.078	0.076	0.004	0.739	0.824	0.782	0.060	0.040	7.785	8.234	5.353	4.607
592	0.079	0.075	0.070	0.078	0.076	0.004	0.739	0.824	0.782	0.060	0.044	7.777	8.226	5.349	4.600
594	0.079	0.075	0.070	0.078	0.075	0.004	0.739	0.824	0.782	0.060	0.044	7.803	8.253	5.367	4.615
596	0.079	0.075	0.069	0.079	0.075	0.004	0.739	0.838	0.789	0.070	0.047	7.795	8.319	5.387	4.632

Table D1 (continued)

	0.45 µm						2.5 µm				8 µm				
	Flux (L/sec/m^2)						Flux (L/sec/m^2)				Flux (L/sec/m^2)				
time,s.	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**	**Set1**	**Set2**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Average**	**Std.**
598	0.079	0.075	0.069	0.079	0.075	0.004	0.739	0.838	0.789	0.070	0.047	7.821	8.347	5.405	4.648
600	0.078	0.074	0.069	0.078	0.075	0.004	0.739	0.838	0.789	0.070	0.047	7.847	8.375	5.423	4.663
602	0.078	0.074	0.069	0.078	0.075	0.004	0.739	0.838	0.789	0.070	0.047	7.873	8.403	5.441	4.679
604	0.078	0.074	0.069	0.078	0.074	0.004	0.739	0.838	0.789	0.070	0.047	7.899	8.431	5.459	4.695
606	0.077	0.074	0.068	0.077	0.074	0.004	0.739	0.838	0.789	0.070	0.047	7.926	8.459	5.477	4.710
608	0.077	0.073	0.068	0.077	0.074	0.004	0.739	0.838	0.789	0.070	0.047	7.952	8.487	5.495	4.726
610	0.077	0.074	0.068	0.077	0.074	0.004	0.726	0.824	0.775	0.069	0.046	7.803	8.329	5.393	4.638
612	0.077	0.074	0.068	0.077	0.074	0.004	0.726	0.824	0.775	0.069	0.046	7.829	8.356	5.410	4.653
614	0.076	0.074	0.067	0.076	0.074	0.004	0.726	0.824	0.775	0.069	0.046	7.855	8.383	5.428	4.668
616	0.076	0.074	0.067	0.076	0.073	0.004	0.726	0.824	0.775	0.069	0.046	7.880	8.411	5.446	4.683
618	0.077	0.073	0.067	0.076	0.073	0.005	0.726	0.824	0.775	0.069	0.050	7.871	8.401	5.441	4.676
622	0.077	0.073	0.067	0.077	0.073	0.005	0.726	0.838	0.782	0.079	0.052	7.887	8.494	5.478	4.708
624	0.077	0.073	0.066	0.077	0.073	0.005	0.726	0.838	0.782	0.079	0.052	7.913	8.521	5.496	4.724
626	0.076	0.072	0.066	0.076	0.073	0.005	0.726	0.838	0.782	0.079	0.052	7.938	8.549	5.513	4.739
628	0.076	0.072	0.066	0.076	0.073	0.005	0.726	0.838	0.782	0.079	0.052	7.963	8.576	5.531	4.754
630	0.076	0.072	0.066	0.076	0.072	0.005	0.726	0.838	0.782	0.079	0.052	7.989	8.603	5.548	4.769
632	0.076	0.072	0.067	0.076	0.072	0.004	0.740	0.838	0.789	0.069	0.046	8.133	8.670	5.616	4.831
634	0.075	0.072	0.067	0.075	0.072	0.004	0.740	0.838	0.789	0.069	0.046	8.159	8.697	5.634	4.847
636	0.075	0.071	0.066	0.075	0.072	0.004	0.740	0.838	0.789	0.069	0.046	8.184	8.725	5.652	4.862

Table D1 (continued)

	0.45 μm						2.5 μm				8 μm				
	Flux (L/sec/m^2)						Flux (L/sec/m^2)				Flux (L/sec/m^2)				
time,s.	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**	**Set1**	**Set2**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Average**	**Std.**
638	0.075	0.071	0.066	0.075	0.072	0.004	0.740	0.838	0.789	0.069	0.046	8.210	8.752	5.669	4.878
640	0.075	0.071	0.066	0.075	0.071	0.004	0.740	0.838	0.789	0.069	0.046	8.236	8.780	5.687	4.893
642	0.074	0.072	0.066	0.074	0.072	0.004	0.727	0.823	0.775	0.068	0.046	8.084	8.618	5.582	4.802
644	0.074	0.072	0.065	0.074	0.071	0.004	0.727	0.823	0.775	0.068	0.046	8.109	8.645	5.600	4.818
646	0.075	0.071	0.065	0.074	0.071	0.004	0.727	0.823	0.775	0.068	0.049	8.099	8.634	5.594	4.810
650	0.075	0.071	0.065	0.073	0.071	0.004	0.727	0.823	0.775	0.068	0.049	8.149	8.688	5.629	4.840
652	0.074	0.071	0.065	0.073	0.071	0.004	0.727	0.823	0.775	0.068	0.049	8.174	8.714	5.646	4.855
654	0.074	0.071	0.064	0.073	0.071	0.004	0.727	0.823	0.775	0.068	0.049	8.200	8.741	5.663	4.870
656	0.074	0.070	0.064	0.073	0.070	0.004	0.727	0.823	0.775	0.068	0.049	8.225	8.768	5.680	4.885
658	0.074	0.070	0.064	0.074	0.070	0.005	0.727	0.837	0.782	0.078	0.052	8.214	8.834	5.700	4.901
660	0.074	0.070	0.064	0.074	0.070	0.005	0.727	0.837	0.782	0.078	0.052	8.239	8.861	5.717	4.916
662	0.073	0.070	0.064	0.073	0.070	0.005	0.727	0.837	0.782	0.078	0.052	8.264	8.888	5.735	4.931
664	0.073	0.070	0.064	0.073	0.070	0.005	0.727	0.837	0.782	0.078	0.052	8.289	8.915	5.752	4.946
666	0.073	0.069	0.065	0.073	0.070	0.004	0.741	0.837	0.789	0.068	0.045	8.435	8.981	5.820	5.009
668	0.073	0.069	0.064	0.073	0.070	0.004	0.741	0.837	0.789	0.068	0.045	8.460	9.008	5.838	5.024
670	0.072	0.069	0.064	0.072	0.069	0.004	0.741	0.837	0.789	0.068	0.045	8.485	9.035	5.855	5.039
672	0.073	0.070	0.064	0.072	0.070	0.004	0.728	0.823	0.776	0.067	0.048	8.296	8.833	5.726	4.924
674	0.073	0.070	0.064	0.072	0.070	0.004	0.728	0.823	0.776	0.067	0.048	8.320	8.860	5.743	4.939
676	0.073	0.069	0.064	0.072	0.069	0.004	0.728	0.823	0.776	0.067	0.048	8.345	8.886	5.760	4.954

Table D1 (continued)

	0.45 μm						2.5 μm				8 μm				
	Flux (L/sec/m^2)						Flux (L/sec/m^2)				Flux (L/sec/m^2)				
time,s.	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**	**Set1**	**Set2**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Average**	**Std.**
678	0.073	0.069	0.063	0.072	0.069	0.004	0.728	0.823	0.776	0.067	0.048	8.370	8.912	5.777	4.969
680	0.073	0.069	0.063	0.071	0.069	0.004	0.728	0.823	0.776	0.067	0.048	8.394	8.938	5.794	4.983
682	0.072	0.069	0.063	0.071	0.069	0.004	0.728	0.823	0.776	0.067	0.048	8.419	8.965	5.811	4.998
684	0.072	0.069	0.063	0.071	0.069	0.004	0.728	0.823	0.776	0.067	0.048	8.444	8.991	5.828	5.013
686	0.072	0.068	0.063	0.071	0.068	0.004	0.728	0.823	0.776	0.067	0.048	8.468	9.017	5.845	5.027
688	0.072	0.068	0.062	0.071	0.068	0.004	0.728	0.823	0.776	0.067	0.048	8.493	9.044	5.862	5.042
690	0.072	0.068	0.062	0.072	0.068	0.004	0.728	0.836	0.782	0.076	0.051	8.482	9.110	5.881	5.059
692	0.071	0.068	0.062	0.071	0.068	0.004	0.728	0.836	0.782	0.076	0.051	8.506	9.137	5.898	5.074
694	0.071	0.068	0.062	0.071	0.068	0.004	0.728	0.836	0.782	0.076	0.051	8.531	9.163	5.915	5.088
696	0.072	0.067	0.062	0.071	0.068	0.005	0.728	0.836	0.782	0.076	0.054	8.520	9.151	5.908	5.080
698	0.072	0.067	0.062	0.071	0.068	0.005	0.728	0.836	0.782	0.076	0.054	8.544	9.177	5.925	5.094
700	0.072	0.067	0.061	0.070	0.068	0.005	0.728	0.836	0.782	0.076	0.054	8.569	9.203	5.942	5.109
702	0.071	0.067	0.062	0.070	0.068	0.004	0.742	0.836	0.789	0.067	0.048	8.716	9.270	6.011	5.172
706	0.071	0.067	0.062	0.070	0.067	0.004	0.742	0.836	0.789	0.067	0.048	8.765	9.323	6.045	5.202
708	0.071	0.066	0.062	0.070	0.067	0.004	0.742	0.836	0.789	0.067	0.048	8.790	9.350	6.063	5.216
710	0.071	0.067	0.062	0.069	0.067	0.004	0.729	0.822	0.776	0.066	0.047	8.632	9.181	5.953	5.122
712	0.070	0.067	0.061	0.069	0.067	0.004	0.729	0.822	0.776	0.066	0.047	8.656	9.207	5.970	5.137
714	0.070	0.067	0.061	0.069	0.067	0.004	0.729	0.822	0.776	0.066	0.047	8.681	9.233	5.987	5.151
716	0.070	0.067	0.061	0.069	0.067	0.004	0.729	0.822	0.776	0.066	0.047	8.705	9.259	6.004	5.166

Table D1 (continued)

	0.45 µm						2.5 µm				8 µm				
	Flux (L/sec/m^2)						Flux (L/sec/m^2)				Flux (L/sec/m^2)				
time,s.	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**	**Set1**	**Set2**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Average**	**Std.**
718	0.070	0.066	0.061	0.069	0.066	0.004	0.729	0.822	0.776	0.066	0.047	8.729	9.285	6.020	5.180
720	0.070	0.066	0.061	0.069	0.066	0.004	0.729	0.822	0.776	0.066	0.047	8.754	9.311	6.037	5.195
722	0.069	0.066	0.061	0.068	0.066	0.004	0.729	0.822	0.776	0.066	0.047	8.778	9.336	6.054	5.209
724	0.069	0.066	0.060	0.068	0.066	0.004	0.729	0.822	0.776	0.066	0.047	8.802	9.362	6.071	5.224
726	0.070	0.066	0.060	0.068	0.066	0.004	0.729	0.822	0.776	0.066	0.051	8.790	9.349	6.063	5.214
728	0.070	0.066	0.060	0.068	0.066	0.004	0.729	0.822	0.776	0.066	0.051	8.814	9.375	6.080	5.229
730	0.070	0.065	0.060	0.068	0.066	0.004	0.729	0.822	0.776	0.066	0.051	8.838	9.401	6.097	5.243
732	0.070	0.065	0.060	0.068	0.066	0.004	0.729	0.836	0.783	0.075	0.053	8.826	9.468	6.116	5.260
734	0.069	0.065	0.060	0.068	0.066	0.004	0.729	0.836	0.783	0.075	0.053	8.850	9.494	6.132	5.274
736	0.069	0.065	0.059	0.068	0.065	0.004	0.729	0.836	0.783	0.075	0.053	8.874	9.519	6.149	5.289
738	0.069	0.065	0.059	0.068	0.065	0.004	0.729	0.836	0.783	0.075	0.053	8.898	9.545	6.166	5.303
740	0.069	0.065	0.060	0.068	0.065	0.004	0.743	0.836	0.789	0.066	0.047	9.047	9.613	6.236	5.367
742	0.069	0.065	0.060	0.068	0.065	0.004	0.731	0.822	0.776	0.065	0.046	8.886	9.442	6.125	5.271
744	0.068	0.065	0.060	0.067	0.065	0.004	0.731	0.822	0.776	0.065	0.046	8.910	9.467	6.141	5.286
748	0.068	0.065	0.060	0.067	0.065	0.004	0.731	0.822	0.776	0.065	0.046	8.958	9.518	6.174	5.314
750	0.068	0.065	0.059	0.067	0.065	0.004	0.731	0.822	0.776	0.065	0.046	8.982	9.544	6.191	5.328
752	0.069	0.065	0.059	0.067	0.065	0.004	0.731	0.822	0.776	0.065	0.050	8.969	9.530	6.183	5.319
754	0.069	0.064	0.059	0.066	0.065	0.004	0.731	0.822	0.776	0.065	0.050	8.993	9.555	6.200	5.333
756	0.068	0.064	0.059	0.066	0.064	0.004	0.731	0.822	0.776	0.065	0.050	9.017	9.581	6.216	5.347

Table D1 (continued)

	0.45 μm						2.5 μm				8 μm				
	Flux (L/sec/m^2)						Flux (L/sec/m^2)				Flux (L/sec/m^2)				
time,s.	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**	**Set1**	**Set2**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Average**	**Std.**
758	0.068	0.064	0.059	0.066	0.064	0.004	0.731	0.822	0.776	0.065	0.050	9.041	9.606	6.232	5.361
760	0.068	0.064	0.059	0.066	0.064	0.004	0.731	0.822	0.776	0.065	0.050	9.065	9.631	6.249	5.376
762	0.068	0.064	0.058	0.066	0.064	0.004	0.731	0.822	0.776	0.065	0.050	9.089	9.657	6.265	5.390
764	0.068	0.064	0.058	0.066	0.064	0.004	0.731	0.822	0.776	0.065	0.050	9.112	9.682	6.282	5.404
766	0.068	0.063	0.058	0.066	0.064	0.004	0.731	0.835	0.783	0.074	0.052	9.099	9.749	6.300	5.421
768	0.067	0.063	0.058	0.066	0.064	0.004	0.731	0.835	0.783	0.074	0.052	9.123	9.775	6.317	5.435
770	0.067	0.063	0.058	0.066	0.064	0.004	0.731	0.835	0.783	0.074	0.052	9.147	9.800	6.333	5.449
772	0.067	0.063	0.058	0.066	0.063	0.004	0.731	0.835	0.783	0.074	0.052	9.170	9.825	6.349	5.463
774	0.067	0.063	0.059	0.066	0.063	0.004	0.744	0.835	0.789	0.065	0.046	9.320	9.893	6.420	5.527
778	0.066	0.063	0.058	0.065	0.063	0.004	0.732	0.821	0.777	0.064	0.046	9.180	9.744	6.323	5.444
780	0.067	0.063	0.058	0.065	0.064	0.004	0.732	0.821	0.777	0.064	0.049	9.167	9.730	6.315	5.434
782	0.067	0.063	0.058	0.065	0.063	0.004	0.732	0.821	0.777	0.064	0.049	9.191	9.755	6.332	5.448
784	0.067	0.063	0.058	0.065	0.063	0.004	0.732	0.821	0.777	0.064	0.049	9.214	9.780	6.348	5.462
786	0.067	0.063	0.058	0.065	0.063	0.004	0.732	0.821	0.777	0.064	0.049	9.238	9.805	6.364	5.476
788	0.067	0.063	0.058	0.065	0.063	0.004	0.732	0.821	0.777	0.064	0.049	9.261	9.830	6.380	5.490
790	0.066	0.062	0.057	0.065	0.063	0.004	0.732	0.834	0.783	0.073	0.051	9.247	9.896	6.398	5.506
792	0.066	0.062	0.057	0.065	0.063	0.004	0.732	0.834	0.783	0.073	0.051	9.271	9.921	6.415	5.520
794	0.066	0.062	0.057	0.065	0.063	0.004	0.732	0.834	0.783	0.073	0.051	9.294	9.946	6.431	5.534
796	0.066	0.062	0.057	0.065	0.062	0.004	0.732	0.834	0.783	0.073	0.051	9.318	9.972	6.447	5.548

Table D1 (continued)

	0.45 μm						2.5 μm				8 μm				
	Flux (L/sec/m^2)						Flux (L/sec/m^2)				Flux (L/sec/m^2)				
time,s.	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**	**Set1**	**Set2**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Average**	**Std.**
798	0.066	0.062	0.057	0.065	0.062	0.004	0.732	0.834	0.783	0.073	0.051	9.341	9.997	6.463	5.562
800	0.066	0.062	0.057	0.065	0.062	0.004	0.732	0.834	0.783	0.073	0.051	9.364	10.022	6.479	5.576
802	0.065	0.062	0.057	0.064	0.062	0.004	0.732	0.834	0.783	0.073	0.051	9.388	10.047	6.495	5.590
804	0.065	0.061	0.056	0.064	0.062	0.004	0.732	0.834	0.783	0.073	0.051	9.411	10.072	6.511	5.604
806	0.065	0.061	0.056	0.064	0.062	0.004	0.732	0.834	0.783	0.073	0.051	9.435	10.097	6.528	5.618
808	0.066	0.061	0.056	0.064	0.062	0.004	0.732	0.834	0.783	0.073	0.055	9.420	10.082	6.519	5.608
812	0.066	0.062	0.056	0.064	0.062	0.004	0.720	0.821	0.771	0.071	0.055	9.280	9.931	6.422	5.524
814	0.065	0.062	0.057	0.064	0.062	0.004	0.733	0.821	0.777	0.063	0.049	9.428	9.997	6.492	5.587
816	0.065	0.061	0.057	0.063	0.062	0.004	0.733	0.821	0.777	0.063	0.049	9.452	10.022	6.507	5.601
818	0.065	0.061	0.056	0.063	0.062	0.004	0.733	0.821	0.777	0.063	0.049	9.475	10.047	6.523	5.615
820	0.065	0.061	0.056	0.063	0.061	0.004	0.733	0.821	0.777	0.063	0.049	9.498	10.071	6.539	5.628
822	0.065	0.061	0.056	0.063	0.061	0.004	0.733	0.821	0.777	0.063	0.049	9.521	10.096	6.555	5.642
824	0.065	0.061	0.056	0.063	0.061	0.004	0.733	0.821	0.777	0.063	0.049	9.544	10.120	6.571	5.656
826	0.065	0.061	0.056	0.063	0.061	0.004	0.733	0.821	0.777	0.063	0.049	9.567	10.145	6.587	5.670
828	0.064	0.061	0.056	0.062	0.061	0.004	0.733	0.821	0.777	0.063	0.049	9.591	10.169	6.603	5.684
830	0.064	0.060	0.056	0.062	0.061	0.004	0.733	0.821	0.777	0.063	0.049	9.614	10.194	6.619	5.697
832	0.064	0.060	0.055	0.062	0.060	0.004	0.733	0.821	0.777	0.063	0.049	9.637	10.219	6.635	5.711
834	0.064	0.060	0.055	0.062	0.060	0.004	0.733	0.821	0.777	0.063	0.049	9.660	10.243	6.651	5.725
836	0.064	0.060	0.055	0.063	0.060	0.004	0.733	0.834	0.783	0.071	0.051	9.645	10.310	6.669	5.741

Table D1 (continued)

	0.45 µm						2.5 µm				8 µm				
	Flux (L/sec/m^2)						Flux (L/sec/m^2)				Flux (L/sec/m^2)				
time,s.	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**	**Set1**	**Set2**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Average**	**Std.**
838	0.065	0.060	0.055	0.063	0.061	0.004	0.733	0.834	0.783	0.071	0.054	9.630	10.294	6.660	5.730
840	0.064	0.060	0.055	0.063	0.060	0.004	0.733	0.834	0.783	0.071	0.054	9.653	10.319	6.676	5.744
842	0.064	0.060	0.055	0.062	0.060	0.004	0.733	0.834	0.783	0.071	0.054	9.676	10.344	6.691	5.758
844	0.064	0.059	0.055	0.062	0.060	0.004	0.733	0.834	0.783	0.071	0.054	9.699	10.368	6.707	5.771
846	0.064	0.059	0.055	0.062	0.060	0.004	0.733	0.834	0.783	0.071	0.054	9.722	10.393	6.723	5.785
848	0.064	0.060	0.054	0.062	0.060	0.004	0.721	0.821	0.771	0.070	0.054	9.556	10.215	6.608	5.686
850	0.064	0.060	0.054	0.062	0.060	0.004	0.721	0.821	0.771	0.070	0.054	9.578	10.239	6.623	5.699
852	0.064	0.060	0.055	0.062	0.060	0.004	0.734	0.821	0.777	0.062	0.048	9.728	10.305	6.694	5.763
854	0.063	0.060	0.055	0.062	0.060	0.004	0.734	0.821	0.777	0.062	0.048	9.751	10.329	6.709	5.776
858	0.063	0.059	0.055	0.061	0.060	0.004	0.734	0.821	0.777	0.062	0.048	9.797	10.378	6.741	5.804
860	0.063	0.059	0.055	0.061	0.059	0.004	0.734	0.821	0.777	0.062	0.048	9.819	10.402	6.756	5.817
862	0.063	0.059	0.054	0.061	0.059	0.004	0.734	0.821	0.777	0.062	0.048	9.842	10.426	6.772	5.831
864	0.063	0.059	0.054	0.061	0.059	0.004	0.734	0.821	0.777	0.062	0.048	9.865	10.450	6.788	5.844
866	0.062	0.059	0.054	0.061	0.059	0.004	0.734	0.821	0.777	0.062	0.048	9.888	10.475	6.803	5.858
868	0.062	0.059	0.054	0.061	0.059	0.004	0.734	0.821	0.777	0.062	0.048	9.911	10.499	6.819	5.871
870	0.063	0.059	0.054	0.060	0.059	0.004	0.734	0.821	0.777	0.062	0.052	9.895	10.482	6.810	5.860
872	0.063	0.058	0.054	0.060	0.059	0.004	0.734	0.821	0.777	0.062	0.052	9.918	10.506	6.825	5.873
874	0.063	0.058	0.054	0.060	0.059	0.004	0.734	0.821	0.777	0.062	0.052	9.941	10.530	6.841	5.887
876	0.063	0.058	0.054	0.060	0.059	0.004	0.734	0.821	0.777	0.062	0.052	9.963	10.554	6.857	5.900

Table D1 (continued)

	0.45 μm						2.5 μm				8 μm				
	Flux (L/sec/m^2)						Flux (L/sec/m^2)				Flux (L/sec/m^2)				
time,s.	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**	**Set1**	**Set2**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Average**	**Std.**
878	0.063	0.058	0.053	0.060	0.058	0.004	0.734	0.821	0.777	0.062	0.052	9.986	10.579	6.872	5.914
880	0.062	0.058	0.053	0.060	0.058	0.004	0.734	0.821	0.777	0.062	0.052	10.009	10.603	6.888	5.928
882	0.062	0.058	0.053	0.060	0.058	0.004	0.734	0.833	0.783	0.070	0.053	9.993	10.670	6.906	5.944
884	0.062	0.059	0.053	0.060	0.059	0.004	0.722	0.820	0.771	0.069	0.053	9.824	10.490	6.789	5.843
886	0.062	0.058	0.053	0.060	0.058	0.004	0.722	0.820	0.771	0.069	0.053	9.846	10.513	6.804	5.856
888	0.062	0.058	0.053	0.060	0.058	0.004	0.722	0.820	0.771	0.069	0.053	9.868	10.537	6.819	5.869
890	0.062	0.058	0.053	0.060	0.058	0.004	0.722	0.820	0.771	0.069	0.053	9.890	10.561	6.835	5.883
892	0.062	0.058	0.053	0.060	0.058	0.004	0.722	0.820	0.771	0.069	0.053	9.912	10.584	6.850	5.896
894	0.061	0.058	0.053	0.060	0.058	0.004	0.722	0.820	0.771	0.069	0.053	9.935	10.608	6.865	5.909
896	0.061	0.058	0.052	0.060	0.058	0.004	0.722	0.820	0.771	0.069	0.053	9.957	10.632	6.881	5.923
898	0.062	0.058	0.053	0.059	0.058	0.004	0.735	0.820	0.777	0.061	0.051	10.071	10.658	6.927	5.962
900	0.062	0.057	0.053	0.059	0.058	0.004	0.735	0.820	0.777	0.061	0.051	10.093	10.682	6.942	5.975
902	0.062	0.057	0.053	0.059	0.058	0.004	0.735	0.820	0.777	0.061	0.051	10.116	10.706	6.957	5.988
904	0.062	0.057	0.053	0.059	0.058	0.004	0.735	0.820	0.777	0.061	0.051	10.138	10.729	6.973	6.002
906	0.061	0.057	0.053	0.059	0.058	0.004	0.735	0.820	0.777	0.061	0.051	10.160	10.753	6.988	6.015
908	0.061	0.057	0.053	0.059	0.057	0.004	0.735	0.820	0.777	0.061	0.051	10.183	10.777	7.004	6.028
912	0.061	0.057	0.052	0.058	0.057	0.004	0.735	0.820	0.777	0.061	0.051	10.228	10.824	7.034	6.055
914	0.061	0.057	0.052	0.058	0.057	0.004	0.735	0.820	0.777	0.061	0.051	10.250	10.848	7.050	6.068
916	0.061	0.056	0.052	0.058	0.057	0.004	0.735	0.820	0.777	0.061	0.051	10.273	10.872	7.065	6.082

Table D1 (continued)

	0.45 µm						2.5 µm				8 µm				
	Flux (L/sec/m^2)						Flux (L/sec/m^2)				Flux (L/sec/m^2)				
time,s.	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**	**Set1**	**Set2**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Average**	**Std.**
918	0.061	0.056	0.052	0.058	0.057	0.004	0.735	0.820	0.777	0.061	0.051	10.295	10.896	7.081	6.095
920	0.061	0.056	0.052	0.058	0.057	0.004	0.735	0.820	0.777	0.061	0.051	10.318	10.919	7.096	6.108
922	0.060	0.057	0.052	0.058	0.057	0.004	0.723	0.808	0.766	0.060	0.051	10.145	10.736	6.977	6.006
924	0.060	0.057	0.052	0.058	0.057	0.004	0.723	0.808	0.766	0.060	0.051	10.167	10.760	6.992	6.019
926	0.060	0.057	0.052	0.058	0.057	0.004	0.723	0.820	0.772	0.068	0.052	10.150	10.827	7.010	6.035
930	0.061	0.056	0.051	0.058	0.057	0.004	0.723	0.820	0.772	0.068	0.056	10.155	10.832	7.015	6.036
932	0.061	0.056	0.051	0.058	0.057	0.004	0.723	0.820	0.772	0.068	0.056	10.177	10.856	7.030	6.049
934	0.060	0.056	0.051	0.058	0.056	0.004	0.723	0.820	0.772	0.068	0.056	10.199	10.879	7.045	6.062
936	0.060	0.056	0.051	0.058	0.056	0.004	0.723	0.820	0.772	0.068	0.056	10.221	10.902	7.060	6.075
938	0.060	0.056	0.051	0.058	0.056	0.004	0.723	0.820	0.772	0.068	0.056	10.243	10.926	7.075	6.088
940	0.060	0.056	0.051	0.058	0.056	0.004	0.723	0.820	0.772	0.068	0.056	10.265	10.949	7.090	6.101
942	0.060	0.056	0.051	0.057	0.056	0.004	0.723	0.820	0.772	0.068	0.056	10.286	10.972	7.105	6.114
944	0.060	0.056	0.051	0.057	0.056	0.004	0.735	0.820	0.778	0.060	0.050	10.441	11.040	7.177	6.179
946	0.060	0.056	0.051	0.057	0.056	0.004	0.735	0.820	0.778	0.060	0.050	10.463	11.063	7.192	6.192
948	0.060	0.055	0.051	0.057	0.056	0.004	0.735	0.820	0.778	0.060	0.050	10.485	11.086	7.207	6.205
950	0.059	0.055	0.051	0.057	0.056	0.004	0.735	0.820	0.778	0.060	0.050	10.507	11.110	7.222	6.219
952	0.059	0.055	0.051	0.057	0.056	0.004	0.735	0.820	0.778	0.060	0.050	10.529	11.133	7.238	6.232
954	0.059	0.055	0.051	0.057	0.055	0.004	0.735	0.820	0.778	0.060	0.050	10.551	11.157	7.253	6.245
956	0.059	0.056	0.051	0.057	0.056	0.004	0.725	0.820	0.772	0.067	0.051	10.338	11.016	7.135	6.144

Table D1 (continued)

	0.45 μm						2.5 μm				8 μm				
	Flux (L/sec/m^2)						Flux (L/sec/m^2)				Flux (L/sec/m^2)				
time,s.	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**	**Set1**	**Set2**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Average**	**Std.**
958	0.059	0.056	0.051	0.057	0.056	0.004	0.725	0.820	0.772	0.067	0.051	10.359	11.039	7.150	6.157
960	0.059	0.056	0.051	0.057	0.056	0.004	0.725	0.820	0.772	0.067	0.051	10.381	11.062	7.165	6.170
962	0.060	0.055	0.050	0.057	0.056	0.004	0.725	0.820	0.772	0.067	0.055	10.364	11.044	7.154	6.157
964	0.059	0.055	0.050	0.057	0.056	0.004	0.725	0.820	0.772	0.067	0.055	10.386	11.067	7.169	6.170
966	0.059	0.055	0.050	0.057	0.055	0.004	0.725	0.820	0.772	0.067	0.055	10.407	11.090	7.184	6.183
968	0.059	0.055	0.050	0.057	0.055	0.004	0.725	0.820	0.772	0.067	0.055	10.429	11.112	7.199	6.196
970	0.059	0.055	0.050	0.057	0.055	0.004	0.725	0.820	0.772	0.067	0.055	10.450	11.135	7.214	6.209
972	0.059	0.055	0.050	0.056	0.055	0.004	0.725	0.820	0.772	0.067	0.055	10.472	11.158	7.228	6.222
974	0.059	0.055	0.050	0.056	0.055	0.004	0.725	0.820	0.772	0.067	0.055	10.493	11.181	7.243	6.235
976	0.059	0.055	0.050	0.056	0.055	0.004	0.725	0.820	0.772	0.067	0.055	10.515	11.204	7.258	6.248
978	0.059	0.055	0.050	0.056	0.055	0.004	0.725	0.820	0.772	0.067	0.055	10.536	11.227	7.273	6.260
980	0.058	0.054	0.050	0.056	0.055	0.004	0.725	0.820	0.772	0.067	0.055	10.558	11.250	7.288	6.273
984	0.058	0.054	0.049	0.056	0.054	0.004	0.725	0.820	0.772	0.067	0.055	10.601	11.296	7.317	6.299
986	0.058	0.054	0.049	0.056	0.054	0.004	0.725	0.820	0.772	0.067	0.055	10.623	11.319	7.332	6.312
988	0.058	0.054	0.050	0.056	0.054	0.003	0.736	0.820	0.778	0.059	0.050	10.779	11.387	7.405	6.377
990	0.058	0.054	0.050	0.055	0.054	0.003	0.736	0.820	0.778	0.059	0.050	10.800	11.410	7.420	6.390
992	0.058	0.054	0.050	0.056	0.054	0.003	0.736	0.831	0.784	0.067	0.051	10.782	11.478	7.437	6.406
994	0.058	0.054	0.050	0.056	0.054	0.004	0.736	0.831	0.784	0.067	0.055	10.764	11.459	7.426	6.393
996	0.058	0.054	0.050	0.056	0.054	0.004	0.736	0.831	0.784	0.067	0.055	10.786	11.482	7.441	6.406

Table D1 (continued)

	0.45 μm						2.5 μm				8 μm				
	Flux (L/sec/m^2)						Flux (L/sec/m^2)				Flux (L/sec/m^2)				
time,s.	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**	**Set1**	**Set2**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Average**	**Std.**
998	0.058	0.053	0.049	0.056	0.054	0.004	0.736	0.831	0.784	0.067	0.055	10.808	11.505	7.456	6.419
1000	0.058	0.054	0.049	0.056	0.054	0.004	0.726	0.819	0.772	0.066	0.054	10.631	11.317	7.334	6.314
1002	0.058	0.054	0.049	0.056	0.054	0.004	0.726	0.819	0.772	0.066	0.054	10.652	11.339	7.349	6.326
1004	0.058	0.054	0.049	0.055	0.054	0.004	0.726	0.819	0.772	0.066	0.054	10.673	11.362	7.363	6.339
1006	0.058	0.054	0.049	0.055	0.054	0.004	0.726	0.819	0.772	0.066	0.054	10.695	11.385	7.378	6.352
1008	0.058	0.054	0.049	0.055	0.054	0.004	0.726	0.819	0.772	0.066	0.054	10.716	11.407	7.392	6.365
1010	0.058	0.054	0.049	0.055	0.054	0.004	0.726	0.819	0.772	0.066	0.054	10.737	11.430	7.407	6.377
1012	0.057	0.053	0.049	0.055	0.054	0.004	0.726	0.819	0.772	0.066	0.054	10.758	11.453	7.422	6.390
1014	0.057	0.053	0.049	0.055	0.054	0.004	0.726	0.819	0.772	0.066	0.054	10.780	11.475	7.436	6.403
1016	0.057	0.053	0.049	0.055	0.053	0.004	0.726	0.819	0.772	0.066	0.054	10.801	11.498	7.451	6.415
1018	0.057	0.053	0.048	0.055	0.053	0.004	0.726	0.819	0.772	0.066	0.054	10.822	11.520	7.466	6.428
1022	0.057	0.053	0.048	0.055	0.053	0.004	0.726	0.819	0.772	0.066	0.054	10.865	11.566	7.495	6.453
1024	0.057	0.053	0.048	0.054	0.053	0.004	0.726	0.819	0.772	0.066	0.054	10.886	11.588	7.510	6.466
1026	0.057	0.053	0.049	0.054	0.053	0.004	0.737	0.819	0.778	0.058	0.053	11.003	11.614	7.556	6.505
1028	0.057	0.053	0.049	0.054	0.053	0.004	0.737	0.819	0.778	0.058	0.053	11.024	11.637	7.571	6.518
1030	0.057	0.053	0.049	0.054	0.053	0.004	0.737	0.819	0.778	0.058	0.053	11.046	11.659	7.586	6.531
1032	0.057	0.052	0.049	0.054	0.053	0.004	0.737	0.819	0.778	0.058	0.053	11.067	11.682	7.601	6.544
1034	0.057	0.052	0.048	0.054	0.053	0.004	0.737	0.819	0.778	0.058	0.053	11.088	11.704	7.615	6.556
1036	0.057	0.052	0.048	0.054	0.053	0.004	0.737	0.819	0.778	0.058	0.053	11.110	11.727	7.630	6.569

Table D1 (continued)

	0.45 µm						2.5 µm				8 µm				
	Flux (L/sec/m^2)						Flux (L/sec/m^2)				Flux (L/sec/m^2)				
time,s.	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**	**Set1**	**Set2**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Average**	**Std.**
1038	0.057	0.052	0.048	0.054	0.053	0.004	0.737	0.819	0.778	0.058	0.053	11.131	11.750	7.645	6.582
1040	0.057	0.052	0.048	0.054	0.053	0.004	0.737	0.831	0.784	0.066	0.054	11.112	11.818	7.661	6.598
1042	0.057	0.053	0.048	0.054	0.053	0.004	0.727	0.819	0.773	0.065	0.053	10.933	11.627	7.538	6.491
1044	0.056	0.053	0.048	0.054	0.053	0.004	0.727	0.819	0.773	0.065	0.053	10.954	11.649	7.552	6.503
1046	0.056	0.052	0.048	0.054	0.053	0.004	0.727	0.819	0.773	0.065	0.053	10.975	11.672	7.567	6.516
1048	0.056	0.052	0.048	0.054	0.053	0.004	0.727	0.819	0.773	0.065	0.053	10.996	11.694	7.581	6.528
1050	0.056	0.052	0.048	0.054	0.052	0.004	0.727	0.819	0.773	0.065	0.053	11.017	11.716	7.595	6.541
1052	0.056	0.052	0.048	0.054	0.052	0.004	0.727	0.819	0.773	0.065	0.053	11.038	11.738	7.610	6.553
1054	0.056	0.052	0.048	0.054	0.052	0.004	0.727	0.819	0.773	0.065	0.053	11.059	11.761	7.624	6.566
1056	0.056	0.052	0.047	0.054	0.052	0.004	0.727	0.819	0.773	0.065	0.053	11.080	11.783	7.639	6.578
1058	0.056	0.052	0.047	0.053	0.052	0.004	0.727	0.819	0.773	0.065	0.057	11.061	11.763	7.627	6.565
1060	0.056	0.052	0.047	0.053	0.052	0.004	0.727	0.819	0.773	0.065	0.057	11.082	11.785	7.641	6.577
1062	0.056	0.052	0.047	0.053	0.052	0.004	0.727	0.819	0.773	0.065	0.057	11.103	11.807	7.656	6.590
1066	0.056	0.052	0.047	0.053	0.052	0.004	0.727	0.819	0.773	0.065	0.057	11.144	11.852	7.684	6.615
1068	0.056	0.051	0.047	0.053	0.052	0.004	0.727	0.819	0.773	0.065	0.057	11.165	11.874	7.699	6.627
1070	0.056	0.051	0.047	0.053	0.052	0.004	0.727	0.819	0.773	0.065	0.057	11.186	11.896	7.713	6.640
1072	0.056	0.051	0.047	0.053	0.052	0.004	0.727	0.819	0.773	0.065	0.057	11.207	11.919	7.728	6.652
1074	0.056	0.051	0.047	0.053	0.051	0.004	0.727	0.819	0.773	0.065	0.057	11.228	11.941	7.742	6.665
1076	0.055	0.051	0.047	0.053	0.052	0.003	0.738	0.819	0.778	0.057	0.052	11.386	12.009	7.816	6.731

Table D1 (continued)

	0.45 μm						2.5 μm				8 μm				
	Flux (L/sec/m^2)						Flux (L/sec/m^2)				Flux (L/sec/m^2)				
time,s.	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**	**Set1**	**Set2**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Average**	**Std.**
1078	0.055	0.051	0.047	0.052	0.051	0.003	0.738	0.819	0.778	0.057	0.052	11.408	12.031	7.830	6.743
1080	0.055	0.051	0.047	0.052	0.051	0.003	0.738	0.819	0.778	0.057	0.052	11.429	12.054	7.845	6.756
1082	0.055	0.051	0.047	0.053	0.051	0.003	0.738	0.830	0.784	0.065	0.053	11.409	12.122	7.862	6.771
1084	0.055	0.051	0.047	0.053	0.051	0.003	0.738	0.830	0.784	0.065	0.053	11.430	12.145	7.876	6.784
1086	0.055	0.051	0.047	0.053	0.051	0.003	0.738	0.830	0.784	0.065	0.053	11.451	12.167	7.891	6.797
1088	0.055	0.050	0.047	0.053	0.051	0.003	0.738	0.830	0.784	0.065	0.053	11.472	12.189	7.905	6.809
1090	0.055	0.051	0.047	0.053	0.051	0.003	0.728	0.819	0.773	0.064	0.053	11.289	11.994	7.779	6.700
1092	0.055	0.051	0.047	0.052	0.051	0.003	0.728	0.819	0.773	0.064	0.053	11.310	12.016	7.793	6.713
1094	0.055	0.051	0.047	0.052	0.051	0.004	0.728	0.819	0.773	0.064	0.056	11.290	11.996	7.781	6.699
1096	0.055	0.051	0.046	0.052	0.051	0.004	0.728	0.819	0.773	0.064	0.056	11.311	12.018	7.795	6.711
1098	0.055	0.051	0.046	0.052	0.051	0.004	0.728	0.819	0.773	0.064	0.056	11.331	12.040	7.809	6.723
1100	0.055	0.051	0.046	0.052	0.051	0.004	0.728	0.819	0.773	0.064	0.056	11.352	12.062	7.823	6.736
1102	0.055	0.051	0.046	0.052	0.051	0.004	0.728	0.819	0.773	0.064	0.056	11.373	12.084	7.838	6.748
1104	0.055	0.050	0.046	0.052	0.051	0.004	0.728	0.819	0.773	0.064	0.056	11.393	12.105	7.852	6.760
1106	0.055	0.050	0.046	0.052	0.051	0.004	0.728	0.819	0.773	0.064	0.056	11.414	12.127	7.866	6.773
1108	0.055	0.050	0.046	0.052	0.051	0.004	0.728	0.819	0.773	0.064	0.056	11.435	12.149	7.880	6.785
1110	0.054	0.050	0.046	0.052	0.051	0.004	0.728	0.819	0.773	0.064	0.056	11.455	12.171	7.894	6.797
1114	0.054	0.050	0.046	0.051	0.050	0.004	0.728	0.819	0.773	0.064	0.056	11.497	12.215	7.923	6.822
1116	0.054	0.050	0.046	0.051	0.050	0.004	0.728	0.819	0.773	0.064	0.056	11.517	12.237	7.937	6.834

Table D1 (continued)

	0.45 µm						2.5 µm				8 µm				
	Flux (L/sec/m^2)						Flux (L/sec/m^2)				Flux (L/sec/m^2)				
time,s.	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**	**Set1**	**Set2**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Average**	**Std.**
1118	0.054	0.050	0.046	0.051	0.050	0.004	0.728	0.819	0.773	0.064	0.056	11.538	12.259	7.951	6.846
1120	0.054	0.050	0.045	0.051	0.050	0.004	0.728	0.819	0.773	0.064	0.056	11.558	12.281	7.965	6.859
1122	0.054	0.050	0.045	0.051	0.050	0.004	0.728	0.819	0.773	0.064	0.056	11.579	12.303	7.979	6.871
1124	0.054	0.050	0.046	0.051	0.050	0.003	0.739	0.819	0.779	0.056	0.051	11.739	12.372	8.054	6.938
1126	0.054	0.049	0.046	0.051	0.050	0.003	0.739	0.819	0.779	0.056	0.051	11.760	12.394	8.068	6.950
1128	0.054	0.050	0.046	0.051	0.050	0.004	0.729	0.818	0.773	0.063	0.056	11.493	12.201	7.917	6.817
1130	0.054	0.050	0.046	0.051	0.050	0.004	0.729	0.818	0.773	0.063	0.056	11.514	12.222	7.931	6.829
1132	0.054	0.050	0.046	0.051	0.050	0.004	0.729	0.818	0.773	0.063	0.056	11.534	12.244	7.945	6.841
1134	0.054	0.050	0.046	0.051	0.050	0.004	0.729	0.818	0.773	0.063	0.056	11.555	12.266	7.959	6.853
1136	0.054	0.050	0.046	0.051	0.050	0.004	0.729	0.818	0.773	0.063	0.056	11.575	12.287	7.973	6.866
1138	0.054	0.050	0.045	0.051	0.050	0.003	0.729	0.818	0.773	0.063	0.056	11.595	12.309	7.987	6.878
1140	0.054	0.050	0.045	0.051	0.050	0.003	0.729	0.818	0.773	0.063	0.056	11.616	12.330	8.001	6.890
1144	0.054	0.049	0.045	0.051	0.050	0.003	0.729	0.818	0.773	0.063	0.056	11.656	12.374	8.029	6.914
1146	0.053	0.049	0.045	0.051	0.050	0.003	0.729	0.818	0.773	0.063	0.056	11.677	12.395	8.043	6.926
1148	0.053	0.049	0.045	0.051	0.050	0.003	0.729	0.818	0.773	0.063	0.056	11.697	12.417	8.057	6.938
1150	0.053	0.049	0.045	0.051	0.049	0.003	0.729	0.818	0.773	0.063	0.056	11.718	12.439	8.071	6.951
1152	0.053	0.049	0.045	0.050	0.049	0.003	0.729	0.818	0.773	0.063	0.056	11.738	12.460	8.085	6.963
1154	0.053	0.049	0.045	0.050	0.049	0.003	0.729	0.818	0.773	0.063	0.056	11.758	12.482	8.099	6.975
1156	0.053	0.049	0.045	0.050	0.049	0.003	0.729	0.818	0.773	0.063	0.056	11.779	12.504	8.113	6.987

Table D1 (continued)

	0.45 µm						2.5 µm				8 µm				
	Flux (L/sec/m^2)						Flux (L/sec/m^2)				Flux (L/sec/m^2)				
time,s.	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**	**Set1**	**Set2**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Average**	**Std.**
1158	0.054	0.049	0.045	0.050	0.049	0.004	0.729	0.818	0.773	0.063	0.060	11.758	12.482	8.100	6.972
1160	0.054	0.049	0.045	0.050	0.049	0.004	0.729	0.818	0.773	0.063	0.060	11.778	12.503	8.114	6.984
1162	0.053	0.049	0.045	0.050	0.049	0.004	0.729	0.818	0.773	0.063	0.060	11.799	12.525	8.128	6.996
1164	0.053	0.049	0.044	0.050	0.049	0.004	0.729	0.818	0.773	0.063	0.060	11.819	12.546	8.142	7.009
1166	0.053	0.049	0.044	0.050	0.049	0.004	0.718	0.807	0.763	0.063	0.059	11.634	12.350	8.015	6.899
1168	0.053	0.049	0.044	0.050	0.049	0.004	0.718	0.807	0.763	0.063	0.059	11.654	12.371	8.028	6.911
1170	0.053	0.049	0.044	0.050	0.049	0.004	0.718	0.807	0.763	0.063	0.059	11.674	12.393	8.042	6.923
1172	0.053	0.049	0.045	0.050	0.049	0.003	0.729	0.807	0.768	0.055	0.054	11.833	12.460	8.116	6.989
1174	0.053	0.049	0.045	0.049	0.049	0.003	0.729	0.807	0.768	0.055	0.054	11.853	12.482	8.130	7.001
1176	0.053	0.049	0.045	0.049	0.049	0.003	0.729	0.807	0.768	0.055	0.054	11.873	12.503	8.143	7.013
1178	0.053	0.049	0.045	0.050	0.049	0.003	0.729	0.818	0.774	0.063	0.055	11.852	12.571	8.159	7.028
1182	0.053	0.048	0.044	0.050	0.049	0.003	0.729	0.818	0.774	0.063	0.055	11.893	12.613	8.187	7.052
1184	0.052	0.048	0.044	0.050	0.049	0.003	0.729	0.818	0.774	0.063	0.055	11.913	12.635	8.201	7.064
1186	0.052	0.048	0.044	0.050	0.049	0.003	0.729	0.818	0.774	0.063	0.055	11.933	12.656	8.215	7.076
1188	0.052	0.048	0.044	0.050	0.049	0.003	0.729	0.818	0.774	0.063	0.055	11.953	12.678	8.228	7.088
1190	0.052	0.048	0.044	0.049	0.048	0.003	0.729	0.818	0.774	0.063	0.055	11.973	12.699	8.242	7.100
1192	0.052	0.048	0.044	0.049	0.048	0.003	0.729	0.818	0.774	0.063	0.055	11.993	12.720	8.256	7.112
1194	0.053	0.048	0.044	0.049	0.048	0.004	0.729	0.818	0.774	0.063	0.059	11.972	12.698	8.243	7.097
1196	0.053	0.048	0.044	0.049	0.048	0.004	0.729	0.818	0.774	0.063	0.059	11.992	12.719	8.257	7.109

Table D1 (continued)

	0.45 µm						2.5 µm				8 µm				
	Flux (L/sec/m^2)						Flux (L/sec/m^2)				Flux (L/sec/m^2)				
time,s.	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**	**Set1**	**Set2**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Average**	**Std.**
1198	0.052	0.048	0.044	0.049	0.048	0.004	0.729	0.818	0.774	0.063	0.059	12.012	12.740	8.270	7.121
1200	0.052	0.048	0.044	0.049	0.048	0.004	0.729	0.818	0.774	0.063	0.059	12.032	12.762	8.284	7.133
1202	0.052	0.048	0.044	0.049	0.048	0.004	0.719	0.807	0.763	0.062	0.058	11.847	12.565	8.156	7.022
1204	0.052	0.048	0.044	0.049	0.048	0.004	0.719	0.807	0.763	0.062	0.058	11.866	12.585	8.170	7.034
1206	0.052	0.048	0.044	0.049	0.048	0.004	0.719	0.807	0.763	0.062	0.058	11.886	12.606	8.184	7.046
1208	0.052	0.048	0.043	0.049	0.048	0.004	0.719	0.807	0.763	0.062	0.058	11.906	12.627	8.197	7.058
1210	0.052	0.048	0.043	0.049	0.048	0.004	0.719	0.807	0.763	0.062	0.058	11.925	12.648	8.211	7.069
1212	0.052	0.048	0.043	0.049	0.048	0.004	0.719	0.807	0.763	0.062	0.058	11.945	12.669	8.224	7.081
1214	0.052	0.048	0.043	0.049	0.048	0.004	0.719	0.807	0.763	0.062	0.058	11.965	12.690	8.238	7.093
1216	0.052	0.048	0.043	0.048	0.048	0.004	0.719	0.807	0.763	0.062	0.058	11.985	12.711	8.251	7.105
1220	0.052	0.048	0.044	0.048	0.048	0.003	0.730	0.807	0.769	0.054	0.053	12.165	12.800	8.339	7.183
1222	0.051	0.048	0.044	0.048	0.048	0.003	0.730	0.807	0.769	0.054	0.053	12.184	12.821	8.353	7.195
1224	0.051	0.047	0.044	0.048	0.048	0.003	0.730	0.807	0.769	0.054	0.053	12.204	12.842	8.367	7.206
1226	0.051	0.047	0.043	0.048	0.048	0.003	0.730	0.807	0.769	0.054	0.053	12.224	12.863	8.380	7.218
1228	0.052	0.047	0.043	0.048	0.048	0.003	0.730	0.807	0.769	0.054	0.058	12.203	12.840	8.367	7.203
1230	0.052	0.047	0.043	0.048	0.048	0.003	0.730	0.807	0.769	0.054	0.058	12.222	12.861	8.380	7.215
1232	0.052	0.047	0.043	0.048	0.048	0.003	0.730	0.818	0.774	0.062	0.058	12.201	12.929	8.396	7.230
1234	0.052	0.047	0.043	0.048	0.048	0.003	0.730	0.818	0.774	0.062	0.058	12.221	12.950	8.410	7.242
1236	0.052	0.047	0.043	0.048	0.047	0.003	0.730	0.818	0.774	0.062	0.058	12.240	12.971	8.423	7.254

Table D1 (continued)

	0.45 µm						2.5 µm				8 µm				
	Flux (L/sec/m^2)						Flux (L/sec/m^2)				Flux (L/sec/m^2)				
time,s.	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**	**Set1**	**Set2**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Average**	**Std.**
1238	0.051	0.047	0.043	0.048	0.047	0.003	0.730	0.818	0.774	0.062	0.058	12.260	12.992	8.437	7.266
1240	0.051	0.047	0.043	0.048	0.047	0.003	0.730	0.818	0.774	0.062	0.058	12.280	13.013	8.450	7.277
1242	0.051	0.047	0.043	0.048	0.047	0.003	0.730	0.818	0.774	0.062	0.058	12.300	13.034	8.464	7.289
1244	0.051	0.047	0.043	0.048	0.047	0.003	0.720	0.807	0.764	0.061	0.058	12.112	12.835	8.335	7.178
1246	0.051	0.047	0.043	0.048	0.047	0.003	0.720	0.807	0.764	0.061	0.058	12.132	12.856	8.348	7.189
1248	0.051	0.047	0.043	0.048	0.047	0.003	0.720	0.807	0.764	0.061	0.058	12.151	12.877	8.362	7.201
1250	0.051	0.047	0.043	0.048	0.047	0.003	0.720	0.807	0.764	0.061	0.058	12.171	12.897	8.375	7.212
1252	0.051	0.047	0.043	0.048	0.047	0.003	0.720	0.807	0.764	0.061	0.058	12.190	12.918	8.388	7.224
1254	0.051	0.047	0.043	0.048	0.047	0.003	0.720	0.807	0.764	0.061	0.058	12.210	12.938	8.402	7.236
1258	0.051	0.047	0.042	0.047	0.047	0.003	0.720	0.807	0.764	0.061	0.058	12.248	12.980	8.429	7.259
1260	0.051	0.047	0.042	0.047	0.047	0.003	0.720	0.807	0.764	0.061	0.058	12.268	13.000	8.442	7.270
1262	0.051	0.047	0.042	0.047	0.047	0.004	0.720	0.807	0.764	0.061	0.061	12.246	12.977	8.428	7.255
1264	0.051	0.047	0.042	0.047	0.047	0.004	0.720	0.807	0.764	0.061	0.061	12.265	12.998	8.442	7.267
1266	0.051	0.047	0.042	0.047	0.047	0.004	0.720	0.807	0.764	0.061	0.061	12.285	13.018	8.455	7.278
1268	0.051	0.046	0.043	0.047	0.047	0.003	0.731	0.807	0.769	0.053	0.057	12.446	13.087	8.530	7.345
1270	0.051	0.046	0.043	0.047	0.047	0.003	0.731	0.807	0.769	0.053	0.057	12.466	13.107	8.543	7.356
1272	0.051	0.046	0.043	0.047	0.047	0.003	0.731	0.807	0.769	0.053	0.057	12.485	13.128	8.557	7.368
1274	0.051	0.046	0.042	0.047	0.047	0.003	0.731	0.807	0.769	0.053	0.057	12.505	13.149	8.570	7.380
1276	0.051	0.046	0.042	0.047	0.046	0.003	0.731	0.807	0.769	0.053	0.057	12.525	13.169	8.584	7.391

Table D1 (continued)

	0.45 µm						2.5 µm				8 µm				
	Flux (L/sec/m^2)						Flux (L/sec/m^2)				Flux (L/sec/m^2)				
time,s.	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**	**Set1**	**Set2**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Average**	**Std.**
1278	0.050	0.046	0.042	0.047	0.047	0.003	0.731	0.817	0.774	0.061	0.057	12.502	13.238	8.599	7.407
1280	0.050	0.046	0.042	0.047	0.046	0.003	0.731	0.817	0.774	0.061	0.057	12.522	13.258	8.612	7.418
1282	0.050	0.046	0.042	0.047	0.046	0.003	0.731	0.817	0.774	0.061	0.057	12.541	13.279	8.626	7.430
1284	0.050	0.046	0.042	0.047	0.046	0.003	0.731	0.817	0.774	0.061	0.057	12.561	13.300	8.639	7.441
1286	0.050	0.046	0.042	0.047	0.046	0.003	0.731	0.817	0.774	0.061	0.057	12.580	13.321	8.653	7.453
1288	0.050	0.046	0.042	0.047	0.046	0.003	0.722	0.806	0.764	0.060	0.057	12.391	13.119	8.522	7.340
1292	0.050	0.046	0.042	0.047	0.046	0.003	0.722	0.806	0.764	0.060	0.057	12.429	13.160	8.549	7.363
1294	0.050	0.046	0.042	0.047	0.046	0.003	0.722	0.806	0.764	0.060	0.057	12.448	13.181	8.562	7.375
1296	0.050	0.046	0.042	0.047	0.046	0.003	0.722	0.806	0.764	0.060	0.057	12.468	13.201	8.575	7.386
1298	0.050	0.046	0.042	0.047	0.046	0.004	0.722	0.806	0.764	0.060	0.061	12.445	13.177	8.561	7.371
1300	0.050	0.046	0.042	0.047	0.046	0.004	0.722	0.806	0.764	0.060	0.061	12.464	13.198	8.574	7.382
1302	0.050	0.046	0.042	0.046	0.046	0.004	0.722	0.806	0.764	0.060	0.061	12.484	13.218	8.587	7.394
1304	0.050	0.046	0.041	0.046	0.046	0.004	0.722	0.806	0.764	0.060	0.061	12.503	13.238	8.601	7.405
1306	0.050	0.046	0.041	0.046	0.046	0.003	0.722	0.806	0.764	0.060	0.061	12.522	13.259	8.614	7.416
1308	0.050	0.046	0.041	0.046	0.046	0.003	0.722	0.806	0.764	0.060	0.061	12.541	13.279	8.627	7.428
1310	0.050	0.046	0.041	0.046	0.046	0.003	0.722	0.806	0.764	0.060	0.061	12.560	13.299	8.640	7.439
1312	0.050	0.045	0.041	0.046	0.046	0.003	0.722	0.806	0.764	0.060	0.061	12.580	13.320	8.653	7.451
1314	0.050	0.045	0.042	0.046	0.046	0.003	0.732	0.806	0.769	0.053	0.056	12.742	13.388	8.729	7.518
1316	0.050	0.045	0.042	0.046	0.046	0.003	0.732	0.806	0.769	0.053	0.056	12.761	13.408	8.742	7.529

Table D1 (continued)

	0.45 µm						2.5 µm				8 µm				
	Flux (L/sec/m^2)						Flux (L/sec/m^2)				Flux (L/sec/m^2)				
time,s.	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**	**Set1**	**Set2**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Average**	**Std.**
1318	0.050	0.045	0.042	0.046	0.046	0.003	0.732	0.806	0.769	0.053	0.056	12.780	13.429	8.755	7.541
1320	0.049	0.045	0.042	0.046	0.046	0.003	0.732	0.806	0.769	0.053	0.056	12.800	13.449	8.768	7.552
1322	0.049	0.045	0.042	0.046	0.045	0.003	0.732	0.806	0.769	0.053	0.056	12.819	13.469	8.782	7.564
1324	0.049	0.045	0.041	0.046	0.046	0.003	0.732	0.817	0.775	0.060	0.056	12.796	13.538	8.797	7.579
1326	0.049	0.045	0.041	0.046	0.045	0.003	0.732	0.817	0.775	0.060	0.056	12.816	13.559	8.810	7.590
1328	0.049	0.045	0.041	0.046	0.045	0.003	0.732	0.817	0.775	0.060	0.056	12.835	13.579	8.823	7.602
1330	0.049	0.045	0.041	0.046	0.045	0.003	0.732	0.817	0.775	0.060	0.056	12.854	13.599	8.837	7.613
1332	0.049	0.045	0.041	0.046	0.045	0.003	0.722	0.806	0.764	0.059	0.056	12.662	13.396	8.705	7.499
1334	0.049	0.045	0.041	0.046	0.045	0.003	0.722	0.806	0.764	0.059	0.056	12.681	13.417	8.718	7.510
1336	0.049	0.045	0.041	0.046	0.045	0.003	0.722	0.806	0.764	0.059	0.056	12.700	13.437	8.731	7.522
1338	0.049	0.045	0.041	0.046	0.045	0.003	0.722	0.806	0.764	0.059	0.060	12.678	13.413	8.717	7.506
1340	0.049	0.045	0.041	0.046	0.045	0.003	0.722	0.806	0.764	0.059	0.060	12.697	13.433	8.730	7.517
1342	0.049	0.045	0.041	0.046	0.045	0.003	0.722	0.806	0.764	0.059	0.060	12.716	13.453	8.743	7.529
1346	0.049	0.045	0.041	0.046	0.045	0.003	0.722	0.806	0.764	0.059	0.060	12.754	13.493	8.769	7.551
1348	0.049	0.045	0.041	0.045	0.045	0.003	0.722	0.806	0.764	0.059	0.060	12.772	13.513	8.782	7.562
1350	0.049	0.045	0.041	0.045	0.045	0.003	0.722	0.806	0.764	0.059	0.060	12.791	13.533	8.795	7.574
1352	0.049	0.045	0.041	0.045	0.045	0.003	0.722	0.806	0.764	0.059	0.060	12.810	13.553	8.808	7.585
1354	0.049	0.045	0.041	0.045	0.045	0.003	0.722	0.806	0.764	0.059	0.060	12.829	13.573	8.821	7.596
1356	0.049	0.045	0.041	0.045	0.045	0.003	0.733	0.806	0.770	0.052	0.055	12.992	13.642	8.896	7.663

Table D1 (continued)

	0.45 μm						2.5 μm				8 μm				
	Flux (L/sec/m^2)						Flux (L/sec/m^2)				Flux (L/sec/m^2)				
time,s.	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**	**Set1**	**Set2**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Average**	**Std.**
1358	0.049	0.045	0.041	0.045	0.045	0.003	0.733	0.806	0.770	0.052	0.055	13.011	13.662	8.909	7.675
1360	0.049	0.044	0.041	0.045	0.045	0.003	0.733	0.806	0.770	0.052	0.055	13.030	13.682	8.922	7.686
1362	0.048	0.044	0.041	0.045	0.045	0.003	0.733	0.806	0.770	0.052	0.055	13.049	13.702	8.936	7.697
1364	0.048	0.044	0.041	0.045	0.045	0.003	0.733	0.806	0.770	0.052	0.055	13.069	13.722	8.949	7.709
1366	0.048	0.044	0.041	0.045	0.045	0.003	0.733	0.806	0.770	0.052	0.055	13.088	13.742	8.962	7.720
1368	0.048	0.044	0.041	0.045	0.045	0.003	0.733	0.806	0.770	0.052	0.055	13.107	13.762	8.975	7.731
1370	0.048	0.044	0.041	0.045	0.044	0.003	0.733	0.806	0.770	0.052	0.055	13.126	13.782	8.988	7.743
1372	0.049	0.044	0.041	0.045	0.045	0.003	0.733	0.806	0.770	0.052	0.059	13.102	13.758	8.973	7.726
1374	0.049	0.045	0.041	0.045	0.045	0.003	0.723	0.796	0.760	0.051	0.059	12.909	13.554	8.841	7.612
1376	0.049	0.045	0.040	0.045	0.045	0.003	0.723	0.806	0.765	0.058	0.059	12.886	13.622	8.856	7.627
1378	0.049	0.044	0.040	0.045	0.045	0.003	0.723	0.806	0.765	0.058	0.059	12.905	13.642	8.869	7.638
1380	0.048	0.044	0.040	0.045	0.045	0.003	0.723	0.806	0.765	0.058	0.059	12.923	13.662	8.881	7.649
1384	0.048	0.044	0.040	0.045	0.044	0.003	0.723	0.806	0.765	0.058	0.059	12.961	13.702	8.907	7.672
1386	0.048	0.044	0.040	0.045	0.044	0.003	0.723	0.806	0.765	0.058	0.059	12.980	13.721	8.920	7.683
1388	0.048	0.044	0.040	0.045	0.044	0.003	0.723	0.806	0.765	0.058	0.059	12.998	13.741	8.933	7.694
1390	0.048	0.044	0.040	0.045	0.044	0.003	0.723	0.806	0.765	0.058	0.059	13.017	13.761	8.946	7.705
1392	0.048	0.044	0.040	0.045	0.044	0.003	0.723	0.806	0.765	0.058	0.059	13.036	13.781	8.959	7.716
1394	0.048	0.044	0.040	0.045	0.044	0.003	0.723	0.806	0.765	0.058	0.059	13.055	13.801	8.971	7.727
1396	0.048	0.044	0.040	0.044	0.044	0.003	0.723	0.806	0.765	0.058	0.059	13.073	13.820	8.984	7.738

Table D1 (continued)

	0.45 µm						2.5 µm				8 µm				
	Flux (L/sec/m^2)						Flux (L/sec/m^2)				Flux (L/sec/m^2)				
time,s.	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**	**Set1**	**Set2**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Average**	**Std.**
1398	0.048	0.044	0.040	0.044	0.044	0.003	0.723	0.806	0.765	0.058	0.059	13.092	13.840	8.997	7.750
1400	0.048	0.044	0.040	0.044	0.044	0.003	0.723	0.806	0.765	0.058	0.059	13.111	13.860	9.010	7.761
1402	0.048	0.044	0.040	0.044	0.044	0.003	0.723	0.806	0.765	0.058	0.059	13.129	13.880	9.023	7.772
1404	0.048	0.044	0.040	0.044	0.044	0.003	0.734	0.806	0.770	0.051	0.055	13.293	13.948	9.099	7.839
1406	0.048	0.044	0.040	0.044	0.044	0.003	0.734	0.806	0.770	0.051	0.059	13.269	13.923	9.084	7.823
1408	0.048	0.044	0.040	0.044	0.044	0.003	0.734	0.806	0.770	0.051	0.059	13.288	13.943	9.097	7.834
1410	0.048	0.043	0.040	0.044	0.044	0.003	0.734	0.806	0.770	0.051	0.059	13.307	13.963	9.109	7.845
1412	0.048	0.043	0.040	0.044	0.044	0.003	0.734	0.806	0.770	0.051	0.059	13.326	13.983	9.122	7.856
1414	0.048	0.043	0.040	0.044	0.044	0.003	0.734	0.806	0.770	0.051	0.059	13.345	14.002	9.135	7.867
1416	0.048	0.044	0.040	0.044	0.044	0.003	0.724	0.796	0.760	0.050	0.058	13.150	13.798	9.002	7.752
1418	0.048	0.044	0.040	0.044	0.044	0.003	0.724	0.806	0.765	0.058	0.058	13.126	13.866	9.017	7.767
1420	0.048	0.044	0.040	0.044	0.044	0.003	0.724	0.806	0.765	0.058	0.058	13.145	13.885	9.030	7.778
1422	0.048	0.044	0.040	0.044	0.044	0.003	0.724	0.806	0.765	0.058	0.058	13.163	13.905	9.042	7.789
1424	0.048	0.044	0.040	0.044	0.044	0.003	0.724	0.806	0.765	0.058	0.058	13.182	13.925	9.055	7.800
1426	0.047	0.044	0.040	0.044	0.044	0.003	0.724	0.806	0.765	0.058	0.058	13.200	13.944	9.068	7.811
1428	0.047	0.043	0.040	0.044	0.044	0.003	0.724	0.806	0.765	0.058	0.058	13.219	13.964	9.080	7.822
1430	0.047	0.043	0.040	0.044	0.044	0.003	0.724	0.806	0.765	0.058	0.058	13.237	13.983	9.093	7.833
1432	0.047	0.043	0.039	0.044	0.043	0.003	0.724	0.806	0.765	0.058	0.058	13.256	14.003	9.106	7.844
1434	0.047	0.043	0.039	0.044	0.043	0.003	0.724	0.806	0.765	0.058	0.058	13.275	14.022	9.118	7.855

Table D1 (continued)

	0.45 μm						2.5 μm				8 μm				
	Flux (L/sec/m^2)						Flux (L/sec/m^2)				Flux (L/sec/m^2)				
time,s.	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**	**Set1**	**Set2**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Average**	**Std.**
1438	0.047	0.043	0.039	0.044	0.043	0.003	0.724	0.806	0.765	0.058	0.058	13.312	14.061	9.144	7.877
1440	0.047	0.043	0.039	0.044	0.043	0.003	0.724	0.806	0.765	0.058	0.058	13.330	14.081	9.156	7.888
1442	0.047	0.043	0.039	0.044	0.043	0.003	0.724	0.806	0.765	0.058	0.062	13.306	14.056	9.141	7.872
1444	0.047	0.043	0.039	0.044	0.043	0.003	0.724	0.806	0.765	0.058	0.062	13.325	14.075	9.154	7.883
1446	0.047	0.043	0.039	0.043	0.043	0.003	0.724	0.806	0.765	0.058	0.062	13.343	14.095	9.167	7.894
1448	0.047	0.043	0.039	0.043	0.043	0.003	0.724	0.806	0.765	0.058	0.062	13.361	14.114	9.179	7.905
1450	0.047	0.043	0.039	0.043	0.043	0.003	0.724	0.806	0.765	0.058	0.062	13.380	14.134	9.192	7.916
1452	0.047	0.043	0.039	0.043	0.043	0.003	0.724	0.806	0.765	0.058	0.062	13.398	14.153	9.205	7.927
1454	0.047	0.043	0.039	0.043	0.043	0.003	0.724	0.806	0.765	0.058	0.062	13.417	14.173	9.217	7.937
1456	0.047	0.043	0.039	0.043	0.043	0.003	0.724	0.806	0.765	0.058	0.062	13.435	14.192	9.230	7.948
1458	0.047	0.043	0.039	0.043	0.043	0.003	0.724	0.806	0.765	0.058	0.062	13.454	14.212	9.243	7.959
1460	0.047	0.043	0.039	0.043	0.043	0.003	0.735	0.806	0.770	0.050	0.058	13.619	14.281	9.319	8.027
1462	0.047	0.042	0.039	0.043	0.043	0.003	0.735	0.806	0.770	0.050	0.058	13.637	14.300	9.332	8.038
1464	0.047	0.042	0.039	0.043	0.043	0.003	0.735	0.806	0.770	0.050	0.058	13.656	14.320	9.344	8.049
1466	0.047	0.042	0.039	0.043	0.043	0.003	0.735	0.806	0.770	0.050	0.058	13.674	14.339	9.357	8.060
1468	0.047	0.042	0.039	0.043	0.043	0.003	0.735	0.806	0.770	0.050	0.058	13.693	14.359	9.370	8.071
1470	0.047	0.042	0.039	0.043	0.043	0.003	0.735	0.806	0.770	0.050	0.058	13.712	14.378	9.383	8.082
1472	0.046	0.042	0.039	0.043	0.043	0.003	0.735	0.806	0.770	0.050	0.058	13.730	14.398	9.395	8.093
1474	0.046	0.043	0.039	0.043	0.043	0.003	0.725	0.806	0.766	0.057	0.058	13.489	14.239	9.262	7.980

Table D1 (continued)

	0.45 µm						2.5 µm				8 µm				
	Flux (L/sec/m^2)						Flux (L/sec/m^2)				Flux (L/sec/m^2)				
time,s.	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**	**Set1**	**Set2**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Average**	**Std.**
1478	0.046	0.043	0.039	0.043	0.043	0.003	0.725	0.806	0.766	0.057	0.058	13.526	14.277	9.287	8.002
1480	0.046	0.042	0.039	0.043	0.043	0.003	0.725	0.806	0.766	0.057	0.058	13.544	14.297	9.300	8.013
1482	0.046	0.042	0.039	0.043	0.043	0.003	0.725	0.806	0.766	0.057	0.058	13.563	14.316	9.312	8.023
1484	0.047	0.042	0.039	0.043	0.043	0.003	0.725	0.806	0.766	0.057	0.061	13.538	14.290	9.297	8.007
1486	0.047	0.042	0.039	0.043	0.043	0.003	0.725	0.806	0.766	0.057	0.061	13.556	14.310	9.309	8.018
1488	0.047	0.042	0.039	0.043	0.043	0.003	0.725	0.806	0.766	0.057	0.061	13.575	14.329	9.322	8.028
1490	0.046	0.042	0.038	0.043	0.042	0.003	0.725	0.806	0.766	0.057	0.061	13.593	14.348	9.334	8.039
1492	0.046	0.042	0.038	0.043	0.042	0.003	0.725	0.806	0.766	0.057	0.061	13.611	14.367	9.347	8.050
1494	0.046	0.042	0.038	0.043	0.042	0.003	0.725	0.806	0.766	0.057	0.061	13.629	14.387	9.359	8.061
1496	0.046	0.042	0.038	0.043	0.042	0.003	0.725	0.806	0.766	0.057	0.061	13.648	14.406	9.372	8.072
1498	0.046	0.042	0.038	0.042	0.042	0.003	0.725	0.806	0.766	0.057	0.061	13.666	14.425	9.384	8.083
1500	0.046	0.042	0.038	0.042	0.042	0.003	0.725	0.806	0.766	0.057	0.061	13.684	14.444	9.397	8.094
1502	0.046	0.042	0.038	0.042	0.042	0.003	0.725	0.806	0.766	0.057	0.061	13.702	14.464	9.409	8.104
1504	0.046	0.042	0.038	0.042	0.042	0.003	0.725	0.806	0.766	0.057	0.061	13.721	14.483	9.422	8.115
1506	0.046	0.042	0.038	0.042	0.042	0.003	0.725	0.806	0.766	0.057	0.061	13.739	14.502	9.434	8.126
1508	0.046	0.042	0.038	0.042	0.042	0.003	0.725	0.806	0.766	0.057	0.061	13.757	14.521	9.447	8.137
1510	0.046	0.042	0.038	0.042	0.042	0.003	0.725	0.806	0.766	0.057	0.061	13.775	14.541	9.459	8.148
1512	0.046	0.042	0.038	0.042	0.042	0.003	0.725	0.806	0.766	0.057	0.061	13.794	14.560	9.472	8.159
1514	0.046	0.042	0.038	0.042	0.042	0.003	0.725	0.806	0.766	0.057	0.061	13.812	14.579	9.484	8.169

Table D1 (continued)

	0.45 μm						2.5 μm				8 μm				
	Flux (L/sec/m^2)						Flux (L/sec/m^2)				Flux (L/sec/m^2)				
time,s.	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**	**Set1**	**Set2**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Average**	**Std.**
1518	0.046	0.042	0.038	0.042	0.042	0.003	0.716	0.806	0.761	0.063	0.061	13.590	14.439	9.363	8.067
1520	0.046	0.042	0.038	0.042	0.042	0.003	0.716	0.806	0.761	0.063	0.061	13.608	14.458	9.376	8.078
1522	0.045	0.042	0.038	0.042	0.042	0.003	0.716	0.806	0.761	0.063	0.061	13.626	14.477	9.388	8.088
1524	0.045	0.042	0.038	0.042	0.042	0.003	0.716	0.806	0.761	0.063	0.061	13.644	14.496	9.400	8.099
1526	0.046	0.042	0.038	0.042	0.042	0.003	0.726	0.806	0.766	0.056	0.061	13.765	14.519	9.448	8.139
1528	0.046	0.042	0.038	0.042	0.042	0.003	0.726	0.806	0.766	0.056	0.061	13.783	14.538	9.461	8.149
1530	0.046	0.042	0.038	0.042	0.042	0.003	0.726	0.806	0.766	0.056	0.061	13.801	14.557	9.473	8.160
1532	0.046	0.042	0.038	0.042	0.042	0.003	0.726	0.806	0.766	0.056	0.061	13.819	14.577	9.485	8.171
1534	0.046	0.042	0.038	0.042	0.042	0.003	0.726	0.806	0.766	0.056	0.061	13.837	14.596	9.498	8.182
1536	0.046	0.041	0.038	0.042	0.042	0.003	0.726	0.806	0.766	0.056	0.061	13.855	14.615	9.510	8.192
1538	0.046	0.041	0.038	0.042	0.042	0.003	0.726	0.806	0.766	0.056	0.061	13.873	14.634	9.523	8.203
1540	0.045	0.041	0.038	0.042	0.042	0.003	0.726	0.806	0.766	0.056	0.061	13.891	14.653	9.535	8.214
1542	0.045	0.041	0.038	0.042	0.042	0.003	0.726	0.806	0.766	0.056	0.061	13.909	14.672	9.547	8.224
1544	0.045	0.041	0.038	0.042	0.041	0.003	0.726	0.806	0.766	0.056	0.061	13.928	14.691	9.560	8.235
1546	0.045	0.041	0.038	0.042	0.041	0.003	0.726	0.806	0.766	0.056	0.061	13.946	14.710	9.572	8.246
1548	0.045	0.041	0.038	0.042	0.041	0.003	0.726	0.806	0.766	0.056	0.061	13.964	14.729	9.584	8.257
1550	0.045	0.041	0.037	0.042	0.041	0.003	0.726	0.806	0.766	0.056	0.061	13.982	14.748	9.597	8.267
1552	0.045	0.041	0.037	0.042	0.041	0.003	0.726	0.806	0.766	0.056	0.061	14.000	14.767	9.609	8.278
1554	0.045	0.041	0.037	0.041	0.041	0.003	0.726	0.806	0.766	0.056	0.061	14.018	14.786	9.621	8.289

Table D1 (continued)

	0.45 µm						2.5 µm				8 µm				
	Flux (L/sec/m^2)						Flux (L/sec/m^2)				Flux (L/sec/m^2)				
time,s.	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**	**Set1**	**Set2**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Average**	**Std.**
1558	0.045	0.041	0.037	0.042	0.041	0.003	0.726	0.816	0.771	0.063	0.061	14.010	14.874	9.648	8.314
1560	0.045	0.041	0.037	0.042	0.041	0.003	0.717	0.806	0.761	0.063	0.061	13.812	14.664	9.512	8.196
1562	0.045	0.041	0.037	0.042	0.041	0.003	0.717	0.806	0.761	0.063	0.061	13.830	14.683	9.524	8.207
1564	0.045	0.041	0.037	0.042	0.041	0.003	0.717	0.806	0.761	0.063	0.061	13.848	14.701	9.537	8.218
1566	0.045	0.041	0.037	0.042	0.041	0.003	0.717	0.806	0.761	0.063	0.064	13.823	14.675	9.521	8.201
1568	0.045	0.041	0.037	0.042	0.041	0.003	0.717	0.806	0.761	0.063	0.064	13.840	14.694	9.533	8.211
1570	0.045	0.041	0.037	0.042	0.041	0.003	0.717	0.806	0.761	0.063	0.064	13.858	14.712	9.545	8.222
1572	0.045	0.041	0.037	0.042	0.041	0.003	0.717	0.806	0.761	0.063	0.064	13.876	14.731	9.557	8.232
1574	0.045	0.041	0.037	0.041	0.041	0.003	0.717	0.806	0.761	0.063	0.064	13.893	14.750	9.569	8.243
1576	0.045	0.041	0.037	0.041	0.041	0.003	0.717	0.806	0.761	0.063	0.064	13.911	14.769	9.581	8.253
1578	0.045	0.041	0.037	0.041	0.041	0.003	0.727	0.806	0.766	0.056	0.060	14.076	14.837	9.658	8.321
1580	0.045	0.041	0.037	0.041	0.041	0.003	0.727	0.806	0.766	0.056	0.060	14.094	14.856	9.670	8.331
1582	0.045	0.041	0.037	0.041	0.041	0.003	0.727	0.806	0.766	0.056	0.060	14.112	14.875	9.682	8.342
1584	0.045	0.041	0.037	0.041	0.041	0.003	0.727	0.806	0.766	0.056	0.060	14.130	14.894	9.694	8.352
1586	0.045	0.041	0.037	0.041	0.041	0.003	0.727	0.806	0.766	0.056	0.060	14.148	14.912	9.707	8.363
1588	0.045	0.041	0.037	0.041	0.041	0.003	0.727	0.806	0.766	0.056	0.060	14.165	14.931	9.719	8.374
1590	0.045	0.041	0.037	0.041	0.041	0.003	0.727	0.806	0.766	0.056	0.060	14.183	14.950	9.731	8.384
1592	0.044	0.040	0.037	0.041	0.041	0.003	0.727	0.806	0.766	0.056	0.060	14.201	14.969	9.743	8.395
1594	0.044	0.040	0.037	0.041	0.041	0.003	0.727	0.806	0.766	0.056	0.060	14.219	14.988	9.755	8.405

Table D1 (continued)

	0.45 µm						2.5 µm				8 µm				
	Flux (L/sec/m^2)						Flux (L/sec/m^2)				Flux (L/sec/m^2)				
time,s.	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**	**Set1**	**Set2**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Average**	**Std.**
1598	0.044	0.040	0.037	0.041	0.041	0.003	0.727	0.806	0.766	0.056	0.060	14.255	15.025	9.780	8.427
1600	0.044	0.040	0.037	0.041	0.041	0.003	0.727	0.806	0.766	0.056	0.060	14.272	15.044	9.792	8.437
1602	0.044	0.040	0.037	0.041	0.041	0.003	0.727	0.806	0.766	0.056	0.060	14.255	15.025	9.780	8.427
1604	0.044	0.040	0.037	0.041	0.041	0.003	0.727	0.806	0.766	0.056	0.060	14.272	15.044	9.792	8.437
1606	0.044	0.040	0.037	0.041	0.041	0.003	0.727	0.806	0.766	0.056	0.060	14.255	15.025	9.780	8.427
1608	0.044	0.040	0.037	0.041	0.041	0.003	0.727	0.806	0.766	0.056	0.060	14.272	15.044	9.792	8.437
1610	0.044	0.040	0.037	0.041	0.041	0.003	0.727	0.806	0.766	0.056	0.060	14.255	15.025	9.780	8.427
1612	0.044	0.040	0.037	0.041	0.041	0.003	0.727	0.806	0.766	0.056	0.060	14.272	15.044	9.792	8.437
1614	0.044	0.040	0.037	0.041	0.041	0.003	0.727	0.806	0.766	0.056	0.060	14.255	15.025	9.780	8.427
1616	0.044	0.040	0.037	0.041	0.041	0.003	0.727	0.806	0.766	0.056	0.060	14.272	15.044	9.792	8.437

D.1.2. High Pressure MF

High pressure MF tests were carried on at a pressure of 3 Bar and for the Mixture. The data belonging to the Mixture are given in Table D2.

Table D2. Raw Data (volume vs. time) of MF for the Mixture (P=3 Bar)

	2.5 μm					0.45μm					
	Flux (L/sec/m^2)					Flux (L/sec/m^2)					
time, s.	**Set1**	**Set2**	**Set3**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**
2.00	0.96	0.72	0.96	0.96	0.88	2.03	2.27	1.67	0.24	1.55	0.91
4.00	0.78	0.66	0.84	0.84	0.76	1.79	1.85	1.73	1.25	1.66	0.27
6.00	0.64	0.52	0.64	0.64	0.60	1.51	1.59	1.59	1.31	1.50	0.13
8.00	0.54	0.45	0.54	0.54	0.51	1.31	1.34	1.43	1.25	1.34	0.07
10.00	0.45	0.38	0.45	0.45	0.43	1.17	1.19	1.29	1.17	1.21	0.06
12.00	0.40	0.34	0.40	0.40	0.38	1.06	1.06	1.17	1.08	1.09	0.06
14.00	0.36	0.29	0.36	0.36	0.34	0.97	0.97	1.08	1.01	1.01	0.05
16.00	0.33	0.27	0.33	0.33	0.31	0.90	0.90	1.00	0.93	0.93	0.05
18.00	0.31	0.25	0.29	0.29	0.28	0.84	0.82	0.93	0.88	0.87	0.05
20.00	0.29	0.23	0.27	0.27	0.26	0.78	0.78	0.88	0.82	0.82	0.05
22.00	0.26	0.22	0.26	0.26	0.25	0.74	0.73	0.84	0.78	0.77	0.05
24.00	0.25	0.21	0.24	0.24	0.23	0.70	0.69	0.80	0.75	0.73	0.05
26.00	0.23	0.19	0.23	0.23	0.22	0.66	0.66	0.75	0.71	0.70	0.04
28.00	0.22	0.19	0.22	0.22	0.21	0.63	0.63	0.73	0.68	0.67	0.05
30.00	0.22	0.18	0.21	0.21	0.20	0.61	0.61	0.69	0.65	0.64	0.04
32.00	0.20	0.17	0.20	0.20	0.19	0.58	0.58	0.66	0.63	0.62	0.04
34.00	0.20	0.16	0.20	0.20	0.19	0.56	0.56	0.64	0.61	0.59	0.04

Table D2 (continued)

	2.5 µm					0.45 µm					
	Flux (L/sec/m^2)					Flux (L/sec/m^2)					
time, s.	**Set1**	**Set2**	**Set3**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**
38.00	0.18	0.15	0.18	0.18	0.17	0.52	0.52	0.60	0.57	0.55	0.04
40.00	0.17	0.15	0.17	0.17	0.17	0.50	0.50	0.58	0.56	0.53	0.04
42.00	0.17	0.14	0.17	0.17	0.16	0.49	0.49	0.56	0.54	0.52	0.04
44.00	0.16	0.14	0.16	0.16	0.16	0.47	0.47	0.55	0.53	0.51	0.04
46.00	0.16	0.14	0.16	0.16	0.15	0.46	0.46	0.53	0.51	0.49	0.04
48.00	0.15	0.13	0.15	0.15	0.15	0.45	0.45	0.52	0.50	0.48	0.04
50.00	0.15	0.13	0.15	0.15	0.14	0.44	0.43	0.51	0.49	0.47	0.04
52.00	0.15	0.12	0.15	0.15	0.14	0.43	0.43	0.49	0.48	0.46	0.03
54.00	0.14	0.12	0.14	0.14	0.14	0.42	0.42	0.48	0.47	0.45	0.03
56.00	0.14	0.12	0.14	0.14	0.13	0.41	0.41	0.47	0.46	0.44	0.04
58.00	0.14	0.12	0.14	0.14	0.13	0.40	0.40	0.46	0.45	0.43	0.03
60.00	0.14	0.12	0.13	0.13	0.13	0.39	0.39	0.45	0.44	0.42	0.03
62.00	0.13	0.11	0.13	0.13	0.12	0.38	0.38	0.44	0.43	0.41	0.03
64.00	0.13	0.11	0.13	0.13	0.12	0.37	0.37	0.43	0.43	0.40	0.03
66.00	0.13	0.11	0.12	0.12	0.12	0.37	0.37	0.43	0.42	0.39	0.03
68.00	0.12	0.11	0.12	0.12	0.12	0.36	0.36	0.42	0.41	0.39	0.03
70.00	0.12	0.10	0.12	0.12	0.11	0.35	0.35	0.41	0.40	0.38	0.03
72.00	0.12	0.10	0.12	0.12	0.11	0.35	0.35	0.40	0.40	0.37	0.03
74.00	0.12	0.10	0.12	0.12	0.11	0.34	0.34	0.40	0.39	0.37	0.03

Table D2 (continued)

	2.5 µm					0.45 µm					
	Flux (L/sec/m^2)					Flux (L/sec/m^2)					
time, s.	**Set1**	**Set2**	**Set3**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**
80.00	0.11	0.10	0.11	0.11	0.11	0.32	0.32	0.38	0.37	0.35	0.03
82.00	0.11	0.09	0.11	0.11	0.10	0.32	0.32	0.37	0.37	0.34	0.03
84.00	0.11	0.09	0.11	0.11	0.10	0.31	0.31	0.37	0.36	0.34	0.03
86.00	0.11	0.09	0.11	0.11	0.10	0.31	0.31	0.36	0.36	0.33	0.03
88.00	0.10	0.09	0.10	0.10	0.10	0.30	0.30	0.36	0.35	0.33	0.03
90.00	0.10	0.09	0.10	0.10	0.10	0.30	0.30	0.35	0.35	0.32	0.03
92.00	0.10	0.09	0.10	0.10	0.10	0.30	0.30	0.35	0.34	0.32	0.03
94.00	0.10	0.09	0.10	0.10	0.10	0.29	0.29	0.34	0.34	0.32	0.03
96.00	0.10	0.08	0.10	0.10	0.09	0.29	0.29	0.34	0.33	0.31	0.03
98.00	0.10	0.08	0.10	0.10	0.09	0.29	0.28	0.33	0.33	0.31	0.03
100.00	0.10	0.08	0.10	0.10	0.09	0.28	0.28	0.33	0.33	0.30	0.03
102.00	0.10	0.08	0.09	0.09	0.09	0.28	0.28	0.33	0.32	0.30	0.03
104.00	0.09	0.08	0.09	0.09	0.09	0.27	0.27	0.32	0.32	0.30	0.03
106.00	0.09	0.08	0.09	0.09	0.09	0.27	0.27	0.32	0.32	0.29	0.03
108.00	0.09	0.08	0.09	0.09	0.09	0.27	0.27	0.31	0.31	0.29	0.03
110.00	0.09	0.08	0.09	0.09	0.09	0.26	0.26	0.31	0.31	0.29	0.03
112.00	0.09	0.08	0.09	0.09	0.08	0.26	0.26	0.31	0.31	0.28	0.03
114.00	0.09	0.08	0.09	0.09	0.08	0.26	0.26	0.30	0.30	0.28	0.03
116.00	0.09	0.08	0.09	0.09	0.08	0.26	0.25	0.30	0.30	0.28	0.03

Table D2 (continued)

	2.5 μm					0.45 μm					
	Flux (L/sec/m^2)					Flux (L/sec/m^2)					
time, s.	**Set1**	**Set2**	**Set3**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**
122.00	0.09	0.07	0.08	0.08	0.08	0.25	0.25	0.29	0.29	0.27	0.03
124.00	0.08	0.07	0.08	0.08	0.08	0.24	0.24	0.29	0.29	0.27	0.03
126.00	0.08	0.07	0.08	0.08	0.08	0.24	0.24	0.28	0.28	0.26	0.02
128.00	0.08	0.07	0.08	0.08	0.08	0.24	0.24	0.28	0.28	0.26	0.02
130.00	0.08	0.07	0.08	0.08	0.08	0.24	0.24	0.28	0.28	0.26	0.02
132.00	0.08	0.07	0.08	0.08	0.08	0.24	0.23	0.28	0.28	0.26	0.02
134.00	0.08	0.07	0.08	0.08	0.08	0.23	0.23	0.27	0.27	0.25	0.02
136.00	0.08	0.07	0.08	0.08	0.08	0.23	0.23	0.27	0.27	0.25	0.02
138.00	0.08	0.07	0.08	0.08	0.08	0.23	0.23	0.27	0.27	0.25	0.02
140.00	0.08	0.07	0.08	0.08	0.07	0.23	0.23	0.27	0.27	0.25	0.02
142.00	0.08	0.07	0.08	0.08	0.07	0.22	0.22	0.26	0.26	0.24	0.02
144.00	0.08	0.07	0.07	0.07	0.07	0.22	0.22	0.26	0.26	0.24	0.02
146.00	0.08	0.07	0.08	0.08	0.07	0.22	0.22	0.26	0.26	0.24	0.02
150.00	0.08	0.07	0.07	0.07	0.07	0.22	0.22	0.26	0.25	0.24	0.02
152.00	0.08	0.06	0.07	0.07	0.07	0.21	0.21	0.25	0.25	0.23	0.02
154.00	0.07	0.06	0.07	0.07	0.07	0.21	0.21	0.25	0.25	0.23	0.02
156.00	0.07	0.06	0.07	0.07	0.07	0.21	0.21	0.25	0.25	0.23	0.02
158.00	0.07	0.06	0.07	0.07	0.07	0.21	0.21	0.25	0.25	0.23	0.02
160.00	0.07	0.06	0.07	0.07	0.07	0.21	0.21	0.25	0.24	0.23	0.02

Table D2 (continued)

	2.5 μm					0.45 μm					
	Flux (L/sec/m^2)					Flux (L/sec/m^2)					
time, s.	**Set1**	**Set2**	**Set3**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**
164.00	0.07	0.06	0.07	0.07	0.07	0.20	0.20	0.24	0.24	0.22	0.02
166.00	0.07	0.06	0.07	0.07	0.07	0.20	0.20	0.24	0.24	0.22	0.02
168.00	0.07	0.06	0.07	0.07	0.07	0.20	0.20	0.24	0.24	0.22	0.02
170.00	0.07	0.06	0.07	0.07	0.07	0.20	0.20	0.24	0.24	0.22	0.02
172.00	0.07	0.06	0.07	0.07	0.07	0.20	0.20	0.23	0.23	0.22	0.02
174.00	0.07	0.06	0.07	0.07	0.07	0.20	0.20	0.23	0.23	0.21	0.02
176.00	0.07	0.06	0.07	0.07	0.06	0.19	0.19	0.23	0.23	0.21	0.02
178.00	0.07	0.06	0.07	0.07	0.06	0.19	0.19	0.23	0.23	0.21	0.02
180.00	0.07	0.06	0.07	0.07	0.06	0.19	0.19	0.23	0.23	0.21	0.02
184.00	0.07	0.06	0.06	0.06	0.06	0.19	0.19	0.22	0.23	0.21	0.02
186.00	0.07	0.06	0.06	0.06	0.06	0.19	0.19	0.22	0.22	0.21	0.02
188.00	0.07	0.06	0.06	0.06	0.06	0.19	0.19	0.22	0.22	0.20	0.02
190.00	0.07	0.06	0.06	0.06	0.06	0.18	0.19	0.22	0.22	0.20	0.02
192.00	0.07	0.05	0.06	0.06	0.06	0.18	0.18	0.22	0.22	0.20	0.02
194.00	0.07	0.05	0.06	0.06	0.06	0.18	0.18	0.22	0.22	0.20	0.02
196.00	0.06	0.05	0.06	0.06	0.06	0.18	0.18	0.22	0.22	0.20	0.02
198.00	0.07	0.05	0.06	0.06	0.06	0.18	0.18	0.21	0.22	0.20	0.02
200.00	0.06	0.05	0.06	0.06	0.06	0.18	0.18	0.21	0.21	0.20	0.02
202.00	0.06	0.05	0.06	0.06	0.06	0.18	0.18	0.21	0.21	0.20	0.02

Table D2 (continued)

	2.5 µm					0.45 µm					
	Flux (L/sec/m^2)					Flux (L/sec/m^2)					
time, s.	**Set1**	**Set2**	**Set3**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**
206.00	0.06	0.05	0.06	0.06	0.06	0.18	0.18	0.21	0.21	0.19	0.02
208.00	0.06	0.05	0.06	0.06	0.06	0.17	0.18	0.21	0.21	0.19	0.02
210.00	0.06	0.05	0.06	0.06	0.06	0.17	0.17	0.21	0.21	0.19	0.02
212.00	0.06	0.05	0.06	0.06	0.06	0.17	0.17	0.21	0.21	0.19	0.02
214.00	0.06	0.05	0.06	0.06	0.06	0.17	0.17	0.20	0.21	0.19	0.02
216.00	0.06	0.05	0.06	0.06	0.06	0.17	0.17	0.20	0.20	0.19	0.02
218.00	0.06	0.05	0.06	0.06	0.06	0.17	0.17	0.20	0.20	0.19	0.02
220.00	0.06	0.05	0.06	0.06	0.06	0.17	0.17	0.20	0.20	0.19	0.02
222.00	0.06	0.05	0.06	0.06	0.06	0.17	0.17	0.20	0.20	0.18	0.02
224.00	0.06	0.05	0.06	0.06	0.06	0.17	0.17	0.20	0.20	0.18	0.02
228.00	0.06	0.05	0.06	0.06	0.06	0.16	0.17	0.20	0.20	0.18	0.02
230.00	0.06	0.05	0.06	0.06	0.06	0.16	0.16	0.20	0.20	0.18	0.02
232.00	0.06	0.05	0.06	0.06	0.05	0.16	0.16	0.19	0.20	0.18	0.02
234.00	0.06	0.05	0.06	0.06	0.05	0.16	0.16	0.19	0.20	0.18	0.02
236.00	0.06	0.05	0.06	0.06	0.05	0.16	0.16	0.19	0.19	0.18	0.02
238.00	0.06	0.05	0.06	0.06	0.05	0.16	0.16	0.19	0.19	0.18	0.02
240.00	0.06	0.05	0.05	0.05	0.05	0.16	0.16	0.19	0.19	0.18	0.02
242.00	0.06	0.05	0.05	0.05	0.05	0.16	0.16	0.19	0.19	0.17	0.02
244.00	0.06	0.05	0.05	0.05	0.05	0.16	0.16	0.19	0.19	0.17	0.02

Table D2 (continued)

	2.5 μm					0.45 μm					
	Flux (L/sec/m^2)					Flux (L/sec/m^2)					
time, s.	**Set1**	**Set2**	**Set3**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**
248.00	0.06	0.05	0.05	0.05	0.05	0.16	0.16	0.19	0.19	0.17	0.02
250.00	0.06	0.05	0.05	0.05	0.05	0.15	0.16	0.19	0.19	0.17	0.02
252.00	0.06	0.05	0.05	0.05	0.05	0.15	0.16	0.18	0.19	0.17	0.02
254.00	0.06	0.05	0.05	0.05	0.05	0.15	0.15	0.18	0.19	0.17	0.02
256.00	0.06	0.05	0.05	0.05	0.05	0.15	0.15	0.18	0.18	0.17	0.02
258.00	0.06	0.05	0.05	0.05	0.05	0.15	0.15	0.18	0.18	0.17	0.02
260.00	0.06	0.05	0.05	0.05	0.05	0.15	0.15	0.18	0.18	0.17	0.02
262.00	0.06	0.05	0.05	0.05	0.05	0.15	0.15	0.18	0.18	0.17	0.02
264.00	0.06	0.05	0.05	0.05	0.05	0.15	0.15	0.18	0.18	0.17	0.02
266.00	0.05	0.05	0.05	0.05	0.05	0.15	0.15	0.18	0.18	0.16	0.02
268.00	0.05	0.05	0.05	0.05	0.05	0.15	0.15	0.18	0.18	0.16	0.02
270.00	0.05	0.05	0.05	0.05	0.05	0.15	0.15	0.18	0.18	0.16	0.02
272.00	0.05	0.04	0.05	0.05	0.05	0.15	0.15	0.18	0.18	0.16	0.02
274.00	0.05	0.04	0.05	0.05	0.05	0.15	0.15	0.18	0.18	0.16	0.02
278.00	0.05	0.04	0.05	0.05	0.05	0.15	0.15	0.17	0.18	0.16	0.02
280.00	0.05	0.04	0.05	0.05	0.05	0.14	0.15	0.17	0.17	0.16	0.02
282.00	0.05	0.04	0.05	0.05	0.05	0.14	0.14	0.17	0.17	0.16	0.02
284.00	0.05	0.04	0.05	0.05	0.05	0.14	0.14	0.17	0.17	0.16	0.02
286.00	0.05	0.04	0.05	0.05	0.05	0.14	0.14	0.17	0.17	0.16	0.02

Table D2 (continued)

	2.5 μm					0.45 μm					
	Flux (L/sec/m^2)					Flux (L/sec/m^2)					
time, s.	**Set1**	**Set2**	**Set3**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**
290.00	0.05	0.04	0.05	0.05	0.05	0.14	0.14	0.17	0.17	0.16	0.02
292.00	0.05	0.04	0.05	0.05	0.05	0.14	0.14	0.17	0.17	0.16	0.02
294.00	0.05	0.04	0.05	0.05	0.05	0.14	0.14	0.17	0.17	0.15	0.02
296.00	0.05	0.04	0.05	0.05	0.05	0.14	0.14	0.17	0.17	0.15	0.02
298.00	0.05	0.04	0.05	0.05	0.05	0.14	0.14	0.17	0.17	0.15	0.02
300.00	0.05	0.04	0.05	0.05	0.05	0.14	0.14	0.17	0.17	0.15	0.02
304.00	0.05	0.04	0.05	0.05	0.05	0.14	0.14	0.16	0.17	0.15	0.02
306.00	0.05	0.04	0.05	0.05	0.05	0.14	0.14	0.16	0.16	0.15	0.02
308.00	0.05	0.04	0.05	0.05	0.05	0.14	0.14	0.16	0.16	0.15	0.02
310.00	0.05	0.04	0.05	0.05	0.05	0.14	0.14	0.16	0.16	0.15	0.02
312.00	0.05	0.04	0.05	0.05	0.05	0.13	0.14	0.16	0.16	0.15	0.02
314.00	0.05	0.04	0.05	0.05	0.05	0.13	0.13	0.16	0.16	0.15	0.02
316.00	0.05	0.04	0.05	0.05	0.05	0.13	0.13	0.16	0.16	0.15	0.02
318.00	0.05	0.04	0.05	0.05	0.05	0.13	0.13	0.16	0.16	0.15	0.02
320.00	0.05	0.04	0.05	0.05	0.05	0.13	0.13	0.16	0.16	0.15	0.02
322.00	0.05	0.04	0.05	0.05	0.05	0.13	0.13	0.16	0.16	0.15	0.02
324.00	0.05	0.04	0.05	0.05	0.05	0.13	0.13	0.16	0.16	0.15	0.02
326.00	0.05	0.04	0.05	0.05	0.05	0.13	0.13	0.16	0.16	0.14	0.02
328.00	0.05	0.04	0.05	0.05	0.04	0.13	0.13	0.16	0.16	0.14	0.02

Table D2 (continued)

	2.5 μm					0.45 μm					
	Flux (L/sec/m²)					Flux (L/sec/m²)					
time, s.	**Set1**	**Set2**	**Set3**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**
332.00	0.05	0.04	0.05	0.05	0.04	0.13	0.13	0.16	0.16	0.14	0.02
334.00	0.05	0.04	0.05	0.05	0.04	0.13	0.13	0.15	0.16	0.14	0.02
336.00	0.05	0.04	0.05	0.05	0.04	0.13	0.13	0.15	0.16	0.14	0.01
338.00	0.05	0.04	0.05	0.05	0.04	0.13	0.13	0.15	0.16	0.14	0.02
340.00	0.05	0.04	0.04	0.04	0.04	0.13	0.13	0.15	0.15	0.14	0.02
342.00	0.05	0.04	0.04	0.04	0.04	0.13	0.13	0.15	0.15	0.14	0.01
344.00	0.05	0.04	0.04	0.04	0.04	0.13	0.13	0.15	0.15	0.14	0.01
346.00	0.05	0.04	0.04	0.04	0.04	0.13	0.13	0.15	0.15	0.14	0.01
348.00	0.05	0.04	0.04	0.04	0.04	0.13	0.13	0.15	0.15	0.14	0.01
350.00	0.05	0.04	0.04	0.04	0.04	0.13	0.13	0.15	0.15	0.14	0.01
352.00	0.05	0.04	0.04	0.04	0.04	0.12	0.13	0.15	0.15	0.14	0.01
354.00	0.05	0.04	0.04	0.04	0.04	0.12	0.12	0.15	0.15	0.14	0.01
356.00	0.05	0.04	0.04	0.04	0.04	0.12	0.12	0.15	0.15	0.14	0.01
360.00	0.05	0.04	0.04	0.04	0.04	0.12	0.12	0.15	0.15	0.14	0.01
362.00	0.05	0.04	0.04	0.04	0.04	0.12	0.12	0.15	0.15	0.14	0.01
364.00	0.05	0.04	0.04	0.04	0.04	0.12	0.12	0.15	0.15	0.13	0.01
366.00	0.05	0.04	0.04	0.04	0.04	0.12	0.12	0.15	0.15	0.13	0.01
368.00	0.05	0.04	0.04	0.04	0.04	0.12	0.12	0.15	0.15	0.13	0.01
370.00	0.05	0.04	0.04	0.04	0.04	0.12	0.12	0.14	0.15	0.13	0.01

Table D2 (continued)

	2.5 μm					0.45 μm					
	Flux (L/sec/m^2)					Flux (L/sec/m^2)					
time, s.	**Set1**	**Set2**	**Set3**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**
374.00	0.05	0.04	0.04	0.04	0.04	0.12	0.12	0.14	0.15	0.13	0.01
376.00	0.05	0.04	0.04	0.04	0.04	0.12	0.12	0.14	0.15	0.13	0.01
378.00	0.05	0.04	0.04	0.04	0.04	0.12	0.12	0.14	0.14	0.13	0.01
380.00	0.05	0.04	0.04	0.04	0.04	0.12	0.12	0.14	0.14	0.13	0.01
382.00	0.05	0.04	0.04	0.04	0.04	0.12	0.12	0.14	0.14	0.13	0.01
384.00	0.04	0.04	0.04	0.04	0.04	0.12	0.12	0.14	0.14	0.13	0.01
386.00	0.05	0.04	0.04	0.04	0.04	0.12	0.12	0.14	0.14	0.13	0.01
388.00	0.04	0.04	0.04	0.04	0.04	0.12	0.12	0.14	0.14	0.13	0.01
390.00	0.04	0.04	0.04	0.04	0.04	0.12	0.12	0.14	0.14	0.13	0.01
392.00	0.04	0.04	0.04	0.04	0.04	0.12	0.12	0.14	0.14	0.13	0.01
396.00	0.04	0.04	0.04	0.04	0.04	0.12	0.12	0.14	0.14	0.13	0.01
398.00	0.04	0.04	0.04	0.04	0.04	0.12	0.12	0.14	0.14	0.13	0.01
400.00	0.04	0.04	0.04	0.04	0.04	0.12	0.12	0.14	0.14	0.13	0.01
402.00	0.04	0.04	0.04	0.04	0.04	0.11	0.12	0.14	0.14	0.13	0.01
404.00	0.04	0.04	0.04	0.04	0.04	0.11	0.11	0.14	0.14	0.13	0.01
406.00	0.04	0.04	0.04	0.04	0.04	0.11	0.11	0.14	0.14	0.13	0.01
408.00	0.04	0.04	0.04	0.04	0.04	0.11	0.11	0.14	0.14	0.13	0.01
410.00	0.04	0.04	0.04	0.04	0.04	0.11	0.11	0.14	0.14	0.13	0.01
412.00	0.04	0.04	0.04	0.04	0.04	0.11	0.11	0.14	0.14	0.12	0.01

Table D2 (continued)

	2.5 µm					0.45 µm					
	Flux (L/sec/m^2)					Flux (L/sec/m^2)					
time, s.	**Set1**	**Set2**	**Set3**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**
416.00	0.04	0.04	0.04	0.04	0.04	0.11	0.11	0.13	0.14	0.12	0.01
418.00	0.04	0.03	0.04	0.04	0.04	0.11	0.11	0.13	0.14	0.12	0.01
420.00	0.04	0.03	0.04	0.04	0.04	0.11	0.11	0.13	0.14	0.12	0.01
422.00	0.04	0.03	0.04	0.04	0.04	0.11	0.11	0.13	0.14	0.12	0.01
424.00	0.04	0.03	0.04	0.04	0.04	0.11	0.11	0.13	0.13	0.12	0.01
426.00	0.04	0.03	0.04	0.04	0.04	0.11	0.11	0.13	0.13	0.12	0.01
428.00	0.04	0.03	0.04	0.04	0.04	0.11	0.11	0.13	0.13	0.12	0.01
430.00	0.04	0.03	0.04	0.04	0.04	0.11	0.11	0.13	0.13	0.12	0.01
434.00	0.04	0.03	0.04	0.04	0.04	0.11	0.11	0.13	0.13	0.12	0.01
436.00	0.04	0.03	0.04	0.04	0.04	0.11	0.11	0.13	0.13	0.12	0.01
438.00	0.04	0.03	0.04	0.04	0.04	0.11	0.11	0.13	0.13	0.12	0.01
440.00	0.04	0.03	0.04	0.04	0.04	0.11	0.11	0.13	0.13	0.12	0.01
442.00	0.04	0.03	0.04	0.04	0.04	0.11	0.11	0.13	0.13	0.12	0.01
444.00	0.04	0.03	0.04	0.04	0.04	0.11	0.11	0.13	0.13	0.12	0.01
446.00	0.04	0.03	0.04	0.04	0.04	0.11	0.11	0.13	0.13	0.12	0.01
448.00	0.04	0.03	0.04	0.04	0.04	0.11	0.11	0.13	0.13	0.12	0.01
450.00	0.04	0.03	0.04	0.04	0.04	0.11	0.11	0.13	0.13	0.12	0.01
452.00	0.04	0.03	0.04	0.04	0.04	0.11	0.11	0.13	0.13	0.12	0.01
454.00	0.04	0.03	0.04	0.04	0.04	0.11	0.11	0.13	0.13	0.12	0.01

Table D2 (continued)

	2.5 μm					0.45 μm					
	Flux (L/sec/m^2)					Flux (L/sec/m^2)					
time, s.	**Set1**	**Set2**	**Set3**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**
458.00	0.04	0.03	0.04	0.04	0.04	0.11	0.11	0.13	0.13	0.12	0.01
460.00	0.04	0.03	0.04	0.04	0.04	0.11	0.11	0.13	0.13	0.12	0.01
462.00	0.04	0.03	0.04	0.04	0.04	0.11	0.11	0.13	0.13	0.12	0.01
464.00	0.04	0.03	0.04	0.04	0.04	0.11	0.11	0.13	0.13	0.12	0.01
466.00	0.04	0.03	0.04	0.04	0.04	0.10	0.11	0.13	0.13	0.12	0.01
468.00	0.04	0.03	0.04	0.04	0.04	0.10	0.10	0.12	0.13	0.11	0.01
470.00	0.04	0.03	0.04	0.04	0.04	0.10	0.10	0.12	0.13	0.11	0.01
474.00	0.04	0.03	0.04	0.04	0.04	0.10	0.10	0.12	0.13	0.11	0.01
476.00	0.04	0.03	0.04	0.04	0.04	0.10	0.10	0.12	0.13	0.11	0.01
478.00	0.04	0.03	0.04	0.04	0.04	0.10	0.10	0.12	0.12	0.11	0.01
480.00	0.04	0.03	0.04	0.04	0.04	0.10	0.10	0.12	0.12	0.11	0.01
482.00	0.04	0.03	0.04	0.04	0.04	0.10	0.10	0.12	0.12	0.11	0.01
484.00	0.04	0.03	0.04	0.04	0.04	0.10	0.10	0.12	0.12	0.11	0.01
486.00	0.04	0.03	0.04	0.04	0.04	0.10	0.10	0.12	0.12	0.11	0.01
488.00	0.04	0.03	0.04	0.04	0.04	0.10	0.10	0.12	0.12	0.11	0.01
490.00	0.04	0.03	0.04	0.04	0.04	0.10	0.10	0.12	0.12	0.11	0.01
492.00	0.04	0.03	0.04	0.04	0.04	0.10	0.10	0.12	0.12	0.11	0.01
494.00	0.04	0.03	0.04	0.04	0.04	0.10	0.10	0.12	0.12	0.11	0.01
496.00	0.04	0.03	0.04	0.04	0.04	0.10	0.10	0.12	0.12	0.11	0.01

Table D2 (continued)

	2.5 µm					0.45 µm					
	Flux (L/sec/m^2)					Flux (L/sec/m^2)					
time, s.	**Set1**	**Set2**	**Set3**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**
500.00	0.04	0.03	0.04	0.04	0.04	0.10	0.10	0.12	0.12	0.11	0.01
502.00	0.04	0.03	0.04	0.04	0.04	0.10	0.10	0.12	0.12	0.11	0.01
504.00	0.04	0.03	0.04	0.04	0.04	0.10	0.10	0.12	0.12	0.11	0.01
506.00	0.04	0.03	0.04	0.04	0.04	0.10	0.10	0.12	0.12	0.11	0.01
508.00	0.04	0.03	0.04	0.04	0.04	0.10	0.10	0.12	0.12	0.11	0.01
510.00	0.04	0.03	0.04	0.04	0.04	0.10	0.10	0.12	0.12	0.11	0.01
512.00	0.04	0.03	0.04	0.04	0.04	0.10	0.10	0.12	0.12	0.11	0.01
514.00	0.04	0.03	0.04	0.04	0.04	0.10	0.10	0.12	0.12	0.11	0.01
516.00	0.04	0.03	0.04	0.04	0.04	0.10	0.10	0.12	0.12	0.11	0.01
518.00	0.04	0.03	0.04	0.04	0.04	0.10	0.10	0.12	0.12	0.11	0.01
520.00	0.04	0.03	0.04	0.04	0.03	0.10	0.10	0.12	0.12	0.11	0.01
522.00	0.04	0.03	0.04	0.04	0.03	0.10	0.10	0.12	0.12	0.11	0.01
524.00	0.04	0.03	0.04	0.04	0.03	0.10	0.10	0.12	0.12	0.11	0.01
528.00	0.04	0.03	0.04	0.04	0.03	0.10	0.10	0.12	0.12	0.11	0.01
530.00	0.04	0.03	0.04	0.04	0.03	0.10	0.10	0.11	0.12	0.11	0.01
532.00	0.04	0.03	0.04	0.04	0.03	0.10	0.10	0.11	0.12	0.11	0.01
534.00	0.04	0.03	0.03	0.03	0.03	0.10	0.10	0.11	0.12	0.11	0.01
536.00	0.04	0.03	0.03	0.03	0.03	0.10	0.10	0.11	0.12	0.11	0.01
538.00	0.04	0.03	0.03	0.03	0.03	0.10	0.10	0.11	0.12	0.11	0.01

Table D2 (continued)

	2.5 µm					0.45 µm					
	Flux (L/sec/m^2)					Flux (L/sec/m^2)					
time, s.	**Set1**	**Set2**	**Set3**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**
542.00	0.04	0.03	0.03	0.03	0.03	0.10	0.10	0.11	0.12	0.10	0.01
544.00	0.04	0.03	0.03	0.03	0.03	0.09	0.10	0.11	0.12	0.10	0.01
546.00	0.04	0.03	0.03	0.03	0.03	0.09	0.09	0.11	0.12	0.10	0.01
548.00	0.04	0.03	0.03	0.03	0.03	0.09	0.09	0.11	0.11	0.10	0.01
550.00	0.04	0.03	0.03	0.03	0.03	0.09	0.09	0.11	0.11	0.10	0.01
552.00	0.04	0.03	0.03	0.03	0.03	0.09	0.09	0.11	0.11	0.10	0.01
554.00	0.04	0.03	0.03	0.03	0.03	0.09	0.09	0.11	0.11	0.10	0.01
556.00	0.04	0.03	0.03	0.03	0.03	0.09	0.09	0.11	0.11	0.10	0.01
558.00	0.04	0.03	0.03	0.03	0.03	0.09	0.09	0.11	0.11	0.10	0.01
560.00	0.04	0.03	0.03	0.03	0.03	0.09	0.09	0.11	0.11	0.10	0.01
562.00	0.04	0.03	0.03	0.03	0.03	0.09	0.09	0.11	0.11	0.10	0.01
564.00	0.04	0.03	0.03	0.03	0.03	0.09	0.09	0.11	0.11	0.10	0.01
566.00	0.04	0.03	0.03	0.03	0.03	0.09	0.09	0.11	0.11	0.10	0.01
570.00	0.04	0.03	0.03	0.03	0.03	0.09	0.09	0.11	0.11	0.10	0.01
572.00	0.04	0.03	0.03	0.03	0.03	0.09	0.09	0.11	0.11	0.10	0.01
574.00	0.04	0.03	0.03	0.03	0.03	0.09	0.09	0.11	0.11	0.10	0.01
576.00	0.04	0.03	0.03	0.03	0.03	0.09	0.09	0.11	0.11	0.10	0.01
578.00	0.04	0.03	0.03	0.03	0.03	0.09	0.09	0.11	0.11	0.10	0.01
580.00	0.04	0.03	0.03	0.03	0.03	0.09	0.09	0.11	0.11	0.10	0.01

Table D2 (continued)

	2.5 μm					0.45 μm					
	Flux (L/sec/m^2)					Flux (L/sec/m^2)					
time, s.	**Set1**	**Set2**	**Set3**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**
584.00	0.04	0.03	0.03	0.03	0.03	0.09	0.09	0.11	0.11	0.10	0.01
586.00	0.04	0.03	0.03	0.03	0.03	0.09	0.09	0.11	0.11	0.10	0.01
588.00	0.04	0.03	0.03	0.03	0.03	0.09	0.09	0.11	0.11	0.10	0.01
590.00	0.04	0.03	0.03	0.03	0.03	0.09	0.09	0.11	0.11	0.10	0.01
592.00	0.04	0.03	0.03	0.03	0.03	0.09	0.09	0.11	0.11	0.10	0.01
596.00	0.04	0.03	0.03	0.03	0.03	0.09	0.09	0.11	0.11	0.10	0.01
598.00	0.04	0.03	0.03	0.03	0.03	0.09	0.09	0.11	0.11	0.10	0.01
600.00	0.04	0.03	0.03	0.03	0.03	0.09	0.09	0.11	0.11	0.10	0.01
602.00	0.04	0.03	0.03	0.03	0.03	0.09	0.09	0.11	0.11	0.10	0.01
604.00	0.04	0.03	0.03	0.03	0.03	0.09	0.09	0.11	0.11	0.10	0.01
606.00	0.04	0.03	0.03	0.03	0.03	0.09	0.09	0.11	0.11	0.10	0.01
608.00	0.04	0.03	0.03	0.03	0.03	0.09	0.09	0.11	0.11	0.10	0.01
610.00	0.04	0.03	0.03	0.03	0.03	0.09	0.09	0.10	0.11	0.10	0.01
612.00	0.04	0.03	0.03	0.03	0.03	0.09	0.09	0.11	0.11	0.10	0.01
614.00	0.04	0.03	0.03	0.03	0.03	0.09	0.09	0.10	0.11	0.10	0.01
616.00	0.04	0.03	0.03	0.03	0.03	0.09	0.09	0.10	0.11	0.10	0.01
618.00	0.04	0.03	0.03	0.03	0.03	0.09	0.09	0.10	0.11	0.10	0.01
620.00	0.04	0.03	0.03	0.03	0.03	0.09	0.09	0.10	0.11	0.10	0.01
622.00	0.03	0.03	0.03	0.03	0.03	0.09	0.09	0.10	0.11	0.10	0.01

Table D2 (continued)

	2.5 µm					0.45 µm					
	Flux (L/sec/m^2)					Flux (L/sec/m^2)					
time, s.	**Set1**	**Set2**	**Set3**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**
626.00	0.03	0.03	0.03	0.03	0.03	0.09	0.09	0.10	0.11	0.10	0.01
628.00	0.03	0.03	0.03	0.03	0.03	0.09	0.09	0.10	0.11	0.10	0.01
630.00	0.03	0.03	0.03	0.03	0.03	0.09	0.09	0.10	0.11	0.10	0.01
632.00	0.03	0.03	0.03	0.03	0.03	0.09	0.09	0.10	0.10	0.10	0.01
634.00	0.03	0.03	0.03	0.03	0.03	0.09	0.09	0.10	0.10	0.09	0.01
636.00	0.03	0.03	0.03	0.03	0.03	0.09	0.09	0.10	0.10	0.09	0.01
638.00	0.03	0.03	0.03	0.03	0.03	0.09	0.09	0.10	0.10	0.09	0.01
640.00	0.03	0.03	0.03	0.03	0.03	0.09	0.09	0.10	0.10	0.09	0.01
642.00	0.03	0.03	0.03	0.03	0.03	0.09	0.09	0.10	0.10	0.09	0.01
646.00	0.03	0.03	0.03	0.03	0.03	0.09	0.09	0.10	0.10	0.09	0.01
648.00	0.03	0.03	0.03	0.03	0.03	0.09	0.09	0.10	0.10	0.09	0.01
650.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.10	0.10	0.09	0.01
652.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.10	0.10	0.09	0.01
654.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.10	0.10	0.09	0.01
656.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.10	0.10	0.09	0.01
658.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.10	0.10	0.09	0.01
660.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.10	0.10	0.09	0.01
662.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.10	0.10	0.09	0.01
664.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.10	0.10	0.09	0.01

Table D2 (continued)

	2.5 μm					0.45 μm					
	Flux (L/sec/m^2)					Flux (L/sec/m^2)					
time, s.	**Set1**	**Set2**	**Set3**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**
668.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.10	0.10	0.09	0.01
670.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.10	0.10	0.09	0.01
672.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.10	0.10	0.09	0.01
674.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.10	0.10	0.09	0.01
676.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.10	0.10	0.09	0.01
678.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.10	0.10	0.09	0.01
680.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.10	0.10	0.09	0.01
682.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.10	0.10	0.09	0.01
684.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.10	0.10	0.09	0.01
686.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.10	0.10	0.09	0.01
690.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.10	0.10	0.09	0.01
692.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.10	0.10	0.09	0.01
694.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.10	0.10	0.09	0.01
696.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.10	0.10	0.09	0.01
698.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.10	0.10	0.09	0.01
700.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.10	0.10	0.09	0.01
702.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.10	0.10	0.09	0.01
704.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.10	0.10	0.09	0.01
706.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.10	0.10	0.09	0.01

Table D2 (continued)

	2.5 µm					0.45 µm					
	Flux (L/sec/m^2)					Flux (L/sec/m^2)					
time, s.	**Set1**	**Set2**	**Set3**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**
710.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.10	0.10	0.09	0.01
712.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.09	0.10	0.09	0.01
714.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.09	0.10	0.09	0.01
716.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.09	0.10	0.09	0.01
718.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.09	0.10	0.09	0.01
720.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.09	0.10	0.09	0.01
722.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.09	0.10	0.09	0.01
724.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.09	0.10	0.09	0.01
728.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.09	0.10	0.09	0.01
730.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.09	0.10	0.09	0.01
732.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.09	0.10	0.09	0.01
734.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.09	0.10	0.09	0.01
736.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.09	0.09	0.09	0.01
738.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.09	0.09	0.09	0.01
740.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.09	0.09	0.09	0.01
742.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.09	0.09	0.09	0.01
744.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.09	0.09	0.09	0.01
746.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.09	0.09	0.09	0.01
748.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.09	0.09	0.09	0.01

Table D2 (continued)

	2.5 μm					0.45 μm					
	Flux (L/sec/m^2)					Flux (L/sec/m^2)					
time, s.	**Set1**	**Set2**	**Set3**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**
752.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.09	0.09	0.08	0.01
754.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.09	0.09	0.08	0.01
756.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.09	0.09	0.08	0.01
758.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.09	0.09	0.08	0.01
760.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.09	0.09	0.08	0.01
762.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.09	0.09	0.08	0.01
764.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.09	0.09	0.08	0.01
766.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.09	0.09	0.08	0.01
768.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.09	0.09	0.08	0.01
770.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.09	0.09	0.08	0.01
774.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.09	0.09	0.08	0.01
776.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.09	0.09	0.08	0.01
778.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.09	0.09	0.08	0.01
780.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.09	0.09	0.08	0.01
782.00	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.09	0.09	0.08	0.01
784.00	0.03	0.02	0.03	0.03	0.03	0.08	0.08	0.09	0.09	0.08	0.01
786.00	0.03	0.02	0.03	0.03	0.03	0.08	0.08	0.09	0.09	0.08	0.01
788.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.09	0.09	0.08	0.01
790.00	0.03	0.02	0.03	0.03	0.03	0.08	0.08	0.09	0.09	0.08	0.01

Table D2 (continued)

	2.5 μm					0.45 μm					
	Flux (L/sec/m^2)					Flux (L/sec/m^2)					
time, s.	**Set1**	**Set2**	**Set3**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**
794.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.09	0.09	0.08	0.01
796.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.09	0.09	0.08	0.01
798.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.09	0.09	0.08	0.01
800.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.09	0.09	0.08	0.01
802.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.09	0.09	0.08	0.01
804.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.09	0.09	0.08	0.01
806.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.09	0.09	0.08	0.01
808.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.09	0.09	0.08	0.01
810.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.09	0.09	0.08	0.01
812.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.09	0.09	0.08	0.01
814.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.09	0.09	0.08	0.01
816.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.09	0.09	0.08	0.01
820.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.09	0.09	0.08	0.01
822.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.09	0.09	0.08	0.01
824.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.09	0.09	0.08	0.01
826.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.09	0.09	0.08	0.01
828.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.09	0.09	0.08	0.01
830.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.09	0.09	0.08	0.01
832.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.09	0.09	0.08	0.01

Table D2 (continued)

	2.5 µm					0.45 µm					
	Flux (L/sec/m^2)					Flux (L/sec/m^2)					
time, s.	**Set1**	**Set2**	**Set3**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**
836.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.09	0.09	0.08	0.01
838.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.09	0.09	0.08	0.01
840.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.09	0.09	0.08	0.01
842.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.09	0.09	0.08	0.01
844.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.09	0.08	0.01
846.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.09	0.08	0.01
848.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.09	0.08	0.01
850.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.09	0.08	0.01
852.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.09	0.08	0.01
854.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.09	0.08	0.01
858.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.09	0.08	0.01
860.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.09	0.08	0.01
862.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.09	0.08	0.01
864.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.09	0.08	0.01
866.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.09	0.08	0.01
868.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.09	0.08	0.01
870.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.09	0.08	0.01
872.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.08	0.08	0.01
874.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.09	0.08	0.01

Table D2 (continued)

	2.5 μm					0.45 μm					
	Flux (L/sec/m^2)					Flux (L/sec/m^2)					
time, s.	**Set1**	**Set2**	**Set3**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**
878.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.08	0.08	0.01
880.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.08	0.08	0.01
882.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.08	0.08	0.01
884.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.08	0.08	0.01
886.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.08	0.08	0.01
890.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.08	0.08	0.01
892.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.08	0.08	0.01
894.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.08	0.08	0.01
896.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.08	0.08	0.01
898.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.08	0.08	0.01
900.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.08	0.08	0.01
902.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.08	0.08	0.01
904.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.08	0.08	0.01
906.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.08	0.08	0.01
908.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.08	0.08	0.01
910.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.08	0.08	0.01
912.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.08	0.07	0.01
914.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.08	0.07	0.01
916.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.08	0.07	0.01

Table D2 (continued)

	2.5 μm					0.45 μm					
	Flux (L/sec/m^2)					Flux (L/sec/m^2)					
time, s.	**Set1**	**Set2**	**Set3**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**
920.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.08	0.07	0.01
922.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.08	0.07	0.01
926.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.08	0.07	0.01
928.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.08	0.07	0.01
930.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.08	0.07	0.01
932.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.08	0.07	0.01
934.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.08	0.07	0.01
936.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.08	0.07	0.01
938.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.08	0.07	0.01
940.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.08	0.07	0.01
942.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.08	0.07	0.01
944.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.08	0.07	0.01
946.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.08	0.07	0.01
948.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.08	0.07	0.01
950.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.08	0.07	0.01
952.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.08	0.07	0.01
954.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.08	0.07	0.01
956.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.08	0.07	0.01
958.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.08	0.07	0.01

Table D2 (continued)

	2.5 µm					0.45 µm					
	Flux (L/sec/m^2)					Flux (L/sec/m^2)					
time, s.	**Set1**	**Set2**	**Set3**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**
962.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.08	0.07	0.01
964.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.08	0.07	0.01
966.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.08	0.07	0.01
968.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.08	0.07	0.01
970.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.08	0.07	0.01
972.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.08	0.07	0.01
974.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.08	0.07	0.01
976.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.08	0.07	0.01
978.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.08	0.07	0.01
982.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.08	0.07	0.01
984.00	0.03	0.02	0.03	0.03	0.03	0.07	0.07	0.08	0.08	0.07	0.01
986.00	0.03	0.02	0.03	0.03	0.03	0.06	0.06	0.08	0.08	0.07	0.01
988.00	0.03	0.02	0.03	0.03	0.03	0.06	0.06	0.08	0.08	0.07	0.01
990.00	0.03	0.02	0.03	0.03	0.03	0.06	0.06	0.08	0.08	0.07	0.01
992.00	0.03	0.02	0.03	0.03	0.02	0.06	0.06	0.08	0.08	0.07	0.01
994.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.08	0.08	0.07	0.01
996.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.08	0.08	0.07	0.01
998.00	0.03	0.02	0.03	0.03	0.02	0.06	0.06	0.08	0.08	0.07	0.01
1000.00	0.03	0.02	0.03	0.03	0.02	0.06	0.06	0.08	0.08	0.07	0.01

Table D2 (continued)

	2.5 µm					0.45 µm					
	Flux (L/sec/m^2)					Flux (L/sec/m^2)					
time, s.	Set1	Set2	Set3	Average	Std.	Set1	Set2	Set3	Set4	Average	Std.
1004.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.08	0.08	0.07	0.01
1006.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.08	0.08	0.07	0.01
1008.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.08	0.08	0.07	0.01
1010.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.08	0.08	0.07	0.01
1012.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.08	0.08	0.07	0.01
1014.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.07	0.08	0.07	0.01
1016.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.07	0.08	0.07	0.01
1020.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.07	0.08	0.07	0.01
1022.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.07	0.08	0.07	0.01
1024.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.07	0.08	0.07	0.01
1026.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.07	0.08	0.07	0.01
1028.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.07	0.08	0.07	0.01
1030.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.07	0.08	0.07	0.01
1032.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.07	0.08	0.07	0.01
1034.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.07	0.08	0.07	0.01
1036.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.07	0.08	0.07	0.01
1038.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.07	0.08	0.07	0.01
1040.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.07	0.08	0.07	0.01
1042.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.07	0.07	0.07	0.01

Table D2 (continued)

	2.5 μm					0.45 μm					
	Flux (L/sec/m^2)					Flux (L/sec/m^2)					
time, s.	**Set1**	**Set2**	**Set3**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**
1046.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.07	0.07	0.07	0.01
1048.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.07	0.07	0.07	0.01
1050.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.07	0.07	0.07	0.01
1052.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.07	0.07	0.07	0.01
1054.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.07	0.07	0.07	0.01
1056.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.07	0.07	0.07	0.01
1058.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.07	0.07	0.07	0.01
1060.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.07	0.07	0.07	0.01
1062.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.07	0.07	0.07	0.01
1066.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.07	0.07	0.07	0.01
1068.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.07	0.07	0.07	0.01
1070.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.07	0.07	0.07	0.01
1072.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.07	0.07	0.07	0.01
1074.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.07	0.07	0.07	0.01
1076.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.07	0.07	0.07	0.01
1078.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.07	0.07	0.07	0.01
1080.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.07	0.07	0.07	0.01
1082.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.07	0.07	0.07	0.01
1084.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.07	0.07	0.07	0.01

Table D2 (continued)

	2.5 μm					0.45 μm					
	Flux (L/sec/m^2)					Flux (L/sec/m^2)					
time, s.	**Set1**	**Set2**	**Set3**	**Average**	**Std.**	**Set1**	**Set2**	**Set3**	**Set4**	**Average**	**Std.**
1088.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.07	0.07	0.07	0.01
1090.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.07	0.07	0.07	0.01
1092.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.07	0.07	0.07	0.01
1094.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.07	0.07	0.07	0.01
1096.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.07	0.07	0.07	0.01
1098.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.07	0.07	0.07	0.01
1100.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.07	0.07	0.07	0.01
1102.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.07	0.07	0.07	0.01
1104.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.07	0.07	0.07	0.01
1106.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.07	0.07	0.07	0.01
1108.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.07	0.07	0.07	0.01
1110.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.07	0.07	0.07	0.01
1112.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.07	0.07	0.07	0.01
1114.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.07	0.07	0.07	0.01
1116.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.07	0.07	0.07	0.01
1118.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.07	0.07	0.07	0.01
1120.00	0.03	0.02	0.02	0.02	0.02	0.06	0.06	0.07	0.07	0.07	0.01