

**T.C.
MARMARA UNIVERSITY
INSTITUTE FOR GRADUATE STUDIES IN
PURE AND APPLIED SCIENCES**

**APPLICATION OF UV DISINFECTION IN MUNICIPAL
WASTEWATER TREATMENT PLANTS FOR
AGRICULTURAL USE OF RECLAIMED
WASTEWATER**

Serkan EVCİMEN

**THESIS
FOR THE DEGREE OF MASTER OF SCIENCE
IN
ENVIRONMENTAL ENGINEERING**

**SUPERVISOR
Assist. Prof. Ashhan KERÇ**

İSTANBUL 2009

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ACCEPTANCE AND APPROVAL DOCUMENT

The jury established by the Executive Board of the *INSTITUTE FOR GRADUATE STUDIES IN PURE AND APPLIED SCIENCES* on has accepted Mr. Serkan Evcimen's thesis titled "Application of UV Disinfection in Municipal Wastewater Treatment Plants for Agricultural Use of Reclaimed Wastewater" as Master of Science thesis in Environmental Engineering Programme.

Advisor : Assist. Prof. Aslıhan KERÇ

1. Member of the jury: Assoc. Prof. Zehra CAN

2. Member of the jury : Assoc. Prof. Nilgün CILIZ

Date : 02.02.2009

APPROVAL

Mr. Serkan Evcimen has satisfactorily completed the requirements for the degree of Master of Science in Environmental Engineering Programme at Marmara University. The Executive Committee approves that he be granted the degree of Master of Science on.....

DIRECTOR OF THE INSTITUTE

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ABSTRACT

APPLICATION OF UV DISINFECTION IN MUNICIPAL WASTEWATER TREATMENT PLANTS FOR AGRICULTURAL USE OF RECLAIMED WASTEWATER

In this research, an Ultraviolet (UV) pilot plant was installed and operated at Paşaköy Wastewater Treatment Plant (WWTP) in order to examine the UV disinfection efficiency based on wastewater quality parameters. The pilot plant also contained a pressurized sand filter. The pilot plant was an open-channel system with three UV banks, each consisting of four low-pressure high-intensity UV lamps. The feed water for the pilot plant was the effluent of the treatment plant.

The primary objective of this study was to determine the appropriate UV dose to achieve a wastewater quality that meets the Turkish Standards for different reuse applications. Also, appropriate UV doses to achieve wastewater quality that complies with different regulations for agricultural reuse were determined. Total coliform (TC) and fecal coliform (FC) concentrations for different UV doses were monitored.

The effect of wastewater quality parameters, such as suspended solids (SS), UV transmittance (UVT), and initial total and fecal coliform concentrations, on UV disinfection efficiency was studied. Microbiological characteristics of Paşaköy WWTP effluent were also monitored and statistically analyzed.

Experiments were conducted with both filtered and unfiltered water to observe the importance of filtration and suspended solids content on disinfection efficiency.

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ÖZET

Arıtılmış Atıksuyun Tarımsal Kullanımı İçin Evsel Atıksu Arıtma Tesislerinde Ultraviyole Dezenfeksiyon Uygulamaları

Bu çalışmada atıksu kalite parametrelerine göre UV dezenfeksiyon veriminin incelenmesi amacıyla Paşaköy Atıksu Arıtma Tesisi'ne bir UV pilot tesisi kurulmuş ve işletilmiştir. Pilot tesis aynı zamanda kum filtresi de içermektedir. Pilot tesis açık kanal bir sistem olup, her biri dört adet düşük basınçlı yüksek yoğunluklu UV lambası içeren üç banktan oluşmaktadır. Pilot tesis, arıtma tesisinin çıkış suyuyla beslenmiştir.

Bu çalışmanın öncelikli hedefi, farklı geri kullanım uygulamaları için Türk Standartları'nda belirlenmiş kalitede atıksu elde etmek için gerekli olan uygun UV dozunun tespit edilmesidir. Ayrıca farklı tarımsal geri kullanım yönetmeliklerine uyacak kalitede atıksu elde etmek için gerekli olan uygun UV dozları da belirlenmiştir. Farklı UV dozlarındaki toplam ve fekal koliform konsantrasyonları izlenmiştir.

Askıda katı madde, UV geçirgenliği ve giriş toplam ve fekal koliform konsantrasyonları gibi atıksu kalite parametrelerinin UV dezenfeksiyon verimine etkileri incelenmiştir. Ayrıca Paşaköy Atıksu Arıtma Tesisi çıkış sularının mikrobiyolojik karakterizasyonları da incelenmiş ve istatistik analizleri yapılmıştır.

Filtrasyonun önemini ve askıda katı madde içeriğinin dezenfeksiyon verimine etkilerini gözlemlemek amacıyla deneyler hem filtre edilmiş hem de filtre edilmemiş sularla yapılmıştır.

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SYMBOLS

A	: UV absorbance at a given wavelength (unitless)
AN	: Avogadro's number $\approx 6.023 \times 10^{23}$ photons/Einstein
C_v	: Speed of electromagnetic radiation in a vacuum (3×10^{17} nm/s)
D	: UV Dose (mJ/cm ²)
E_λ	: Radiant energy associated with given wavelength (kcal/einstein)
h	: Planck's constant = 1.583×10^{-37} kcal.s
I	: UV Intensity (mW/cm ²)
I₀	: UV Intensity of light entering solution (mW / cm ²)
m₁	: Initial weight of the filter paper, g
m₂	: Final weight of the filter paper, g
N	: The concentration of infectious microorganisms after exposure to UV light
N₀	: The concentration of infectious microorganisms before exposure to UV light
N_p	: Particulate coliform density
s	: Standard deviation
t	: Exposure time (s)
t_{0,125}	: student- <i>t</i> value associated with a 75 percent level of confidence
V_f	: Filtered volume of sample, mL
λ	: Wavelength of electromagnetic radiation (nm)

ABBREVIATIONS

AWWA	: American Water Works Association
BOD	: Biochemical Oxygen Demand
COD	: Chemical Oxygen Deman
DALY	: Disability Adjusted Life Years
DNA	: Deoxyribonucleic Acid
EPA	: Environment Protection Agency
FC	: Fecal Coliform
HLP	: High Level Probe
HMI	: Human Machine Interface
LLP	: Low Level Probe
MF	: Microfiltration
MPN	: Most Probable Number
N	: Nitrogen
NF	: Nanofiltration
ORP	: Oxidation Reduction Potential
P	: Phosphorus
PLC	: Programmable Logic Controller
RNA	: Ribonucleic Acid
RO	: Reverse Osmosis
SS	: Suspended Solids
TC	: Total Coliform
THM	: Tri-halomethane
TOC	: Total Organic Carbon
TSS	: Total Suspended Solids
UF	: Ultrafiltration
UV	: Ultraviolet
UVT	: UV Transmittance of Water at 254 nm
WHO	: World Health Organization
WWTP	: Wastewater Treatment Plant

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CHAPTER I

INTRODUCTION AND AIM

Water shortage is currently one of the biggest concerns of human beings world wide. It is a global problem that seriously affects the lives of significant proportions of the world population. Population growth, rise in living standards, the contamination of surface and groundwater sources increase the demand for clean water, and force the water agencies to search for new sources. Wastewater reuse may be considered as a reliable, practical and economic alternative water source. There is an increasing interest over the past decade in wastewater reuse in many parts of the world, in particular in arid regions. In order to handle increased water demand, the purified wastewater has to be reused and the ways to reuse the effluent from municipal wastewater treatment plants have to be developed. Conventional wastewater treatment plants aim to reduce the organic content and particulate matter in wastewater. However, the reuse of treated effluent necessitates the improvement of microbiological quality as well. Water, which does not comply with the microbiological requirements of wastewater regulations, has to be treated and disinfected (Metcalf & Eddy, 2007).

Reclaimed wastewater reuse for agricultural purposes is now expanding, and the advantages of applying UV disinfection to enable wastewater to be reused are widely recognized (Kashimada et al., 1996). UV radiation is the safest and one of the most effective treatment techniques to eliminate disease-causing bacteria from wastewater.

Ultraviolet irradiation is a physical disinfection process that achieves disinfection by inducing photobiochemical changes within microorganisms. An Ultraviolet disinfection system transfers electromagnetic energy from a UV lamp to an organism's genetic material (DNA and RNA). The energy absorbed by the nucleic acids causes photoproducts such as thymine dimers on the same nucleic acid strand (Harm, 1980). If the damage is not repaired, DNA replication is blocked, leading to inactivation of microorganisms (Ko et al., 2005).

Efficiency of UV irradiation depends on many factors such as wastewater quality, lamp ageing, or the depositions on the lamps.

The purpose of this study was to demonstrate the disinfection efficiency of a UV system in an existing wastewater treatment plant in Istanbul. The microbiological characteristics of the wastewater was not studied in details previously, so the results of this study would also indicate the total and fecal coliform concentration ranges observed in Istanbul wastewaters. The results of the pilot plant studies will be used as a guidance for the design of a full scale UV disinfection system.

Results of the experiments conducted in the pilot plant installed in Paşaköy Wastewater Treatment Plant (WWTP) with varying wastewater characteristics and operational parameters will be used to determine the required UV dosages for the targeted reuse application.

CHAPTER II

GENERAL BACKGROUND

II.1. WASTEWATER RECLAMATION AND REUSE

Fresh water is vital to sustain human life, however, only 3% of total water on earth is fresh water and two-thirds of that is in frozen forms such as the polar ice caps, glaciers and icebergs. The remaining 1% of the total fresh water is either surface water or groundwater. Continued population growth, contamination of both surface water and groundwater, uneven distribution of water resources, and periodic droughts have increased the demand for water and forced water agencies to search for new sources of water supply (Metcalf&Eddy, 2003). Especially in arid areas, the future demands for water cannot meet with traditional water resources such as surface and groundwater. In 1995, 31 countries were classified as water-scarce or water-stressed, and it is estimated that 48 and 54 countries will fall into these categories by 2025 and 2050, respectively. These numbers do not include people living in arid regions of large countries where there is enough water but it is poorly distributed. Growing competition between agriculture and urban areas for high-quality fresh water supplies, particularly in arid, semi-arid and densely populated regions, will increase the pressure on this resource (WHO Guidelines, 2006).

It is estimated that more than 40% of the world's population will live in countries facing water scarcity or water stress, within the next 50 years. Figure II.1 shows the population living in water-scarce and water-stressed countries.

Istanbul is one of the most populated cities in the world, and has a limited per capita water capability. During summer months, it has been monitored that, reservoir capacities may drop to as low as 23.3 percent levels. Experts pointed out that evaporation in the city's water supply due to high temperatures immensely contributed to this problem. Water shortages have also influenced agricultural production across Turkey. There have been several reports about the adverse effects of water shortages on the production of wheat, olives and olive oil, figs, grapes, sunflowers and sunflower oil, and cotton.

As the populations increase and become more urban, water use and consequent wastewater generation increase.

It has been recognized that wastewater reuse or reclamation serves as an efficient and valuable way to cope with the scarcity of water resources and severity of water pollution (Chu et al., 2004). There is an increasing interest over the past decade in wastewater reuse in many parts of the world, in particular in arid regions, to promote sustainable, efficient and appropriate water uses.

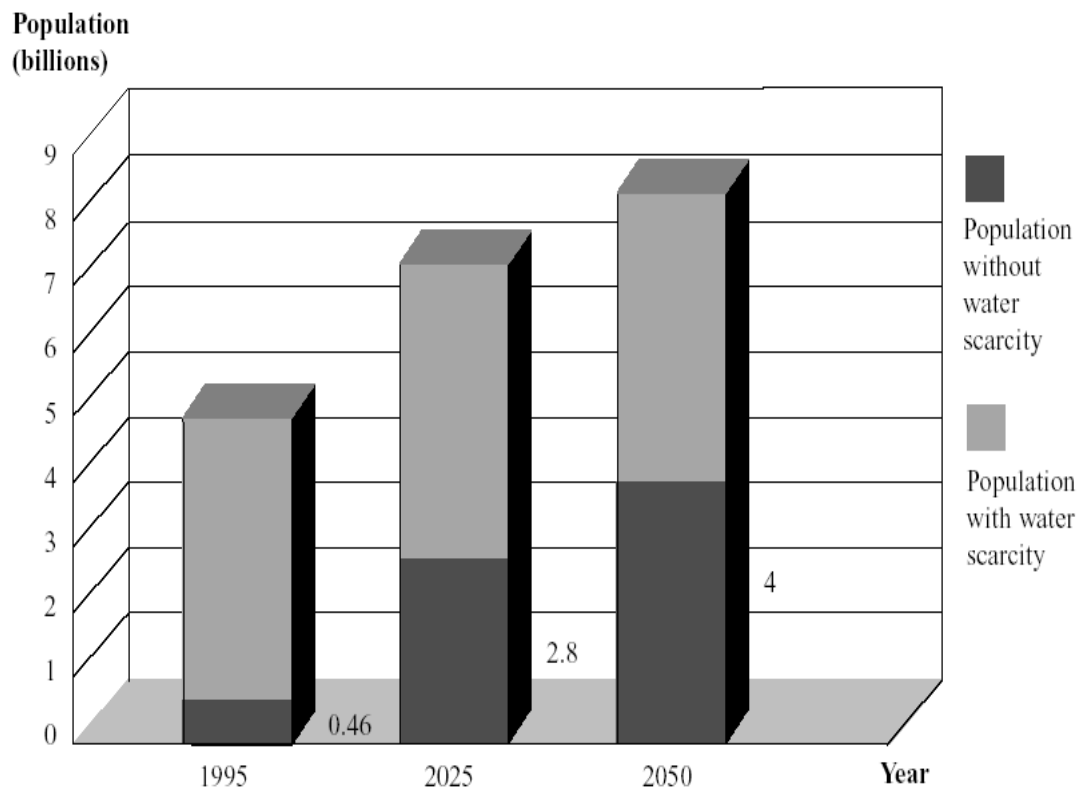


Figure II.1 Population living in water-scarce and water-stressed countries, 1995-2050 (Hinrichsen et al., 1998)

Potential applications for wastewater reuse are extremely wide-ranging and include any instance where water is needed for non-potable use. The seven principal categories of municipal wastewater reuse are, agricultural irrigation, landscape irrigation, industrial recycling and reuse, groundwater recharge, recreational / environmental uses, nonpotable urban uses, and potable uses. The required water quality for reclaimed water varies with each reuse application. Water reuse applications have been limited primarily to nonpotable uses such as agricultural and

landscape irrigation because of costs of treatment, health issues, and safety concerns (Metcalf&Eddy, 2003).

Agricultural irrigation is the largest current use of reclaimed water. As fresh water becomes increasingly scarce due to population growth, urbanization and climate change, the use of wastewater in agriculture will increase even more (WHO Guidelines, 2006). At least 10% of the world's population is thought to consume foods produced by irrigation with wastewater (Smit and Nasr, 1992). The water and nutrient value of wastewater are important resources for farmers in both industrialized and developing countries. The use of wastewater for crop irrigation reduces the use of artificial fertilizers and is thus an important form of nutrient recycling.

Because wastewater contains impurities, careful consideration must be given to the possible long-term effects on soils and plants from salinity, sodicity, nutrients and trace elements that occur normally manageable if associated problems with these impurities are understood and allowances made for them. On the other hand, municipal wastewater and some agro-industrial effluents which may be re-used for irrigation require guidelines to estimate public health hazards. The degree of risk associated with such effluents is related to the microbiological characteristics.

Wastewater contains correspondingly high concentrations of excreted pathogens- bacteria, viruses, protozoa and helminthes. Many pathogens are capable of survival in the environment for periods long enough to allow transmission to humans. The primary pathways of transmission of or exposure to pathogens or contaminants associated with the use of wastewater in agriculture are:

- Human contact with the wastewater (or contaminated crops) before, during or after irrigation (farmers, their families, vendors, local communities),
- Inhalation of wastewater aerosols (workers, local communities),
- Consumption of contaminated wastewater-irrigated products,
- Consumption of drinking-water contaminated as a result of wastewater use activities (e.g. chemical or pathogen contamination of aquifers or surface waters),
- Consumption of animals (e.g. beef or pork) or animal products (e.g. milk) that have been contaminated through exposure to wastewater,

- Vector-borne disease transmission resulting from the development and management of wastewater irrigation schemes and waste stabilization ponds (WHO Guidelines, 2006).

II.1.1. Current Regulations for Wastewater Reuse

For the reuse of wastewater in agriculture, the type of the crops to be irrigated has to be taken into consideration. The classification of irrigation water is made as:

- unrestricted irrigation, and
- restricted irrigation.

Restricted irrigation is the irrigation of all crops except salad crops and vegetables that may be eaten uncooked. For restricted irrigation, WHO recommends the treated wastewater should contain no more than one human intestinal nematode egg per liter. The WHO Guidelines did not include a limit for fecal coliform bacteria in the case of restricted irrigation. Table II.1 shows the 1989 WHO guidelines for using treated wastewater in agriculture, and these guidelines are still in effect. However, recent evidence indicate that a guideline limit should be added and WHO recommends a limit of $\leq 10^5$ fecal coliform bacteria per 100 ml of treated water when adult farm workers are exposed to spray irrigation. A limit of $\leq 10^3$ fecal coliform bacteria/100 ml is recommended if flood irrigation is used or children are exposed. Table II.2 shows the recommended revised microbiological guidelines for treated wastewater use in agriculture. More stringent standards are set for unrestricted irrigation, since the edible agricultural products will be in contact with the reclaimed wastewater. WHO recommends the same helminthes egg value, and additionally no more than 1000 fecal coliform bacteria per 100 ml of treated wastewater (Blumenthal et al., 2000).

Table II.1. 1989 WHO Guidelines for using treated wastewater in agriculture

Category	Reuse Conditions	Exposed Group	Intestinal nematodes (arithmetic mean no. of eggs per liter)	Fecal coliforms (geometric mean no. per 100 ml)	Wastewater treatment expected to achieve the required microbiological guideline
A	Irrigation of crops likely to be eaten uncooked, sports fields, public parks	Workers, consumers, public	≤ 1	≤ 1000	A series of stabilization ponds designed to achieve the microbiological quality indicated, or equivalent treatment
B	Irrigation of cereal crops, industrial crops, fodder crops, pasture and trees	Workers	≤ 1	No standard recommended	Retention in stabilization ponds for 8-10 days or equivalent helminth and fecal coliform removal
C	Localized irrigation of crops in category B if exposure to workers and the public does not occur	None	Not applicable	Not applicable	Pretreatment as required by irrigation technology but not less than primary sedimentation

Table II.2. Recommended revised microbiological guidelines for treated wastewater use in agriculture (2000)

Category	Reuse conditions	Exposed group	Irrigation technique	Intestinal nematodes ^b (arithmetic mean no. of eggs per litre ^c)	Faecal coliforms (geometric mean no. per 100 ml ^d)	Wastewater treatment expected to achieve required microbiological quality
A	Unrestricted irrigation					Well-designed series of waste stabilization ponds (WSP), sequential batch-fed wastewater storage and treatment reservoirs (WSTR) or equivalent treatment (e.g., conventional secondary treatment supplemented by either polishing ponds or filtration and disinfection)
	A1 For vegetable and salad crops eaten uncooked, sports fields, public parks ^e	Workers, consumers, public	Any	$\leq 0.1^f$	$\leq 10^3$	
B	Restricted irrigation					Retention in WSP series including one maturation pond or in sequential WSTR or equivalent treatment (e.g., conventional secondary treatment supplemented by either polishing ponds or filtration)
	Cereal crops, industrial crops, fodder crops, pasture and trees ^g	B1 Workers (but no children <15 years), nearby communities	Spray or sprinkler	≤ 1	$\leq 10^5$	
		B2 as B1	Flood/furrow	≤ 1	$\leq 10^3$	
		B3 Workers including children <15 years, nearby communities	Any	≤ 0.1	$\leq 10^3$	As for Category A
C	Localized irrigation of crops in category B if exposure of workers and the public does not occur	None	Trickle, drip or bubbler	Not applicable	Not applicable	Pretreatment as required by the irrigation technology, but not less than primary sedimentation

The U.S. Environmental Protection Agency (U.S. EPA, 1992) has suggested reclaimed water quality guidelines for the following reuse categories:

- Urban reuse
- Restricted-access-area irrigation

- Agricultural reuse – food crops
- Agricultural reuse – nonfood crops
- Recreational impoundments
- Landscape impoundments
- Construction uses
- Industrial reuse
- Groundwater recharge
- Indirect potable reuse

For each reuse category, levels of treatment, minimum reclaimed water quality, reclaimed water monitoring, and setback distances are suggested. The guidelines are summarized in Table II.3 (Metcalf&Eddy, 2003).

Table II.3. Summary of EPA Suggested Guidelines for Water Reuse (U.S. EPA, 1992)

Level of treatment	Types of Reuse	Reclaimed Water Quality	Reclaimed Water Monitoring	Setback Distances
1. Disinfected tertiary	Urban Reuse	pH = 6 – 9	Weekly	15 m to potable supply wells
	Food crop irrigation	BOD ₅ ≤ 10 mg/L	Weekly	
		Turb. ≤ 2 NTU	Cont.	
	Recreational impoundments	E. coli = none	Daily	
		Res. Cl ₂ ≥ 1 mg/L	Cont.	
2. Disinfected secondary	Restricted access area irrigation	pH = 6 – 9	Weekly	30 m to areas accessible to public (if spray irrigation)
	Food crop irrigation	BOD ₅ ≤ 30 mg/L	Weekly	
		TSS = 30 mg/L	Cont.	
	Nonfood crop irrigation	E.coli=200/100mL	Daily	
		Res. Cl ₂ ≥ 1 mg/L	Cont.	
	Landscape impoundments (restricted access)			90 m to potable water supply well
	Construction			
Wetlands habitat				

According to the current Turkish Water Pollution Control Regulation (1991), the irrigation waters are classified into 5 classes based on their fecal coliform content as well as other chemical / physical characteristics.

Table II.4. Classification of irrigation waters based on fecal coliform counts (Turkish Water Pollution Control Regulation, 1991).

	Classes of irrigation water				
Quality Criteria	Class 1 (excellent)	Class 2 (good)	Class 3 (permissible)	Class 4 (doubtful)	Class 5 (unsuitable)
Fecal coliform 1/100 ml	0-2	2-20	20-100	100-1000	>1000

In California, USA, water reuse regulations have been developed progressively since 1918, and are the most comprehensive regulations with regard to public health (Metcalf & Eddy, 2003). California Water Recycling Criteria (Title 22 regulations); which were revised in December 2000, are summarized in Table II.5.

Table II.5. California Water Recycling Criteria

Category of reclaimed water	Criteria for:	
	TC*, MPN** / 100 mL	Turbidity, NTU
Disinfected tertiary	<2.2	2 average 5 maximum
Disinfected secondary- 2.2	<2.2	Not applicable
Disinfected secondary- 23	<23	Not applicable
Undisinfected secondary	Not applicable	Not applicable

* : Total Coliform, ** : Most Probable Number

Reclaimed water in the category of disinfected tertiary are suitable for agricultural irrigation, landscape irrigation, industrial recycling and reuse,

groundwater recharge, recreational/environmental uses, nonpotable urban uses and potable reuse. Disinfected secondary-2.2 category of waters are suitable for all uses that are suitable for disinfected tertiary waters, except irrigation of parks and playgrounds, food crops contacted by reclaimed water, nonrestricted impoundments. Disinfected secondary-23 has the same restrictions as disinfected secondary-2.2, except no food crop irrigation, no nonrestricted impoundment, and no watering of yards. Undisinfected secondary are suitable for drip or surface irrigation of fodder, fiber, seed orchard, and tree crops and sugar beets.

WHO has adopted a tolerable burden of waterborne disease from consuming drinking-water of $\leq 10^{-6}$ DALY (Disability adjusted life years) per person per year. Such a high level of health protection is required for drinking water, since it is expected to be safe by those who drink it. Since food crops irrigated with treated wastewater, especially those eaten uncooked, are also expected to be as safe as drinking water by those who eat them, the same high health protection level of $\leq 10^{-6}$ DALY per person per life is used for wastewater use in agriculture (WHO Guidelines, 2006). Table II.6 shows the health based targets for the reuse of wastewater in agriculture.

Table II.6. Health-based targets for wastewater use in agriculture

Exposure scenario	Health-based target (DALY per person per year)	Log₁₀ pathogen reduction needed	Number of helminth eggs per litre
Unrestricted irrigation	$\leq 10^{-6}$		
Lettuce		6	≤ 1
Onion		7	≤ 1
Restricted irrigation	$\leq 10^{-6}$		
Highly mechanized		3	≤ 1
Labour intensive		4	≤ 1
Localized irrigation	$\leq 10^{-6}$		
High-growing crops		2	No recommendation
Low-growing crops		4	≤ 1

To achieve the health-based targets, microbial reduction targets are developed. Figure II.2. shows pathogen reductions achieved by several options for combining wastewater treatment and other health protection measures to achieve $\leq 10^{-6}$ DALY per person per year (WHO Guidelines, 2006).

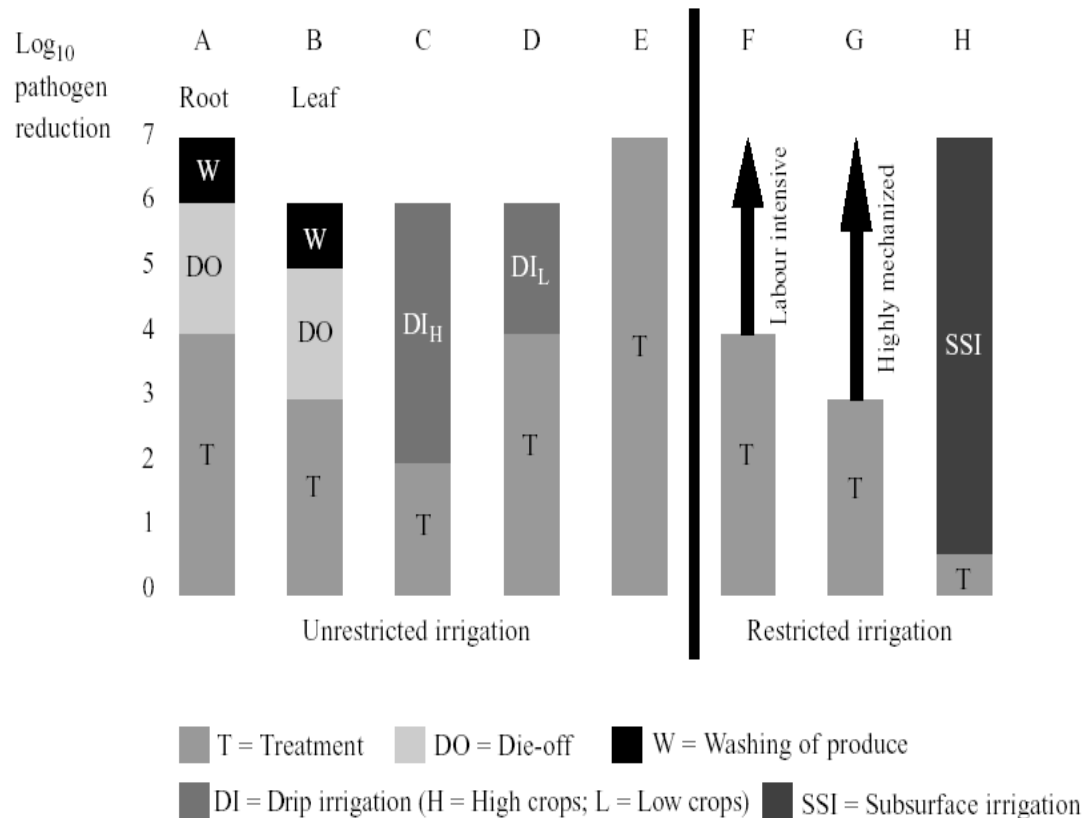


Figure II.2. Examples of options for the reduction of viral, bacterial and protozoan pathogens by different combinations of health protection measures that achieve $\leq 10^{-6}$ DALY per person per year (WHO Guidelines, 2006)

Option A in Figure II.2. shows that the required pathogen reduction is achieved by the combination of wastewater treatment, which provides a 4 log unit pathogen reduction; pathogen die-off between the last irrigation and consumption (2 log unit reduction); and washing the salad crops or vegetables with water prior to a consumption (a 1 log unit reduction). This option is suitable when roots crops that may be eaten uncooked are irrigated with treated wastewater.

Option B has a lower degree of wastewater treatment than Option A. This option is suitable for the irrigation of non-root salad crops and vegetables eaten uncooked.

Option C combines an even lower degree of treatment but with drip irrigation of high-growing crops (such as tomatoes), which achieves the required remaining 4 log unit pathogen reduction.

Option D incorporates the drip irrigation of low growing non-root crops, so a greater degree of treatment is provided.

Option E relies solely on wastewater treatment to achieve the required 6-7 log unit reduction. A typical sequence of wastewater treatment process to achieve this would compromise conventional wastewater treatment followed by chemical coagulation, flocculation, sedimentation and disinfection (chlorination or ultraviolet irradiation).

Options F, G and H relate to restricted irrigation (WHO Guidelines, 2006).

Although conventional treatment processes are known to remove up to 90-99% of some microorganisms, their efficiency is not sufficient to meet existing requirements for wastewater reuse (Yanko, 1993). Therefore, specific disinfection steps have to be included in the treatment chains.

II.2. WASTEWATER DISINFECTION

Disinfection refers to the partial destruction of disease-causing organisms (Metcalf&Eddy, 2003). Water, whether or not previously treated and even if perfectly clear, is often contaminated by microbes dangerous to the human organism. Certain filters with a very low filtration rate can provide quite effective bacteriological purification, but they must nevertheless always be followed by efficient disinfection (Degremont, 1973). The main objective of disinfection is to reduce the concentration of water-borne pathogens to a level below the infective limit.

II.2.1. Pathogens and Indicator Organisms

Because of the potential presence of multitudes of pathogenic organisms in wastewater, routine monitoring for all types of organisms would be prohibitively expensive. Hence, the presence, absence, or quantity of pathogenic organisms has largely been estimated using indicator organisms such as total coliform, fecal

coliform, *E. coli*, or *Streptococcus*. Among these, total coliform and fecal coliform in wastewater treatment have been widely used. Laboratory enumeration of these indicator organisms involves growth of the organisms in a suitable culture medium with optimal temperature and pH conditions. Various procedures such as membrane filtration and multiple-tube fermentation are available (Pelczar, 1993).

Pathogenic organisms are removed in proportion to indicator organisms (total and/or fecal coliforms). Conventional treatment of domestic wastewater without disinfection cannot be considered sufficient for removal of human pathogens when water is to be beneficially reused or body contact will occur.

The term indicator microorganism refers to a kind of microorganism whose presence in water is evidence that the water is polluted with fecal material from humans or other warm-blooded animals. This kind of pollution means that any pathogenic microorganisms that occur in the intestinal tract of these animals may also be present. Some of the important characteristics of an indicator organism are:

- It is present in polluted water and absent from unpolluted water
- It is present in water when pathogens are present
- The quantity of indicator organism correlates with the amount of pollution
- It survives better and longer than the pathogens
- It has uniform and stable properties
- It is generally harmless to humans and other animals
- It is easily detected by standard laboratory techniques (Pelczar, 1993).

Since it is difficult, time-consuming, and expensive to test directly for the presence of a large variety of pathogens, water is usually tested for coliforms and fecal streptococci instead. Sources of fecal contamination to surface waters include wastewater treatment plants, on-site septic systems, domestic and wild animal manure, and storm runoff.

The most commonly tested fecal bacteria indicators are total coliforms, fecal coliforms, *Escherichia coli*, fecal streptococci, and enterococci. All but *E. coli* are composed of a number of species of bacteria that share common characteristics such as shape, habitat, or behavior; *E. coli* is a single species in the fecal coliform group.

Total coliforms are a group of bacteria that are widespread in nature. All members of the total coliform group can occur in human feces, but some can also be present in animal manure, soil, and submerged wood and in other places outside the

human body. Thus, the usefulness of total coliforms as an indicator of fecal contamination depends on the extent to which the bacteria species found are fecal and human in origin. For recreational waters, total coliforms are no longer recommended as an indicator. For drinking water, total coliforms are still the standard test because their presence indicates contamination of a water supply by an outside source.

Fecal coliform bacteria are a group of bacteria that are passed through the fecal excrement of humans, livestock and wildlife. A specific subgroup of this collection is the fecal coliform bacteria, the most common member being *Escherichia coli*. These organisms may be separated from the total coliform group by their ability to grow at elevated temperatures and are associated only with the fecal material of warm-blooded animals. For recreational waters, fecal coliforms and *E. coli* are the primary bacteria indicators.

II.2.2. Wastewater Disinfection Techniques

Disinfection can be achieved by any method that destroys pathogens. A variety of physical or chemical methods are capable of destroying microorganisms under certain conditions. Chemical agents that have been used as disinfectants include chlorine and its compounds, bromine, iodine, ozone, phenol and phenolic compounds, alcohols, heavy metals and related compounds, dyes, soaps and synthetic detergents, quaternary ammonium compounds, hydrogen peroxide, peracetic acid, various alkalies, and various acids (Metcalf&Eddy, 2003).

Physical disinfectants that can be used are heat, light, and sound waves.

The treatment of wastewaters for the destruction of pathogens demands the use of practical measures that can be used economically and efficiently at all times on large quantities of wastewaters which have been treated to various degrees. Significant factors are important for the selection of disinfectant types. Table II.7. shows the factors in evaluating disinfectant alternatives.

Chlorine dioxide is an effective water disinfectant. It is capable of oxidizing iron and manganese, removing color, and lowering tri-halomethane (THM) formation potential. It also oxidizes many organic and sulfurous compounds that cause taste-and-odor problems (Tchobonoglous, 1987). But concerns have been raised over possible health effects of its main degradation byproducts, ClO_2^- and ClO_3^- .

Table II.7. Significant factors in evaluating disinfectant alternatives (WEF, 1997)

Factors	Properties
Effectiveness	Ability to achieve target levels of selected indicator organism
	Broad-spectrum disinfecting ability
	Reliability
Cost	Capital cost
	Amortization cost
	Operation and maintenance cost
	Cost of special wastewater pretreatment
Practically	Ease of transport and storage or ease of on-site generation
	Ease of application and control
	Flexibility
	Complexity
	Ability to predict results
	Safety considerations
Pilot studies required	Dose requirements
	refine design details
Potential adverse effects	Toxicity to aquatic life
	Formation and transmission of undesirable bio-accumulating substances
	Formation and transmission of toxic, mutagenic, or carcinogenic substances

Bromine is an alternative disinfectant to chlorine. The residual formed when bromine is added to water is as effective a disinfectant as chlorine, but it is not stable. Consequently, depending on the constituents in the water being treated, it may be necessary to add bromine at two or three times the concentration required for chlorine. Because of the higher cost of bromine and its handling hazards, liquid bromine is not used to disinfect public water supplies.

II.2.2.1. Chlorination

Wastewater treatment practices have principally relied on the use of chlorine for disinfection. Chlorine has been prevalently used, because it is an excellent disinfecting chemical and, until recently, has been available at a reasonable cost. However, the rising cost of chlorine coupled with the fact that chlorine even at low concentrations is toxic to fish and other biota as well as the possibility that potentially harmful chlorinated hydrocarbons may be formed has made chlorination less favored as the disinfectant of choice in wastewater treatment. Disinfection by-products of chlorine are THMs and haloacetic acids. As a result, the use of ozone

(ozonation), membrane filtration or ultraviolet light has increased in wastewater disinfection. Both ozone and ultraviolet light, as well as being an effective disinfecting agent, leave no toxic residual. The difference between the chlorine residual in the wastewater after some time interval and the initial dose of chlorine is referred to as chlorine demand. The 15 minute chlorine demand of septic tank effluent may range from 30 to 45 mg/L as Cl₂; for biological treatment effluents, it may range from 10 to 25 mg/L; and for sand filtered effluent, it may be 1 to 5 mg/L. Table II.8 shows chlorine disinfection dose design guidelines for onsite applications for different pretreatment qualities and pH values.

Table II.8. Chlorine disinfection dose (in mg/L) design guidelines for onsite applications (EPA Onsite Manuel)

Calcium hypochlorite	Septic tank effluent	Biological Treatment Effluent	Sand Filter Effluent
pH 6	35 – 50	15 – 30	2 – 10
pH 7	40 – 55	20 – 35	10 – 20
pH 8	50 – 65	30 – 45	20 – 35

II.2.2.2. Ozonation

Ozone is a strong oxidising agent, effective in destroying bacteria, viruses, and also cyst-forming protozoan parasites which are particularly resistant to other disinfectants. The high efficiency of ozone towards viruses makes it especially attractive when regulations for reuse or discharge involve viruses. Several studies on wastewater ozonation reported an enhancement of water quality with up to 20% of COD reduction and decrease of color (Lazarova et al., 1997).

The ozone dosages required to meet the initial demand will depend on the wastewater constituents. Table II.9 shows the typical values for the ozone demand for various wastewaters based on a contact time of 15 min.

Ozonation is a more complex technology than chlorine or UV disinfection, requiring complicated equipment and efficient contacting systems. Also it is not economical for wastewater with high levels of suspended solids, biochemical oxygen demand, chemical oxygen demand, or total organic carbon. Ozone is extremely irritating and possibly toxic, so off-gases from the contactor must be destroyed to prevent worker exposure. Because of operational and maintenance problems, ozone

is generally considered a less attractive alternative to chlorine than UV disinfection (Gomez et al., 2006).

Table II.9. Typical ozone dosages required to achieve different effluent coliform disinfection standards for various wastewaters based on a 15-min contact time (Metcalf & Eddy, 2003).

Type of wastewater	Initial coliform count, MPN/100 mL	Ozone Dose, mg/L			
		Effluent Standard, MPN/100 mL			
		1000	200	23	<2.2
Raw wastewater	$10^7 - 10^9$	15-40			
Primary effluent	$10^7 - 10^9$	10-40			
Trickling filter eff.	$10^5 - 10^6$	4-10			
Activated-sludge eff.	$10^5 - 10^6$	4-8	4-10	16-30	30-40
Filtered activated-sludge eff.	$10^4 - 10^6$	6-8	4-10	16-25	30-40
Nitrified eff.	$10^4 - 10^6$	3-6	4-6	8-20	18-24
Filtered nitrified eff.	$10^4 - 10^6$	3-6	3-8	4-15	15-20
Microfiltration eff.	$10^1 - 10^3$	2-6	2-6	3-8	4-8
Reverse osmosis					1-2
Septic tank eff.	$10^7 - 10^9$	15-40			
Intermittent sand filter eff.	$10^2 - 10^4$	4-8	10-15	12-20	16-25

II.2.2.3. Membrane Filtration

Membrane filtration, widely used in chemical and biotechnology processes, is already established as a valuable means of filtering and cleaning wastewater.

Water and wastewater treatment membranes are typically classified in order of decreasing pore size as microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO). As a general rule, MF is suitable for the removal of suspended solids, including larger microorganisms like protozoa and bacteria. UF is required for the removal of viruses and organic macromolecules down to a size of around 20 nm. Smaller organics and multivalent ions may be removed by NF while RO is even suitable for the removal of all dissolved species (Wintgens et al., 2005).

Membrane filtration technology is based on a physical barrier concept. Because of the high quality of the treated water, membrane filtration is used for specific water reuse applications in several countries. The absence of bacterial regrowth and residual toxicity may give membranes important advantages over other processes for groundwater recharge and potable reuse (Lazarova et al., 1999).

II.2.2.4. Comparison of Disinfection Techniques

Main disinfectants that have been used in wastewater are compared in Table II.10, using the criteria defined in Table II.7.

Table II.10. Applicability of alternative disinfection techniques (WEF, 1996)

Considerations	Chlorination	Chlorination /Dechlorination	Bromine chloride	Chlorine dioxide	Ozonation	Ultraviolet radiation
Size of plant	All sizes	All sizes	All sizes	Small to medium	Medium to large	Small to medium
Applicable level of treatment before disinfection	All levels	All levels	Secondary	Secondary	Secondary	Secondary
Equipment reliability	Good	Fair to good	Unknown	Unknown	Fair to good	Fair to good
Process control	Well developed	Fairly well developed	Problematic	No experience	Fairly well developed	Fairly well developed
Relative complexity of technology	Simple to moderate	Moderate	Moderate	Moderate	Complex	Simple to moderate
Safety concerns	Yes	Yes	Yes	Yes	Yes	No
Transportation on site	Substantial	Substantial	Substantial	Substantial	Minimal	Minimal
Bactericidal	Good	Good	Good	Good	Good	Good
Virucidal	Poor	Poor	Fair to good	Good	Good	Good
Cysticidal	Poor	Poor	Unknown	Fair	Good	Ineffective
Fish toxicity	Toxic	Non toxic	Slight to moderate	Toxic	None expected	Nonetoxic
hazardous byproducts	Yes	Yes	Yes	Yes	Yes	No
Persistent residual	Long	None	Short	Moderate	None	None
Contact time	Long	Long	Moderate	Moderate to long	Moderate	Short
Contributes dissolved oxygen	No	No	No	No	Yes	No
Reacts with ammonia	Yes	Yes	Yes	No	Yes (high pH only)	No

Table II.10 (Continued)

Color removal	Moderate	Moderate	Unknown	Yes	Yes	No
Increased dissolved solids	Yes	Yes	Yes	Yes	No	No
pH dependent	Yes	Yes	Yes	No	Slight (high pH)	No
Operation and maintenance Sensitive	Minimal	Moderate	Moderate	Unknown	High	Moderate
Corrosive	Yes	Yes	Yes	Yes	Yes	No

II.3. UV DISINFECTION

II.3.1. UV Radiation

UV light is the region of the electromagnetic spectrum that lies between X-rays and visible light. The UV spectrum is divided into four sub-regions, which are vacuum UV (100 to 200 nm), UV-C (200 to 280 nm), UV-B (280 to 315 nm) and UV-A (315 to 400 nm). Figure II.3 shows the electromagnetic spectrum and sub-regions of UV spectrum.

UV disinfection primarily occurs due to the germicidal action of UV-B and UV-C light on microorganisms. UV-C radiation, called the germicidal bandwidth, has a strong disinfecting ability, reaching its maximum at a wavelength of 260 nm (Corin et al., 1998). The germicidal action of UV-A light is small relative to UV-B light and UV-C light; therefore, very long exposure times are necessary for UV-A light to be effective as a disinfectant. Although light in the vacuum UV range can disinfect microorganisms, vacuum UV light is impractical for water disinfection applications because it rapidly dissipates in water over very short distances. (EPA Guidance Manual, 2006)

Ultraviolet disinfection is a physical process, achieving disinfection by inducing photobiochemical changes within microorganisms. At a minimum, two conditions must be met for a photochemical reaction to take place:

- Radiation of sufficient energy to alter chemical bonds must be available, and
- Such radiation must be absorbed by the target molecule or microorganism (WEF, 1996).

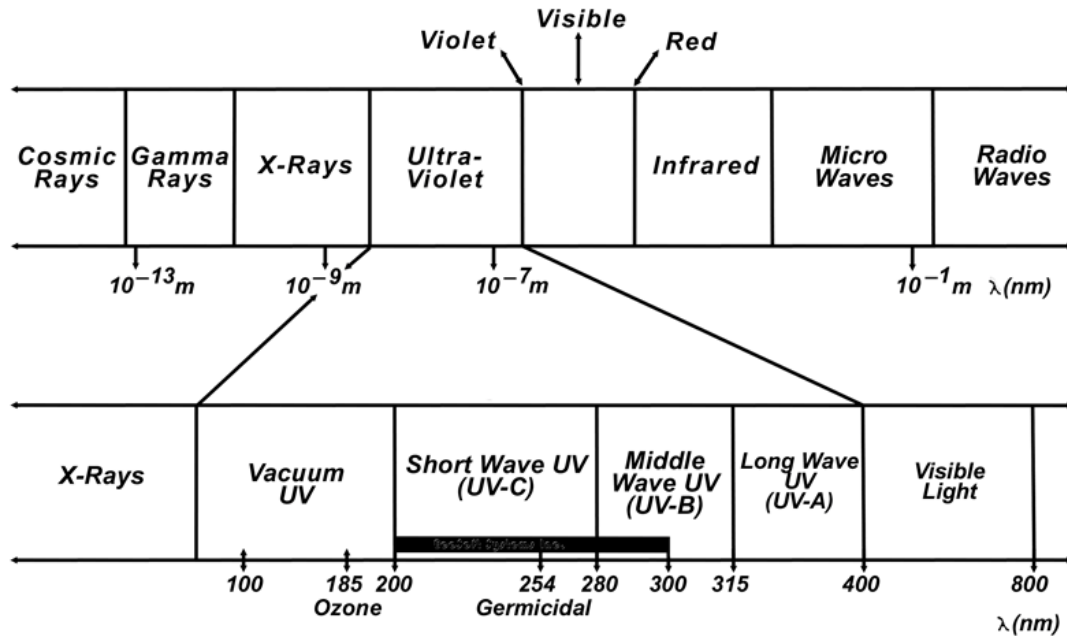


Figure II.3. UV Light in the Electromagnetic Spectrum

Low-pressure mercury arc lamps have been chosen as the source of UV radiation in the majority of UV disinfection applications. These lamps generate essentially monochromatic radiation at a wavelength of 253.7 nm, which is close to the 260 nm wavelength that is considered to be most effective for microbial inactivation (Metcalf&Eddy, 2004).

In a photochemical reaction, one Einstein represents one “mole” (Avogadro number) of photons. Photochemical reactions almost always proceed via interactions between single photons and single molecules. Therefore, an expression of radiation energy per einstein allows direct comparison with bond energies per mole.

The energy associated with electromagnetic radiation may be calculated with the following formula (WEF, 1996):

$$E_{\lambda} = (h \times C_v \times AN) / \lambda \quad (\text{II.1.})$$

Where,

E_{λ} = Radiant energy associated with given wavelength, kcal/einstein;

C_v = Speed of electromagnetic radiation in a vacuum, 3×10^{17} nm/s;

h = Planck’s constant = 1.583×10^{-37} kcal.s;

λ = Wavelength of electromagnetic radiation, nm;

AN = Avogadro's number $\approx 6.023 \times 10^{23}$ photons/einstein.

Equation II.1. indicates that ultraviolet radiation at a wavelength of 253.7 nm has an associated energy of 112.8 kcal/einstein, which is sufficient to break several important bonds in microbial systems, for which required energy levels are listed below in Table II.11.

Table II.11. Bond Energies of Importance in Microbiological Systems

Bond	Bond Dissociation Energy, (kcal/mole)
O – H	110 – 111
C – H	96 – 99
N – H	93
C = O	173 – 181
C – N	69 – 75
C = C	146 – 151
C – C	83 – 85

As mentioned earlier, sufficient energy of radiation is not enough for a photochemical reaction to take place, but also such radiation must be absorbed by the target microorganism.

Nucleic acid is the molecule responsible for defining the metabolic functions and reproduction of all forms of life. DNA and RNA are the two most common forms of nucleic acid, that consist of single- or double-stranded polymers comprising building blocks called nucleotides. In DNA, the nucleotides are classified as either purines (adenine and guanine) or pyrimidines (thymine and cytosine). In RNA, the purines are the same as in DNA, but the pyrimidines are uracil and cytosine (EPA Guidance Manual, 2006). Figure II.4 shows the structure of DNA and nucleotide sequences within DNA.

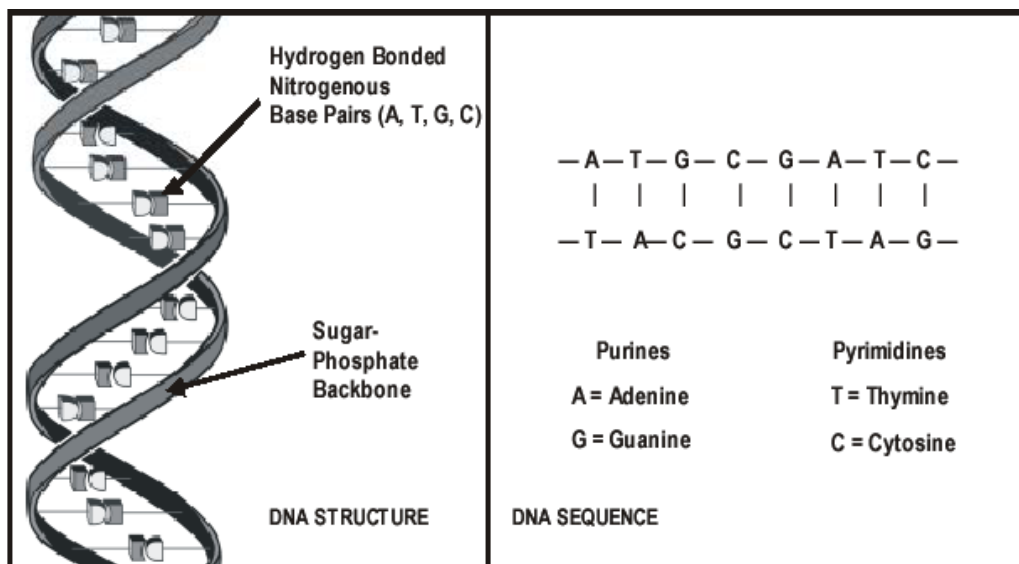


Figure II.4. Structure of DNA and Nucleotide Sequences Within DNA (EPA Guidance Manuel, 2006)

All purines and pyrimidines strongly absorb UV light, but the rate of UV-induced damage is greater with pyrimidines (Jagger, 1967). These materials absorb strongly over the range $240 \leq \lambda \leq 260$ nm. UV absorption spectra for purine and pyrimidine bases can be seen at Figure II.5. Absorbed UV light induces three types of damage in the pyrimidines of nucleic acid that contribute to UV disinfection (Setlow, 1967; Snowball and Hornsey, 1988; Pfeifer, 1997). Pyrimidine dimers form when covalent bonds are present between adjacent pyrimidines on the same DNA or RNA strand. They are the most common form of nucleic acid damage. Thymine-thymine dimers are the most common of the three possible pyrimidine dimers that can form within DNA (thymine-thymine, cytosine-cytosine, and thymine-cytosine); therefore microorganisms with DNA rich in thymine tend to be more sensitive to UV disinfection (EPA Guidance Manuel, 2006).

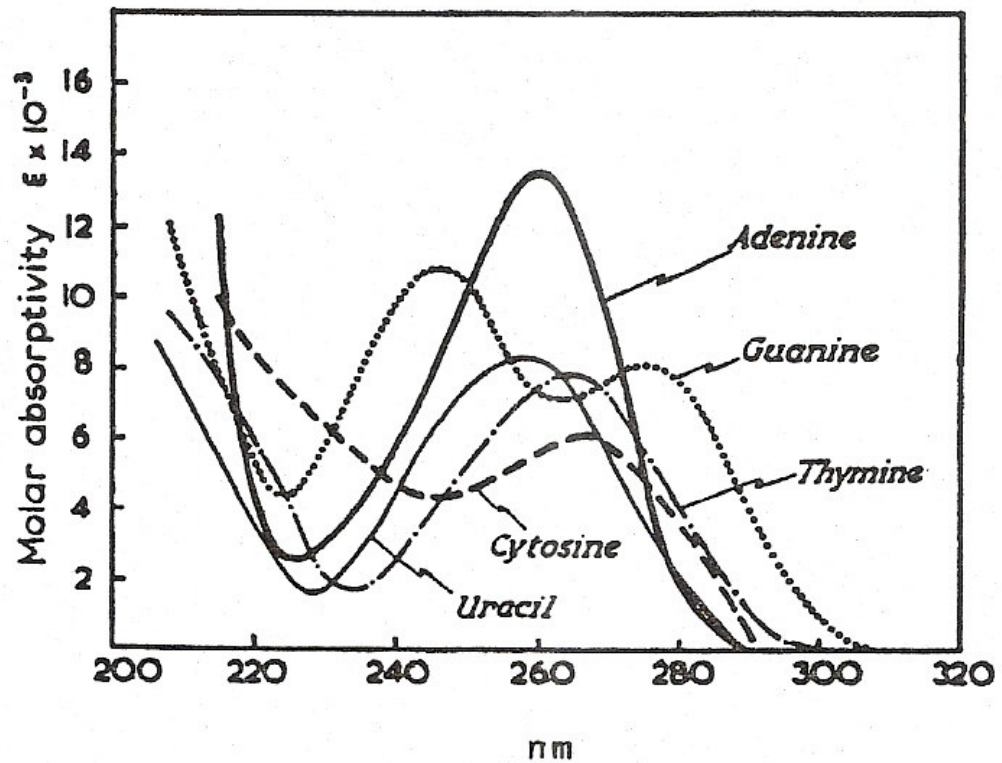


Figure II.5. Ultraviolet absorption spectra for purine and pyrimidine bases (WEF, 1996)

II.3.2. Repair Mechanisms

Some organisms are known to possess mechanisms to repair UV-damaged DNA. These repair mechanisms allow UV-inactivated microorganisms to regain viability following disinfection process (WEF, 1996). Repair mechanisms are classified as photoreactivation and dark repair.

II.3.2.1. Photoreactivation

Photoreactivation is a repair mechanism, by which UV-inactivated organisms regain their activity via photorepair of UV-induced lesions in the DNA by utilizing the energy of near-UV light (310 to 490 nm) and an enzyme called photolyase. Therefore, UV-A is essential for photoreactivation, although it also has lethal and sublethal effects on organisms. Special attention has been paid to photoreactivation because it may greatly impair the efficacy of UV disinfection within a few hours after treatment (Ogumo et al., 2002).

Bacteria have the enzymes necessary for photorepair. Viruses lack the necessary enzymes for repair but can repair using the enzymes of a host cell (Rauth, 1965).

The significance of photoreactivation will depend in large part on the initial dose of UV radiation, the dose of photoreactivating radiation, and the microorganisms (WEF, 1996).

Photoreactivation can be prevented by keeping the UV disinfected water in the dark for at least two hours before exposure to room light or sunlight (EPA Guidance Manuel, 2006).

II.3.2.2. Dark Repair

Dark repair does not require light to repair the damaged DNA; however dark repair can also occur in the presence of light. Dark repair processes are thought to involve enzymatic recognition of a dimer on a DNA strand. The dimer is excised from the DNA molecule, and the strand is repaired (US. EPA, 1986).

Dark repair has been demonstrated in almost all bacteria but some lack the enzymes needed for dark repair. Viruses also lack the necessary enzymes for repair but can repair using the enzymes of a host cell (Rauth, 1965).

The existence of repair mechanisms brings questions about design considerations. The availability of repair mechanisms would dictate a larger UV dose than would be required if no repair were possible. Similarly, the inclusion of reactivation mechanisms in the design process requires more UV hardware.

II.3.3. Source of UV Radiation

To produce UV radiation, lamps that contain mercury vapor are charged by striking an electric arc. The energy generated by the excitation of the mercury vapor contained in the lamp results in the emission of UV light (Metcalf & Eddy, 2003). Mercury gas is advantageous for UV disinfection applications because it emits light in the germicidal wavelength range. Also some other gases like xenon emit light in the germicidal range (EPA Guidance Manuel, 2006).

In general, UV disinfection systems fall into three categories based on the internal operating parameters of the UV lamp, which are, low-pressure low-intensity, low-pressure high-intensity, and medium-pressure high-intensity systems.

II.3.3.1. Low-Pressure Low-Intensity UV Lamps

Low-pressure low-intensity UV lamps produce essentially monochromatic (one wavelength) UV light at 253.7 nm, which is close to the 260 nm wavelength that is considered to be most effective for microbial inactivation. Low-pressure low-intensity lamps also emit small amounts of light at 185, 313, 365, 405, 436, and 546 nm due to higher energy electron transition in the mercury. UV light is produced by mercury at low vapor pressure (near vacuum; 2×10^{-5} to 2×10^{-3} psi) and moderate temperature (40 °C). Low-pressure low-intensity UV lamps are of a slim line design with an overall length of 0.75 to 1.5 m and diameters varying from 15 to 20 mm. The output of low-pressure low-intensity lamps is about 25 to 27 W at 254 nm for a power input of 70 to 80 W. Approximately 85 to 88 percent of the lamp output is monochromatic at 254 nm, making it an efficient choice for disinfection process (Metcalf & Eddy, 2003).

Quartz sleeves are used to isolate the UV lamps from direct water contact and to control the lamp wall temperature by buffering the effluent temperature extremes to which the UV lamps are exposed, thereby maintaining a fairly uniform UV lamp output. Because there is an excess of liquid mercury in the low- pressure low-intensity UV lamp, the mercury vapor pressure is controlled by the coolest part of the lamp wall. If the lamp wall does not remain at its optimum temperature of 40°C, some of the mercury in the lamp condenses back to its liquid state, thereby decreasing the number of mercury atoms available to release photons of UV; hence UV output declines. The output of UV disinfection systems also decreases with time due to a reduction in the electron pool within the UV lamp, deterioration of the electrodes, and the aging of the quartz sleeve. The useful life of a low- pressure low-intensity UV lamp will vary from 9000 to 13000 hours depending on the number of on-off cycles per day. The useful life of the quartz sleeve is about 4 to 8 years (Metcalf & Eddy, 2003).

II.3.3.2. Low-Pressure High-Intensity UV Lamps

Low-pressure high-intensity UV lamps are similar to the low-pressure low-intensity lamps with the exception that a mercury-indium amalgam is used in place of mercury. These lamps operate at a higher current discharge and pressures between 0.001 and 0.01 mm Hg. Use of the mercury amalgam allows greater UV-C output, typically from 2 to 4 times the output of conventional low-intensity lamps.

The amalgam in the low pressure high-intensity UV lamps is used to maintain a constant level of mercury atoms, and thus provides greater stability over a broad temperature range, and greater lamp life (25 % greater than other low-pressure lamps) (Metcalf & Eddy, 2003).

II.3.3.3. Medium-Pressure High-Intensity UV Lamps

Medium-pressure high-intensity UV lamps employ the same basic principle as low-pressure lamps. The major difference is that the mercury vapor emission is carried out at significantly higher lamp pressures and temperatures (WEF, 1996). In medium-pressure UV lamps, a vapor pressure of 2 to 200 psi, and higher operating temperatures (600 – 900 °C) is used to increase the frequency of collisions between mercury atoms, which produces UV light over a broad spectrum (polychromatic) with an overall higher intensity (EPA Guidance Manual, 2006). About 27 to 44 % of the total energy of medium-pressure high-intensity lamps is in the germicidal UV-C wavelength range. Only about 7 to 15 % of the output is near 254nm. However, medium-pressure high-intensity UV lamps generate approximately 50 to 100 times the total UV-C output of the conventional low-pressure low-intensity UV lamp. Their use is limited primarily to higher wastewater flows, storm water overflows, or on space-limited sites because fewer lamps are required and the footprint of the disinfection system is greatly reduced (Metcalf & Eddy, 2003).

The typical arc length of a medium-pressure lamp is about 1.6 meters. Medium-pressure lamps have a rated life of 4000 hours, although experience has shown an expected life exceeding 8000 hours. The actual lamp life is dependent on lamp operating power (WEF, 1996).

UV output of low-pressure and medium-pressure lamps is shown at Figure II.6.

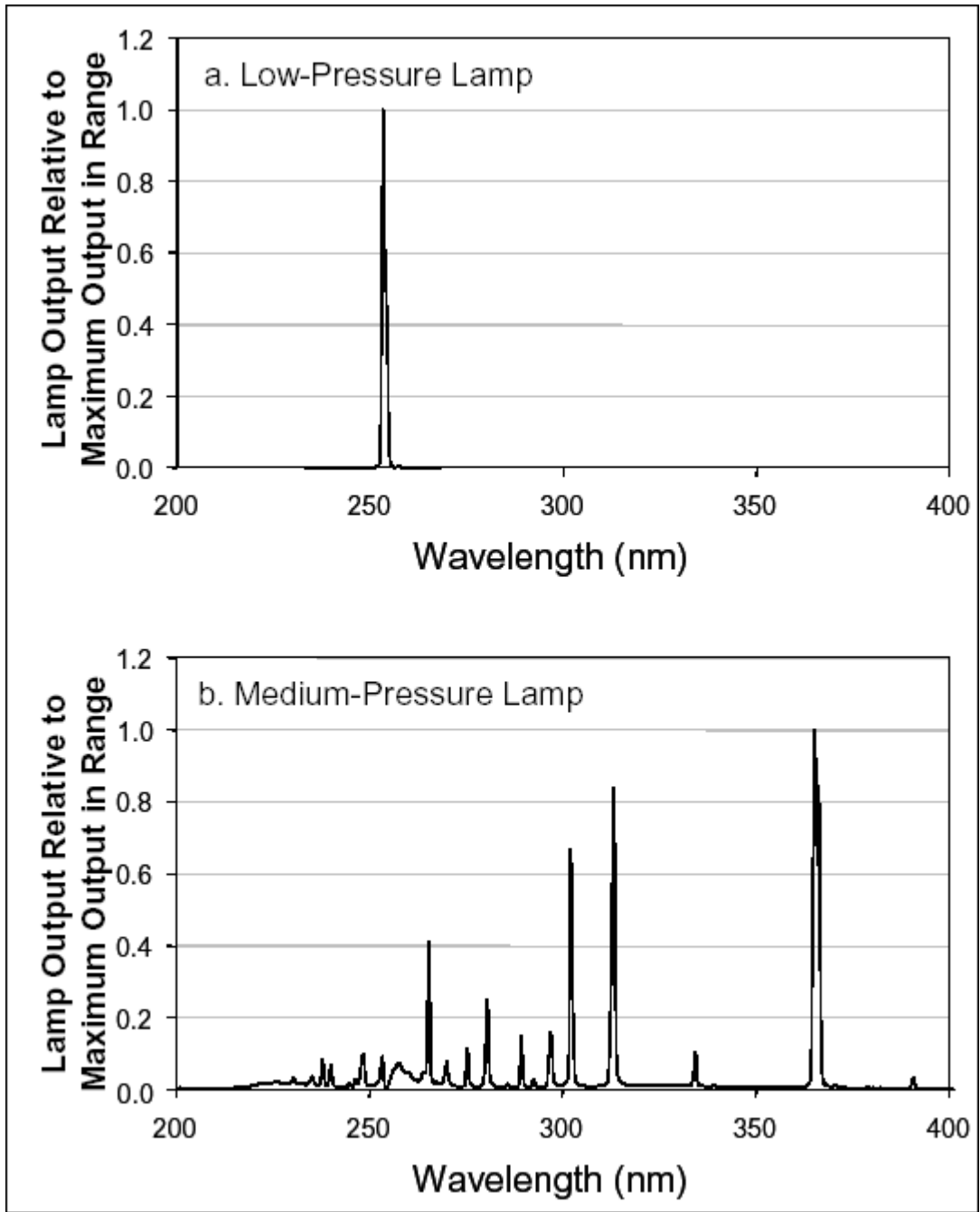


Figure II.6. UV Output of Low-Pressure and Medium-Pressure Lamps (EPA Guidance Manual, 2006)

Figure II.7 shows the output of low-pressure and medium-pressure lamps superimposed on the DNA absorption spectrum (EPA Guidance Manual, 2006).

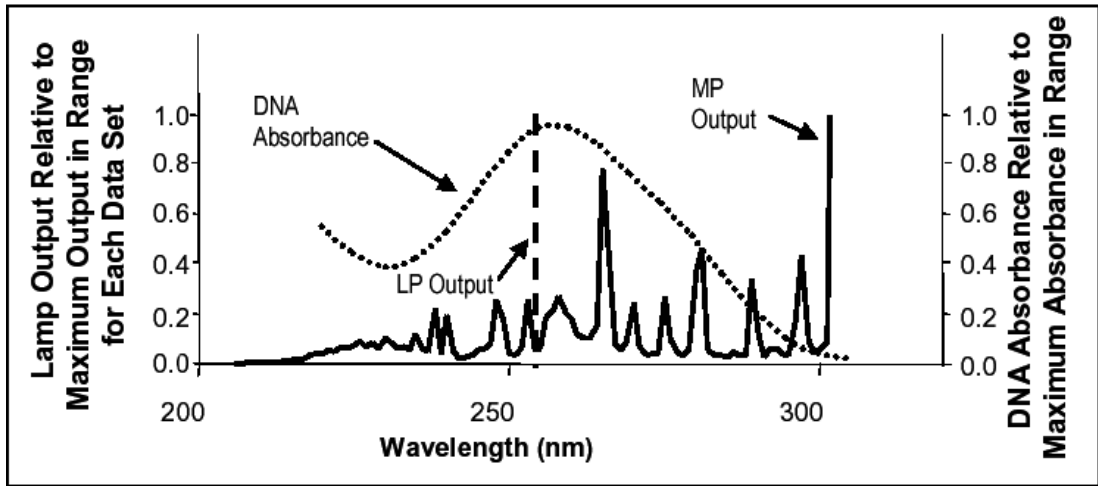


Figure II.7. UV Absorbance of Nucleotides (EPA Guidance Manual, 2006)

II.3.4. UV Disinfection Equipments

UV reactors consist of open or closed-channel vessels, which contain UV lamps, quartz sleeves in which the UV lamp is placed, the supporting structure for the UV lamps and quartz sleeves, the ballasts used to supply regulated power to the UV lamps, the power supply which is used to power the ballasts.

UV lamps are housed within lamp sleeves to help keep the lamp at optimal operating temperature and to protect the lamp from breaking. Lamp sleeves are tubes of quartz that are open at one or both sides. Lamp sleeves absorb some UV light, which may influence dose delivery by the reactor (EPA Guidance Manual, 2006).

Ballasts are used to regulate the incoming power supply at the level needed to energize and operate the UV lamps. Without a ballast to limit current, the lamp would destroy itself. UV reactors typically use three types of ballasts; standard (core coil), energy-efficient (core coil), and electronic (solid-state).

II.3.5. UV Reactor Configuration

UV disinfection systems may be classified as open-channel or closed-pipe based on their hydraulic characteristics.

II.3.5.1. Open – Channel Disinfection Systems

Open – channel disinfection systems have been preferred in the majority of UV disinfection systems. Lamp placement can be horizontal, uniform arrays with flow directed parallel to lamp axes, or vertical, staggered arrays with flow directed

perpendicular to lamp axes. The horizontal lamp orientation is the most frequently used application.

The design flowrate is usually divided equally into a number of open channels. Each channel typically contains two or more banks of UV lamps in series, and each bank is comprised of a specified number of modules (or racks of UV lamps). A standby bank or channel should be provided for system reliability (Metcalf & Eddy, 2003).

UV system manufacturers generally use 2, 4, 8, 12 or 16 UV lamps in each module and they usually use a lamp configuration that has a spacing of 75 mm between the centers of UV lamps.

A weight flap gate, an extended sharp-crested weir or an automatic level controller is used to control the depth of flow through each disinfection channel. To overcome the effect of fouling, which reduces the intensity of light in the liquid medium, the lamps must be removed occasionally from the flow channel and cleaned. Mechanically cleaned systems are used with low-pressure high-intensity systems to avoid fouling of the quartz sleeves (Metcalf & Eddy, 2003). Occasionally chemical cleaning of the lamps with a weak acid is necessary to clean the deposition on the lamp sleeves totally.

II.3.5.2. Closed – Channel Disinfection Systems

A number of low- and medium-pressure high-intensity UV disinfection systems are designed to operate in closed channels. In most design configurations, the direction of flow is perpendicular to the placement of the lamps. In the medium-pressure UV disinfection system, the lamps are arranged in modules and are positioned in a reactor with a fixed geometry. Because the high-intensity UV lamps operate at a lamp wall temperature of between 600 and 800°C, the UV output of these lamps is unaffected by the effluent temperature. Essentially all the closed or fixed geometry systems used for the disinfection of the wastewater incorporate some form of mechanical wiping of the quartz sleeves to maintain performance (Metcalf&Eddy, 2003).

II.3.6. UV Intensity and UV Dose

The UV irradiation intensity is a measure of radiative power per unit of exposed area. The total UV intensity at a point in space is the sum of the intensity of UV light from all directions.

UV Dose is the integral of UV intensity during the exposure period. If the UV intensity is constant over the exposure time, UV dose is defined as the product of the intensity and the exposure time (EPA Guidance Manual, 2006).

The effectiveness of UV disinfection is based on the UV dose to which the microorganisms are exposed. The UV dose D is defined as follows:

$$D = I \times t \quad (\text{II.2.})$$

Where:

D = UV Dose, $\text{mJ}/\text{cm}^2 = \text{mWs}/\text{cm}^2$

I = UV Intensity, mW/cm^2

t = Exposure time, s

UV dose can be varied by changing either the intensity or the exposure time (Metcalf&Eddy, 2003). In a completely mixed batch system the UV dose that the microorganisms receive is equal to the volume-averaged UV intensity within the system. But in a continuous flow UV reactor, dose delivery is more complex. The UV intensity attenuates with distance from the quartz sleeve. Therefore, microorganisms that travel close to the UV lamps experience a higher dose, while others that travel close to the reactor walls may experience a lower dose. Also some microorganisms move through the reactor quickly, while others travel a more circuitous path. The result is that each microorganism leaving the reactor receives a different UV dose. Accordingly, UV dose delivered to the microorganisms passing through the reactor is best described using dose distribution as opposed to a single dose value. A dose distribution can be defined as a histogram of dose delivery. Alternatively, the dose distribution can be defined as a probability distribution that a microorganism leaving a UV reactor will receive a given dose (EPA Guidance Manual, 2006). The dose distribution a UV reactor delivers can be estimated by using mathematical models.

II.3.7. UV Disinfection Kinetics

Microbial response is a measure of the sensitivity of the microorganism to UV light and is unique to each microorganism (EPA Guidance Manual, 2006). The experimental procedure used to evaluate inactivation dose – response behavior involves exposure of a microbial population to a measurable source of radiation for a known period of time, followed by quantification of microbial viability. The source of radiation is a collimated beam in most cases (WEF, 1996). The collimated beam procedure involves placing a shallow petri dish and exposing the sample to collimated UV light for a predetermined amount of time. Water depth is typically maintained at 10 mm or less. To ensure uniform irradiation of all microorganisms in the liquid, a micromagnetic stir bar is used to mix the liquid containing the microbial population.

The UV dose is calculated using the measured intensity of the UV light, UV absorbance of the water, and exposure time. The measured concentration of microorganisms before and after exposure provides the “response”, or log inactivation of microorganisms from exposure to UV light.

The microbial response is calculated by using the following equation;

$$\text{Log inactivation} = \log (N_0 / N) \quad (\text{II.3.})$$

Where:

N_0 = the concentration of infectious microorganisms before exposure to UV light,

N = the concentration of infectious microorganisms after exposure to UV light.

UV dose – response relationships can be expressed as either the proportion of microorganisms inactivated or the proportion of microorganisms remaining as a function of UV dose. Microbial inactivation has a dose – response curve with a positive slope, while microbial survival has a dose – response curve with a negative slope (EPA Guidance Manual, 2006).

II.3.8. Factors Affecting UV Disinfection Efficiency

The quality of the wastewater is one of the factors that affect the performance of UV disinfection. Previous studies have shown that suspended particles in

wastewater can increase microbial survival by shielding microorganisms from UV irradiation. Qualls and co-workers (1983) observed significant greater disinfection effect in filtered effluent than in unfiltered effluent. Loge and co-workers (1999) concluded that UV light cannot penetrate particles by transmission through solid material. Coliform bacteria, which are typically between 1 and 10 μm in size, have been shown to be shielded during the UV disinfection of wastewater by being enmeshed within particles greater than 10 μm in diameter (Qualls et al., 1985; Emerick et al., 2000). In a study by Ormeci and Linden (2002), filtration was found to be effective in reducing particle – associated coliform and decreasing the total number of particles at all particle sizes. However, viruses are one or two orders of magnitude smaller than bacteria and may therefore be protected by much smaller particles that may routinely pass through even well-operated filters in water treatment facilities (Templeton et al., 2005).

UV Transmittance (UVT) is a measure of the fraction of incident light transmitted through a material and has a strong effect on the dose delivery of a UV reactor. UVT can also be described as the percentage of light passing through material over a specified distance. UV transmittance can be calculated using Beer's law;

$$\% \text{ UVT} = 100 \times I / I_0 \quad (\text{II.4.})$$

Where;

UVT = UV Transmittance at a specified wavelength (e.g., 254 nm) and pathlength (e.g., 1 cm)

I = Intensity of light transmitted through the sample (mW/cm^2)

I_0 = Intensity of light incident on the sample (mW/cm^2)

UV Transmittance can also be determined by using the absorbance.

$$\text{UVT, \%} = 100 \times 10^{-A} \quad (\text{II.5.})$$

Where:

UVT = UV Transmittance at a specified wavelength (e.g., 254 nm) and pathlength (e.g., 1 cm)

A = UV absorbance at a given wavelength (unitless)

As UV transmittance decreases, the intensity throughout the reactor decreases, which reduces the dose the reactor delivers (EPA Guidance Manuel, 2006). The variations in transmittance are often caused by industrial discharges, which can lead to diurnal as well as seasonal variations.

The effectiveness of the UV disinfection process depends on the characteristics of the microorganisms. Table II.12 presents the relative effectiveness of UV radiation for disinfection of various discrete organisms. However, knowledge concerning the required UV dose for specific pathogen inactivation is changing continuously as improved methods of analysis are applied (Metcalf&Eddy, 2003)

Table II.12. Estimated Relative Effectiveness of UV Radiation for the Disinfection of Representative Microorganisms of Concern in Wastewater (Metcalf&Eddy, 2003).

Organism	Dosage relative to total coliform dosage
Bacteria:	
Fecal coliform	0.5 – 0.9
Pseudomonas aeruginosa	1.5 – 2.0
Salmonella typhosa	0.7 – 0.9
Staphylococcus aureus	1.0 – 1.5
Total coliform	1.0
Viruses:	
Adenovirus	0.7 – 0.9
Coxsackie A2	1.0 – 1.5
F specific bacteriophage	0.4 – 0.8
Polio type 1	0.9 – 1.1
MS-2 bacteriophage	0.9 – 1.0
Protozoa:	
Acanthamoeba castellanii	10 – 12
Acanthamoeba culbertsoni	10 – 12
Cryptosporidium parvum oocysts	0.2 – 0.4
Giardia lamblia cysts	0.2 – 0.6
Other:	
Clostridium spores	

Some wastewater constituents also affect the UV disinfection efficiency. Dissolved contaminants impact UV disinfection either directly via absorbance impacts or via fouling of UV lamps such that a reduced intensity is applied to the bulk liquid medium. Table II.13 shows the effect of wastewater constituents on UV disinfection (Metcalf&Eddy, 2003).

Another factor that can attenuate the performance of the UV disinfection is the accumulation of insoluble materials on the surfaces of the quartz sleeves. Fouling on the lamp sleeves reduces the transmittance of UV light through the sleeve into the water, thereby reducing the output from the lamp into the water. Hardness, alkalinity, temperature, ion concentration, oxidation reduction potential (ORP), and pH all influence the rate of fouling and, subsequently, the necessary frequency of sleeve cleaning (EPA Guidance Manuel, 2006). Compounds for which the solubility decreases as temperature increases, and compounds with low solubility may precipitate and cause fouling. Photochemical reactions that are independent of sleeve temperature may cause sleeve fouling. Particles may deposit on the lamp sleeve surface due to gravity settling and turbulence-induced collisions (Lin et al., 1999). Inorganic constituents can also oxidize and precipitate (Wait et al., 2005). Control of lamp fouling is achieved by a variety of techniques. Chemical removal of scale is achieved by applying dilute acid (pH of approximately 1 to 2) to the fouled surface. Acid can be applied by either wiping the individual lamps or immersing entire lamp modules. Immersion techniques are more efficient for scale removal (WEF, 1996).

Lamp aging is another factor that may affect the UV disinfection efficiency. Ultraviolet output from mercury arc lamps changes as a function of time. In general, lamps begin with relatively high output power (WEF, 1996). But UV lamps degrade as they age, resulting in a reduction in output that causes a drop in UV dose delivery over time. Lamp degradation is a function of the number of lamp hours in operation, number of on/off cycles, power applied per unit (lamp) length, water temperature, and heat transfer from lamps (EPA Guidance Manuel, 2006).

Any deposits on the inner or outer surfaces of the lamp envelope and metallic impurities within the envelope can absorb UV light and cause premature lamp aging. In low-pressure and low-pressure high intensity lamps using UV-transmitting glass, mercury may combine with sodium in the glass to create a UV-absorbing coating.

Electrode sputtering during start-up can also coat the inside surface of the lamp envelope with tungsten as the lamp ages. The tungsten coating is black, non-uniform, concentrated within a few inches of the electrode, and can absorb UV light.

Table II.13. Impact of wastewater constituents on the use of UV radiation for wastewater disinfection (Metcalf&Eddy, 2003)

CONSTITUENT	EFFECT
BOD, COD, TOC, etc	No or minor effect, unless humic materials comprise a large portion of the BOD
Humic materials	Strong absorbers of UV radiation
Oil and grease	Can accumulate on quartz sleeves of UV lamps, can adsorb UV radiation
TSS	Absorption of UV radiation, can shield embedded bacteria
Alkalinity	Can impact scaling potential. Also affects solubility of metals that may absorb UV light
Hardness	Calcium, magnesium, and other salts can form mineral deposits on quartz tubes, especially at elevated temperature
Ammonia	No or minor effect
Nitrite	No or minor effect
Nitrate	No or minor effect
Iron	Strong adsorber of UV radiation, can precipitate on quartz tubes, can adsorb on suspended solids and shield bacteria by adsorption
Manganese	Strong adsorber of UV radiation
pH	Can affect solubility of metals and carbonates
TDS	Can impact scaling potential and the formation of mineral deposits
Industrial Discharges	Depending on the constituents, may lead to diurnal and seasonal variations in the transmittance
Stormwater inflow	Depending on the constituents, may lead to short-term as well as seasonal variation in the transmittance

II.3.9. Design

UV system design relies on a combination of past experience, pilot testing, and numerical modeling. Each factor is related, and the degree to which each is used often depends on the size of the system being considered, the budget, and the schedule.

The characterization of the effluent quantity and quality should be obtained. Critical data to be evaluated in design include flow, UV transmittance, suspended solids, and viable indicator organism concentrations. When collecting UV transmittance data, it is important to measure the parameter on both filtered and unfiltered samples. The filtered measurement presents a more representative estimate of the transmissibility through the effluent water and is critical for the design sizing of the system. The lower the transmittance, the greater the size requirements will be. It may be necessary to reduce the spacing of the lamps or consider using higher intensity systems to overcome the lower transmissibility of the water at low transmittance levels.

Suspended solids will affect the transmittance of UV, and occlude bacteria. This, in effect, establishes a limit of disinfection efficiency that can be accomplished by UV; this limit is a function of the particulate matter in the effluent. In biologically treated wastewaters, the concentrations of viable organisms associated with particulate matter can be significant and account for essentially all residual coliforms in the final effluent after clarification.

Scheible (1987) suggested a correlation with SS to predict the level of particulate coliform after UV disinfection of treated municipal effluents:

$$N_p = c SS^m \quad (\text{II.6.})$$

Where,

N_p = particulate coliform density, and

c, m = coefficients representing intercept and slope, respectively, of a log-log regression analysis of SS, with the effluent coliforms measured after imposition of high UV doses.

Another critical design factor is the initial bacterial concentration.

In the design of UV systems, the variability of the relevant wastewater characteristics and the targeted effluent goals must be taken into account. The

facility permit requirements are generally stated in terms of maximum daily, 7-day, and/or 30-day averages. It is essential to consider the type of the permit definition, for instance designing a system meet a 30-day maximum average effluent coliform on the basis of maximum daily influent characteristics will only result in a significantly oversized system.

Final design of a full-scale UV system will include establishing the number of lamps required to meet disinfection requirements under design conditions. Equally critical is the manner in which they are configured in the full-scale design. Typically, lamp banks are arranged in series, usually two or three for horizontal lamp systems and three to six for conventional vertical lamp systems. It is preferable to design the system with relatively long, narrow channels to encourage plug flow and avoid any degree of short-circuiting.

Hydraulic design is also another critical factor to be considered when laying out the full-scale system. An ineffective hydraulic design can cause failure of the system to meet disinfection requirements.

II.3.10. Advantages of UV Disinfection

The advantages of UV disinfection over other disinfection technologies can be listed as follows :

- Effective disinfectant
- More effective than chlorine in inactivating most viruses, spores, cysts
- No chemical addition required
- No formation of disinfection byproducts at dosages used for disinfection
- Water retains its natural flavour and smell
- Microorganism inactivation achieved within seconds
- Maximum operational safety
- Minimal operating costs
- No reaction tanks or secondary pumps required to operate the system
- No corrosion problems
- Effective in the destruction of resistant organic constituents such as NDMA
- No residual toxicity
- Does not increase TDS level of treated effluent
- Reliable technology tried and tested in thousands of installations

CHAPTER III

THE STUDY

III.1. MATERIALS

In order to examine the UV disinfection efficiency based on wastewater quality parameters and to find out the appropriate UV dose for providing the fecal and total coliform values declared at the Turkish Standards for different reuse applications, a UV pilot plant was installed and operated in Paşaköy Wastewater Treatment Plant (WWTP).

III.1.1. Paşaköy Wastewater Treatment Plant

Paşaköy Wastewater Treatment Plant was designed in 2000 for removal of organic matter (COD), nitrogen (N) and phosphorus (P). The design capacity of the plant is 250000 people equivalent and 100000 m³/d of domestic wastewater. Treatment plant is based on advanced biological treatment process technology and designed as A2/O process; anaerobic zone followed by anoxic then oxic zones in aeration units. The treatment plant consists of inlet pumping station, fine screens, aerated grit chamber, selector-distribution chamber, 3 anaerobic tanks, 4 aeration tanks, 4 final clarifiers, DAF unit, aerated sludge storage tanks, sludge dewatering and return of dewatering supernatant to the distribution chamber. Table III.1. shows the design parameters of Paşaköy WWTP. Paşaköy WWTP discharges its effluent to the Riva River. Figure III.1 shows the geographic location of Paşaköy WWTP.

Table III.1. Design parameters of Paşaköy WWTP (Ozdemir, 2004)

Load	Unit	Value
<i>Plant loading</i>	P.E.	250000
<i>Hydraulic loading</i>		
Average flow rate	m ³ / d	100000
Peak flow rate	m ³ / d	125000
<i>Effluent quality</i>		
BOD ₅	mg BOD / L	20
TSS	mg TSS / L	30
TN	mg N / L	10
TP	mg P / L	2

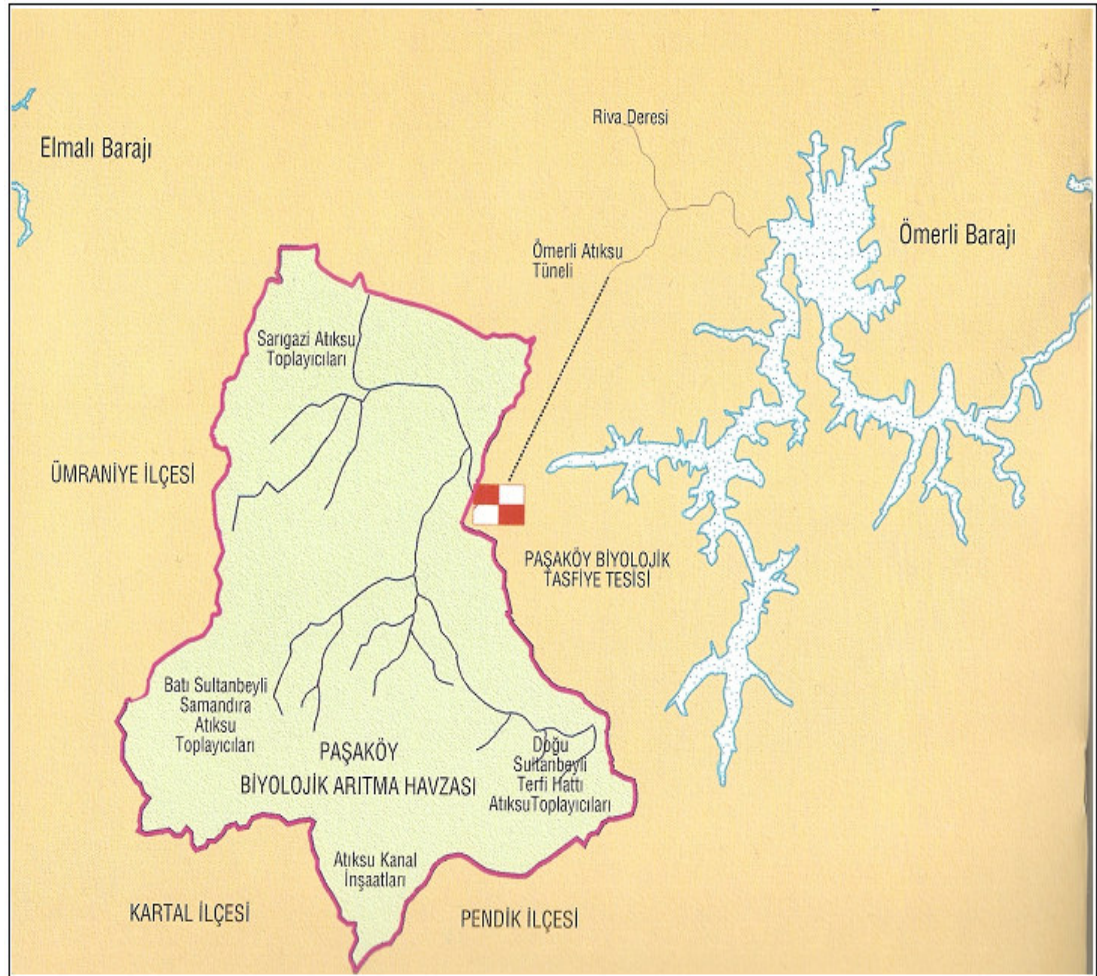


Figure III.1. Geographic Location of Paşaköy WWTP

III.1.2. The Pilot Plant

The pilot plant was manufactured by WEDECO Company. The feed water for the pilot plant was taken from the collection box (CDC5) receiving wastewater from the final clarifier effluents (Figure III.3.).

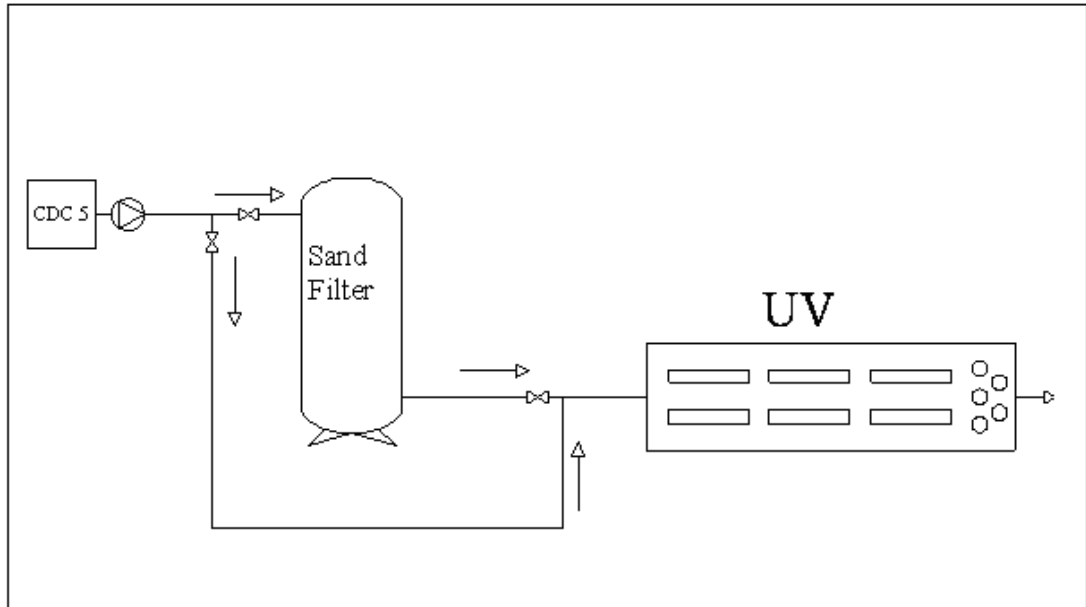


Figure III.2. The pilot plant flow diagram

Experiments have been conducted with both filtered and unfiltered wastewater to observe the importance of filtration on UV disinfection efficiency. The pilot plant also contained a pressurized sand filter. The depth of the filter sand was 100 cm. The sand filter can be seen from Figure III.4.



Figure III.3. Sand Filter

The UV pilot plant is an open-channel system with three UV banks, each consisting of four UV lamps, giving a total of 12 UV lamps. The capacity of the pilot plant is 100 m³/h of wastewater. Main parts of the UV system are;

- Baffle plate
- Lamp module
- UV Module
- Junction Box
- Low Level Probe
- High Level Probe
- Compressor
- Control Cabinet
- Electronic Lamp Ballast
- Human Machine Interface (HMI)

A baffle plate was installed upstream the first UV Bank at the inlet end of the UV channel, for equal distribution of the flow and to improve the flow condition

within the UV channel. It also retained the big particles that could damage the lamps within the UV channel. A picture of the baffle plate can be seen at Figure III.5.



Figure III.4. Baffle Plate at the inlet of the UV channel

Each lamp module consists of a UV lamp, enclosed in an individual quartz sleeve, with the ends appropriately sealed using end plugs. The UV lamps are low-pressure high intensity type with an arc length of 143 cm. The UV lamp produces an output of UV light at a wavelength of 254 nm. Figure III.6 shows a diagram of a lamp module.

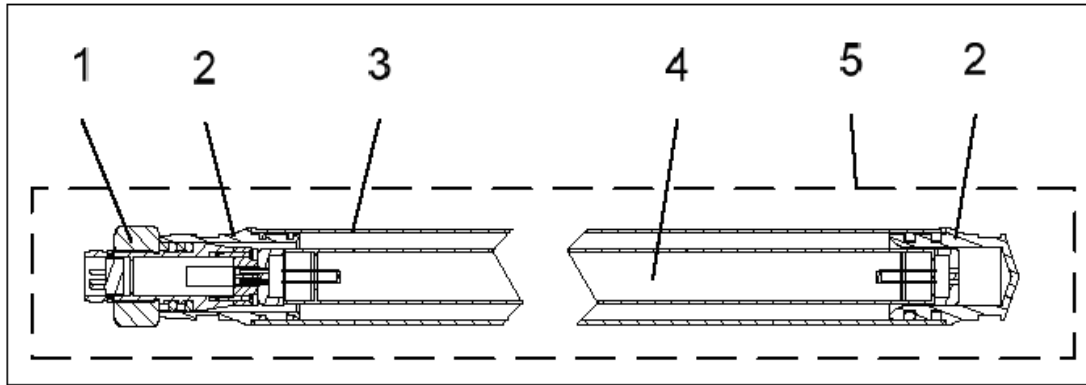


Figure III.5. Lamp Module (1- Watertight connector, 2- End plugs, 3- Quartz sleeve, 4- UV lamp, 5- Lamp module)

Each UV Bank consists of a dual (side-by-side) row configuration of UV lamp modules, with two pairs of lamp modules in the vertical direction, giving a total of four lamp modules per UV Bank.

The UV Module is connected with quick connecting plugs and sockets on the junction box for ease of removal.

Each UV Module is equipped with an automatic wiping system to prolong the period between the quartz sleeves needing to be removed from the UV channel and cleaned manually. It operates with a pneumatically powered cylinder located under the top plate of the module frame. The wiping system is controlled by the UV PLC and provides fully automatic, unattended operation. The wiping interval and number of wipes per interval are adjustable via the HMI. The design allows the cleaning over the complete length of the quartz sleeves. Two brushes wipe the UV Sensor head automatically as they are attached to the wiping system.

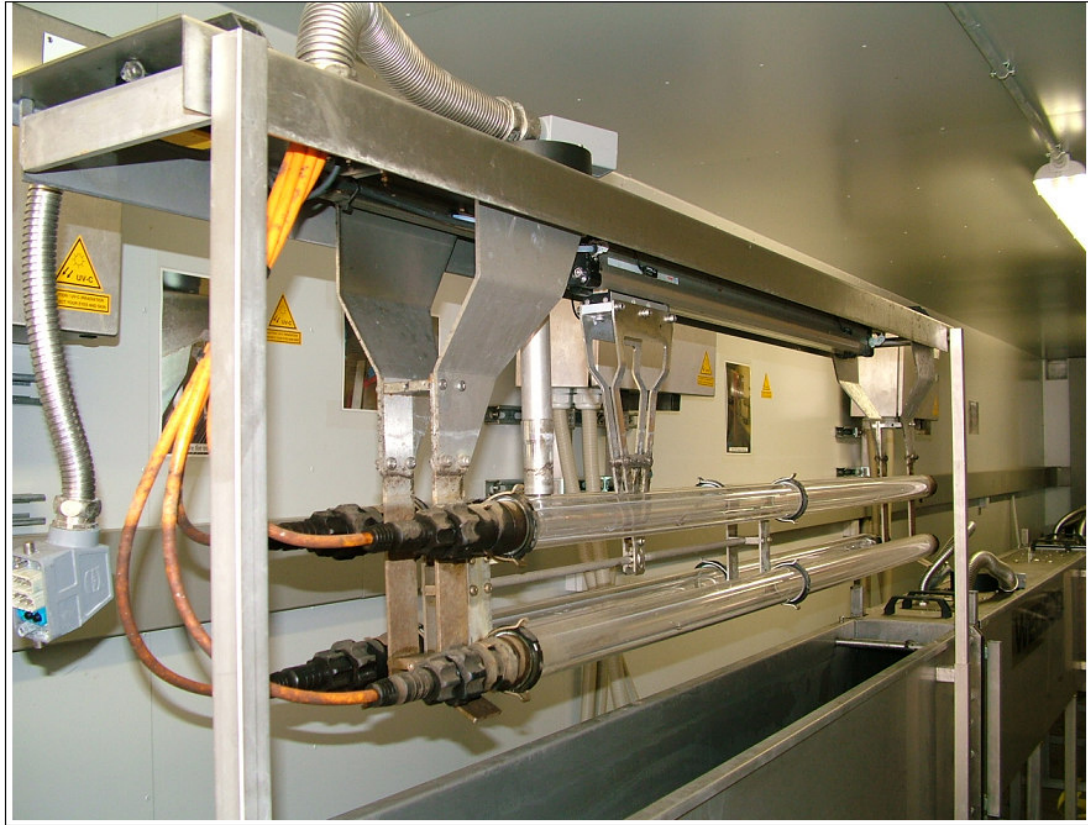


Figure III.6. UV Module

In order to maintain sufficient performance the UV Intensity of the UV Bank is supervised continuously by means of a UV Sensor, which is positioned in the centre module of the bank (Figure III.7.). The sensor head is located between the top pair of UV lamps so that these nearest lamps play a leading role for the sensor reading.

The operation of every UV lamp is supervised by the UV PLC and any faulty lamp is indicated on the HMI.

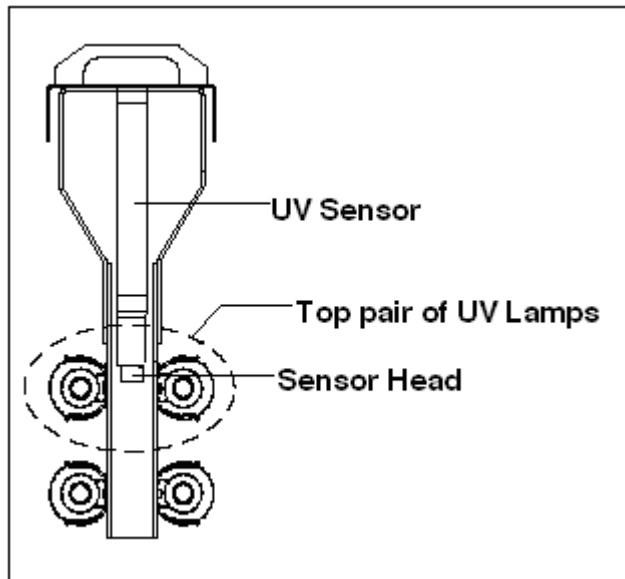


Figure III.7. UV Sensor

There is a Low Level Probe (LLP) and a High Level Probe (HLP) installed at the downstream of the last UV Bank. LLP is used to provide a protection for the UV Lamps against overheating in the event of water leakage within the UV channel. HLP is used to provide a module flooding indication for the UV lamps.

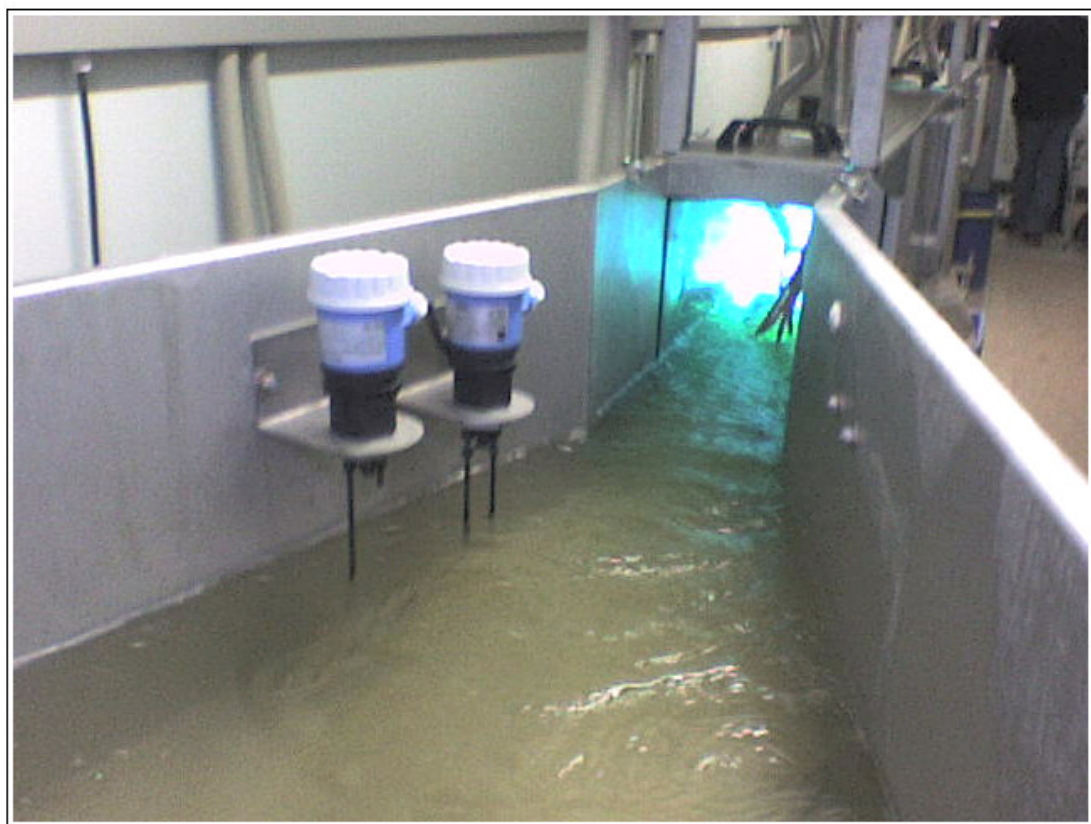


Figure III.8. LLP and HLP

The HMI is used to visualise information and to allow the site operator to interact with the UV System. It is a touch screen type display (Figure III.10). The main functions of the HMI are as follows.

- Display of Event Messages and Alarm Messages
- Data Input of Process Parameters
- Display of Process Values
- Display of Event Buffer
- Display of Alarm Buffer
- Alarm Knowledge

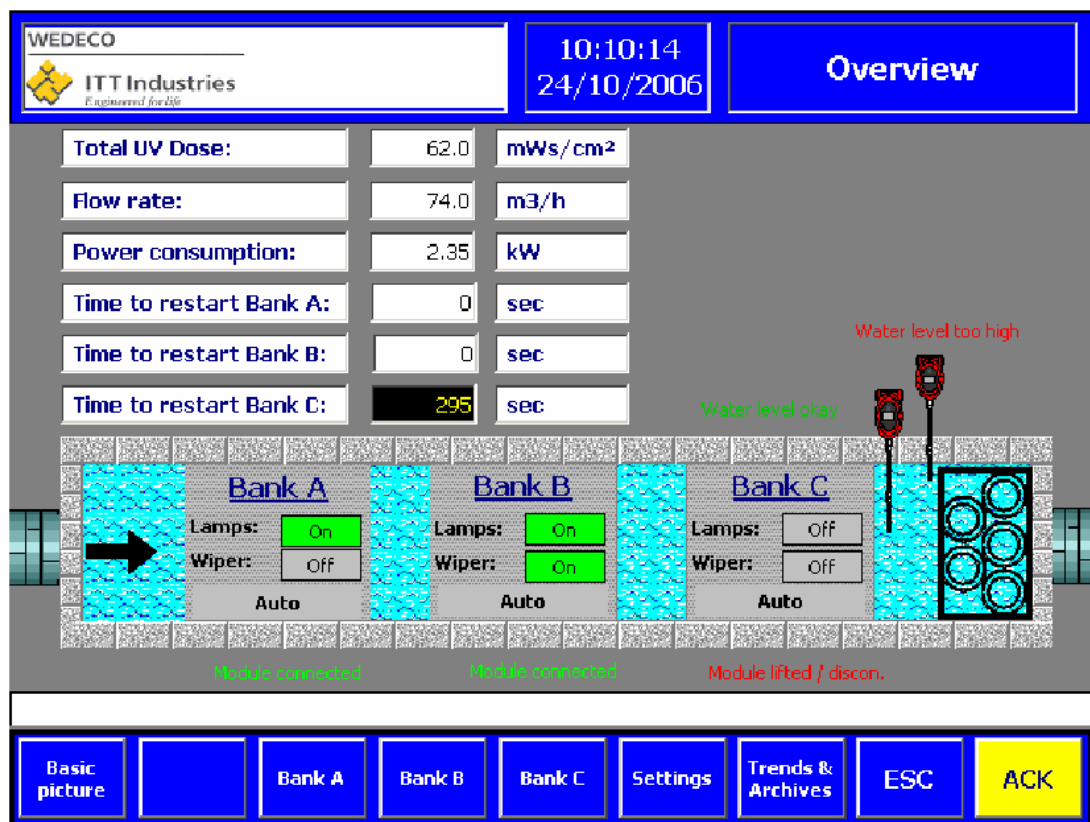


Figure III.9. The HMI Overview Screen

III.1.3. Experimental Procedure

The feed water for the pilot plant was pumped from CDC5, where the effluent from the final clarifiers is distributed. The existing submersible pump in CDC5 was used for this purpose. Treated influent passes the baffle plate installed at the upstream end of the UV channel and flows through the UV Banks, where the bacteria within the water is exposed to sufficient UV light to leave them inactive or dead.

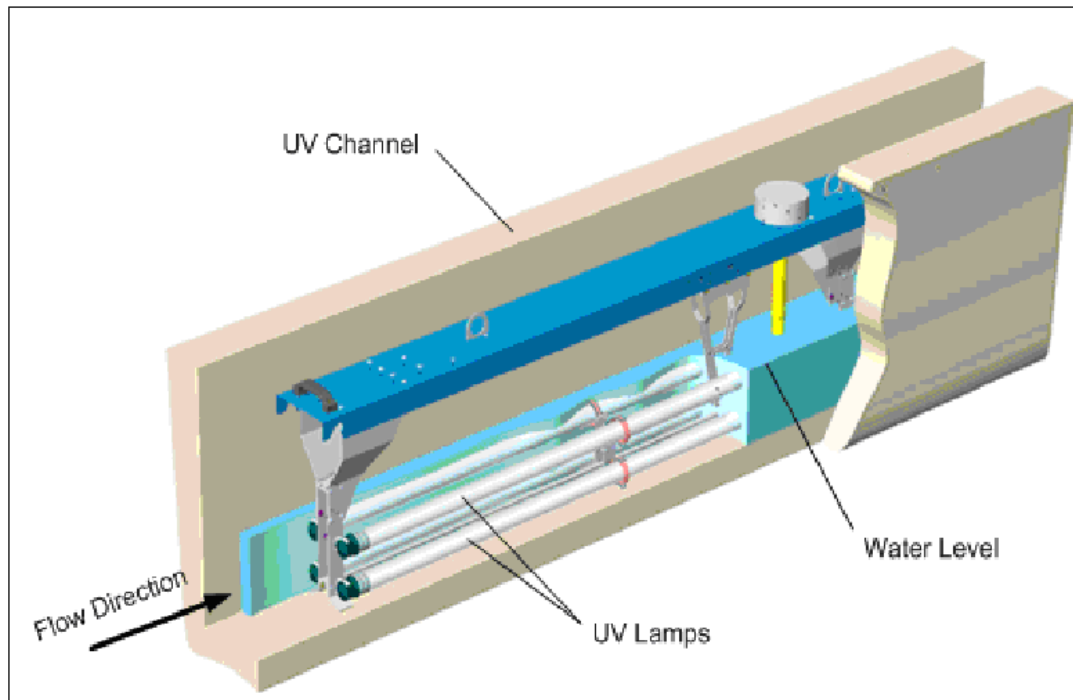


Figure III.10. UV Channel

The actual UV Dose was continuously calculated by the UV PLC.

The effectiveness of the UV System is affected by flow rate, water quality, coating, and lamp age.

The flow rate was set by a valve at the upstream of the UV channel. Experiments have been conducted with various flow rates within a range of 20 to 90 m³/h, depending on the desired UV Dose. Since UV Dose is calculated by multiplying average UV Intensity with exposure time; lower flow rates were set to achieve higher UV Doses.

Water quality is another variable that affects the efficiency of the system. UV transmittance, inlet coliform concentrations, and SS values of the water are important for disinfection effectiveness.

UV lamp power decays against time. Maximum running hours of the lamps are 12000 hours. Throughout the study, total running hours of lamps were not higher than 200 hours; therefore lamp age could not be an important factor for the system effectiveness; but to achieve the worst running conditions, and to simulate the performance of an aged lamp, power output was set to 80% in most of the experiments.

The UV lamps are housed within quartz sleeves. Over a period of time coating will build-up on the surface of the quartz, having the effect of decreasing the quartz transmissivity. The wiping system minimizes this effect. The wiping interval was set to 30 minutes and number of wipes per interval was set to three.

Samples were taken from the upstream and downstream of each running UV bank (Figure III.12). Sterile bottles were used for sampling. Samples were taken from the mid width and mid depth of the channel and transported to the laboratory for analysis immediately after they were collected.

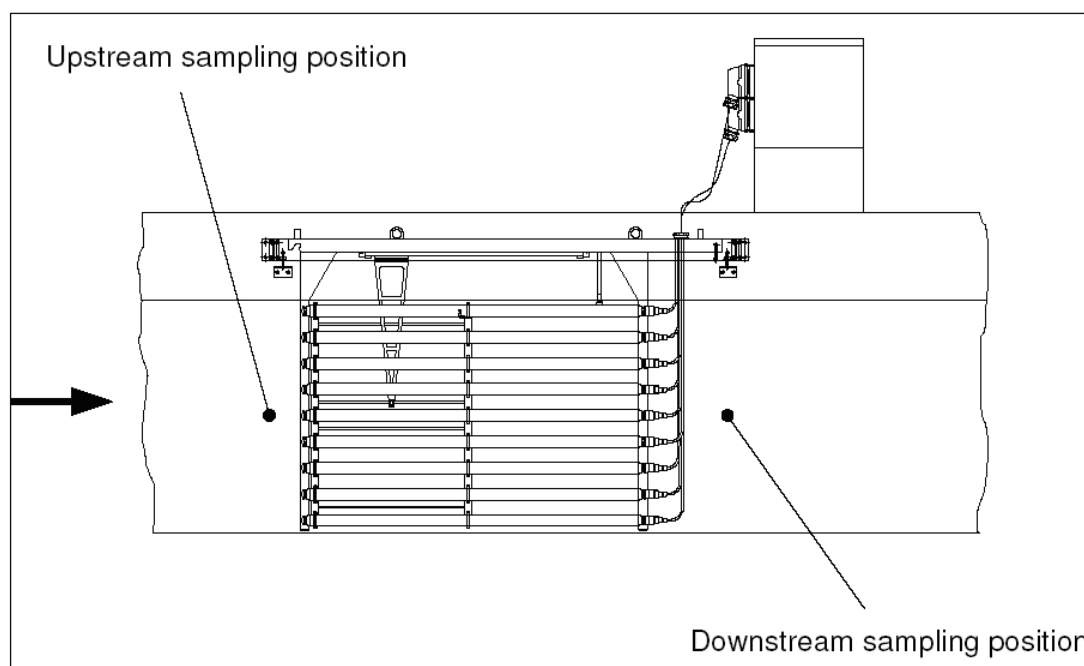


Figure III.11. Sampling positions

III.2. ANALYTICAL METHODS

III.2.1. UV Transmittance

UVT analyses were performed with a Wedeco model spectrophotometer before each sampling. 1 cm thick quartz cells were used for the analysis. Transmittance values were measured at 254 nm wavelength and reported as UVT. The spectrophotometer was calibrated before each sampling. 1 cm thick quartz cell was filled with distilled water and cleaned until no finger prints remained. The cell was then put in the calibration and UV Intensity was calibrated to 100%. After that, cell was filled with the sample from the inlet of the system and put in the calibration; the UVT was read as percent.

III.2.2. Suspended Solids

Suspended solids analyses were conducted in accordance with the Standard Methods (APHA; AWWA; WPCF, 1998).

Millipore glass fiber filter papers were dried in a 105°C oven and then cooled in a desiccator. The filter papers were then weighed (m_1). Water samples (V_f) were filtered through the filter papers with the vacuum filtration apparatus. Filter papers were dried in a 105°C oven for one hour and cooled in the desiccator. Cooled and dried filter papers were weighed (m_2).

Suspended solids content of the water samples was calculated with the following formula.

$$SS = (m_2 - m_1) / V_f \times 10^6 \quad (\text{III.1.})$$

Where:

SS = Suspended solids content of the water, mg/L

m_1 = Initial weight of the filter paper, g

m_2 = Final weight of the filter paper, g

V_f = Filtered volume of sample, mL

III.2.3. Microbiological Analysis

Membrane Filter Technique was used for bacteriological analysis in accordance with the Standard Methods (APHA; AWWA; WPCF; 1998). The membrane filter (MF) technique involves direct plating for detection and estimation of coliform densities. The MF technique is extremely useful in monitoring drinking water and a variety of natural waters. However, it has limitations, particularly when testing waters with turbidity or large numbers of noncoliform (background) bacteria.

Turbidity caused by the presence of algae, particulates, or other interfering material may not permit testing of a sample volume sufficient to yield significant results. Low coliform estimates may be caused by the presence of high numbers of noncoliforms or of toxic substances. The MF technique is not applicable to the examination of wastewaters that have received only primary treatment followed by chlorination because of turbidity in high volume samples or wastewaters containing toxic metals or toxic organic compounds such as phenols. In this study, since

effluents from secondary treatment are used, application of MF technique is appropriate.

Sartorius nutrient pad sets were used for total coliform (Sartorius 14056, Tergitol TTC-NPS) and fecal coliform (Sartorius 14068, M-FC-NPS).

Specific incubation conditions and nutrient types given by Sartorius for each species are given in Table III.2.

Table III.2. Nutrients Used in Total and Fecal Coliform Analysis

Microorganism Type	Nutrient	Incubation Conditions
Total Coliform	Tergitol TTC-NPS (Sartorius 14056)	21±3 hours at 36±2 °C
Fecal Coliform	M-FC-NPS (Sartorius 14068)	20±4 hours at 36±2 °C

Nutrient pads used for total coliform and fecal coliform counting can be seen in Figure III.13.

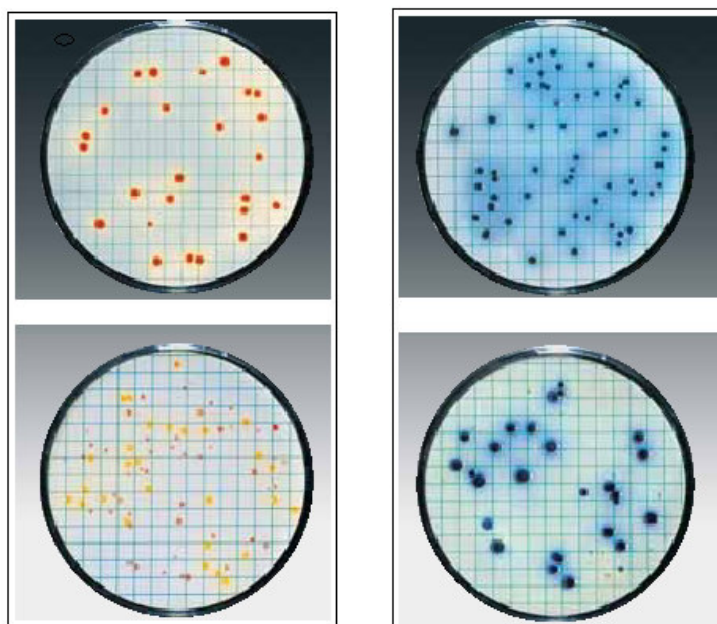


Figure III.12. Nutrient pads for total and fecal coliforms

Sample sizes were governed by expected bacterial density. The ideal sample volume is identified by Standard Methods (APHA, AWWA, WPCF, 1998) as those yield 20 – 80 colonies for total coliform analysis, 20 – 60 colonies for fecal coliform analysis and not more than 200 colonies of all types on a membrane-filter surface.

Dilutions were selected to get a total number of colonies on a plate between these numbers.

Sterile filtration units were used for each filtration to avoid accidental contamination. Filter units were sterilized with flame after each sample.

Using sterile forceps, a sterile membrane filter (grid side up) was placed over porous plate of receptacle. Flame ignition was used for the sterilization of the forceps. Matched funnel unit was placed carefully over receptacle and locked in place. Samples were filtered under partial vacuum. Interior surface of the funnel was rinsed by filtering three 20 – 30 mL portions of sterile dilution water with filter still in place. Carryover contaminations were prevented by rinsing between samples. Upon completion of final rinse and the filtration process vacuum was disengaged, funnel was unlocked and removed. The membrane filter was immediately removed with sterile forceps and placed on the selected medium with a rolling motion to avoid entrapment of air. The petri dishes were incubated in a Binder model incubator at the proper temperatures and for the appropriate time periods.

A sterile rinse water sample of 100 mL was inserted after filtration of a series of 10 samples, to check for possible cross-contamination or contaminated rinse water. The rinse water control membrane cultures were incubated under the same conditions as the samples.

The following formula was used to calculate the coliform density:

$$\text{Coliforms} / 100 \text{ mL} = \text{Coliform colonies counted} \times 100 / \text{mL sample filtered}$$

Coliform colonies were reported as <1 coliform / 100 mL, when no coliform colonies counted.

III.2.3.1. Total Coliform Analysis

E. Coli forms yellow colonies with a yellow surrounding, Enterobacter orange colonies with a small yellow surrounding. Coliform colonies are red and have a yellow dot under the membrane filter. According to ISO 9308-1 all colonies that show yellow color under the membrane filter are counted as positive.

II.2.3.2. Fecal Coliform Analysis

Colonies produced by fecal coliform bacteria are various shades of blue. Nonfecal coliform colonies are gray-to-cream colored. Colony density to be observed on the membrane filter for fecal coliforms, 20 to 60 colonies, is more restrictive than the total coliform range.

CHAPTER IV

RESULTS AND DISCUSSION

IV.1. MICROBIOLOGICAL CHARACTERISTICS OF PAŞAKÖY WWTP EFFLUENT

The experiments were performed with the Paşaköy WWTP effluent between the dates 01.04.2008. and 03.12.2008. Figure IV.1 and Figure IV.2 show the variations in total coliform (TC) and fecal coliform (FC) content of the Paşaköy WWTP effluent, respectively within this period.

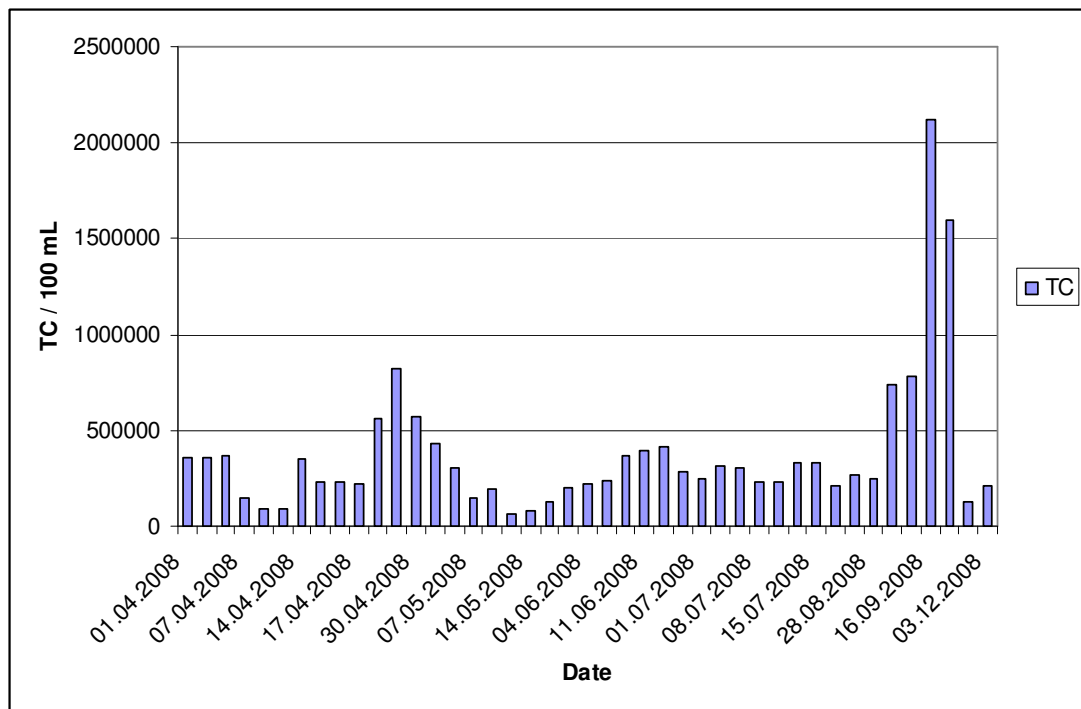


Figure IV.1. Total Coliform Content of Paşaköy WWTP Effluent

Until September, the highest total coliform concentration was observed as 820000 TC/100 mL, and the average TC content was approximately 285000 TC / 100 mL. However, in September, a significant increase was observed. Repetitive experiments in this month have revealed that the TC contents were between 740000 and 2120000 TC / 100 mL.

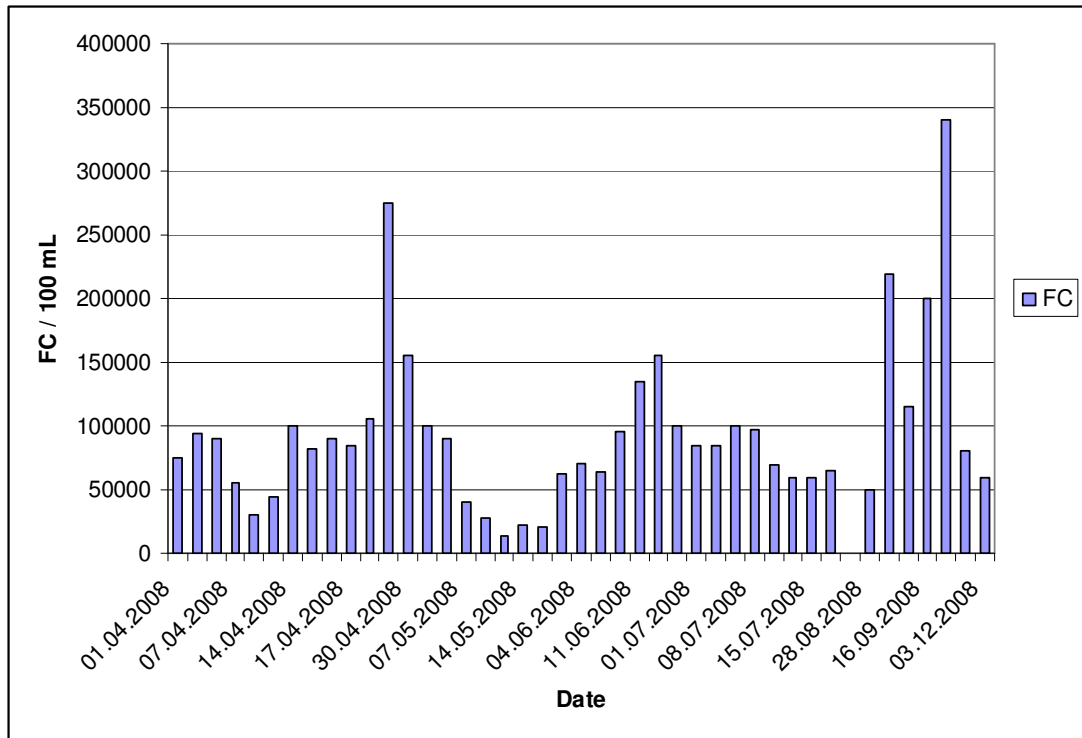


Figure IV.2. Fecal Coliform Content of Paşaköy WWTP.

According to the analysis results, the range of total coliform values of the effluent of Paşaköy WWTP was 60000 - 2120000 TC/100 mL and fecal coliform values of the effluent of Paşaköy WWTP varied from 14000 to 340000 FC/100 mL. These results revealed an average total coliform concentration of 282975 TC/100 mL and an average fecal coliform concentration of 78086 FC/100 mL. No seasonal variations were observed both for TC and FC.

Figure IV.3. shows both total and fecal coliform contents of the Paşaköy WWTP effluent. The analysis of the whole measurement results showed that fecal coliform to total coliform ratio for Paşaköy WWTP effluent is approximately 0,27.

In Figure IV.4. TC and FC distributions are presented as log survival values for the same period.

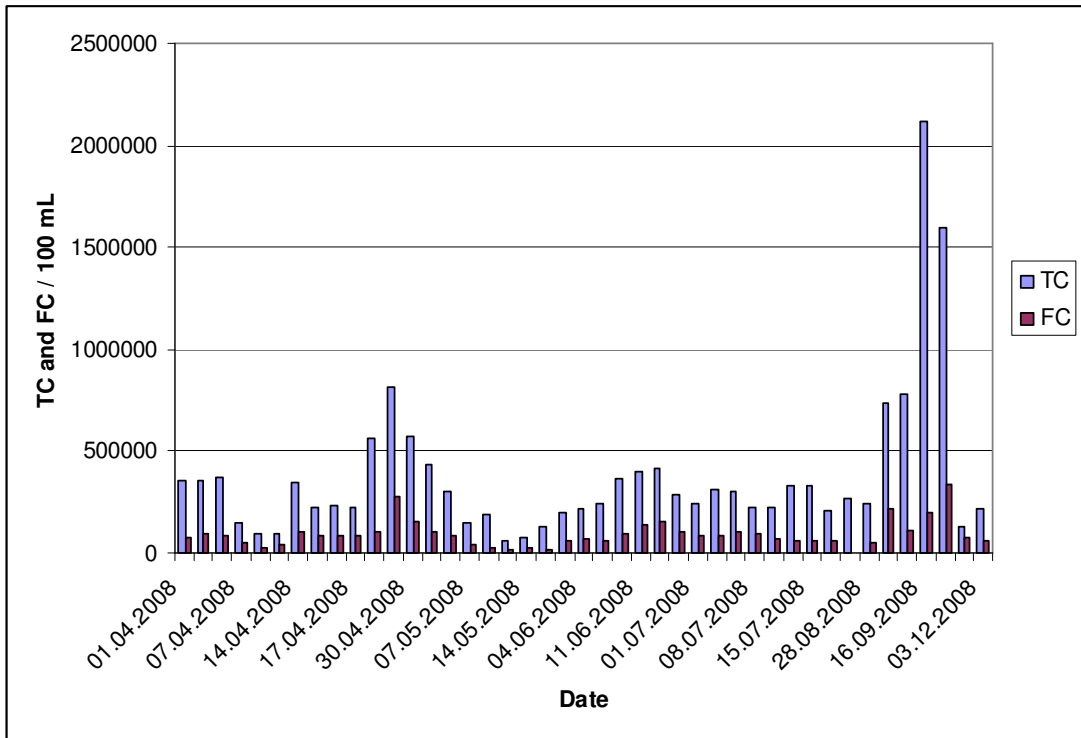


Figure IV.3. Total and fecal coliform values of Paşaköy WWTP Effluent

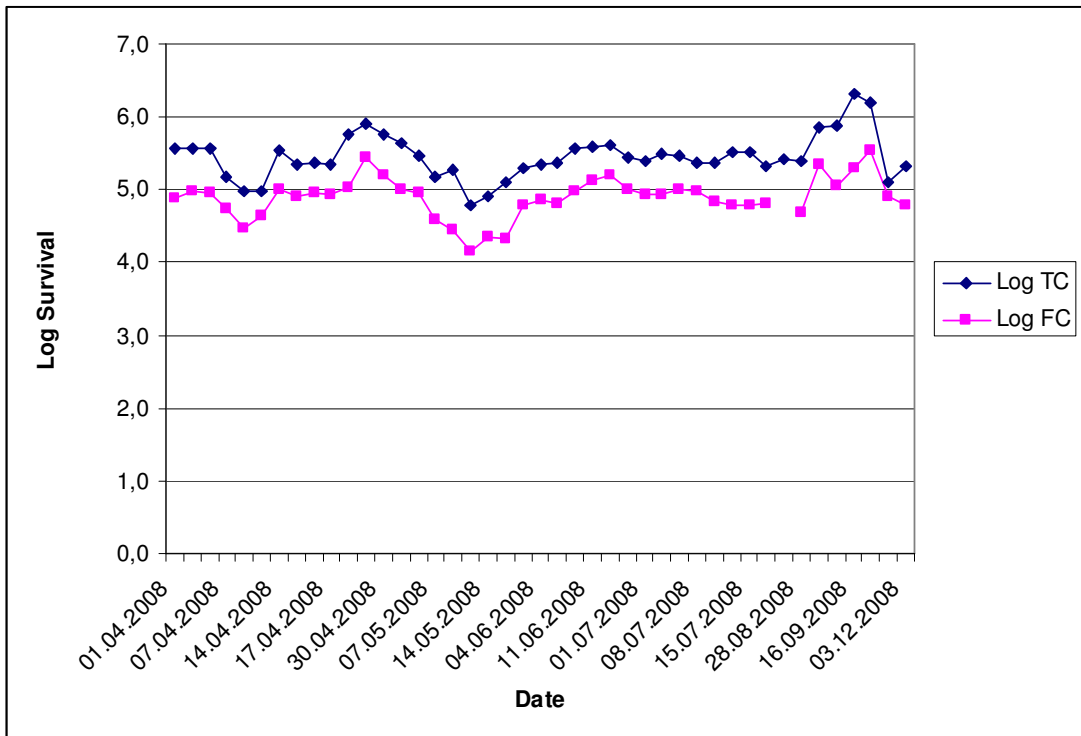


Figure IV.4. Logarithmic values of total and fecal coliform contents of Paşaköy WWTP Effluent

TC and FC values show a parallel trend almost for the whole set of data. This is an indication for the same ratio of 0,27 between FC and TC.

Typical levels of total and fecal coliform bacteria in domestic wastewater are summarized in Table IV.1. below. Data collected during the experiments indicate that almost all of the samples taken from the effluent of Paşaköy WWTP comply with the values given in the literature for secondary effluent.

Table IV.1. Typical levels of coliform bacteria in domestic wastewater after various wastewater treatment steps (WEF, 1997)

Wastewater	Total coliforms,no./100mL	Fecal coliforms,no./100mL
Raw	$10^7 - 10^8$	$10^6 - 10^7$
Primary Effluent	$10^7 - 10^8$	$10^6 - 10^7$
Secondary	$10^5 - 10^6$	$10^4 - 10^5$
Filtered Secondary	$10^4 - 10^5$	$10^3 - 10^5$
Nitrified	$10^4 - 10^5$	$10^3 - 10^5$
Filtered Nitrified	$10^4 - 10^5$	$10^3 - 10^5$

UV transmittance and suspended solids analysis were also conducted in the samples collected for bacteriological analysis. During the research period, it was observed that UV Transmittance values of Paşaköy WWTP effluent varied between 56% and 70%. It is known that typical UVT values for secondary effluents vary from 60 to 75% (USEPA, 1986). Therefore, Paşaköy WWTP effluent complies with the typical wastewater characteristics defined in literature. Figure IV.5 shows the variation of UVT values for Paşaköy WWTP effluent.

Suspended solids content of Paşaköy WWTP effluent varied from 5 mg/L to 36 mg/L within the research period and these values are presented in Figure IV.6.

Both for UVT and SS, there is not a significant seasonal variation. All the analytical data collected for TC, FC, UVT and SS parameters are presented in Table IV.2.

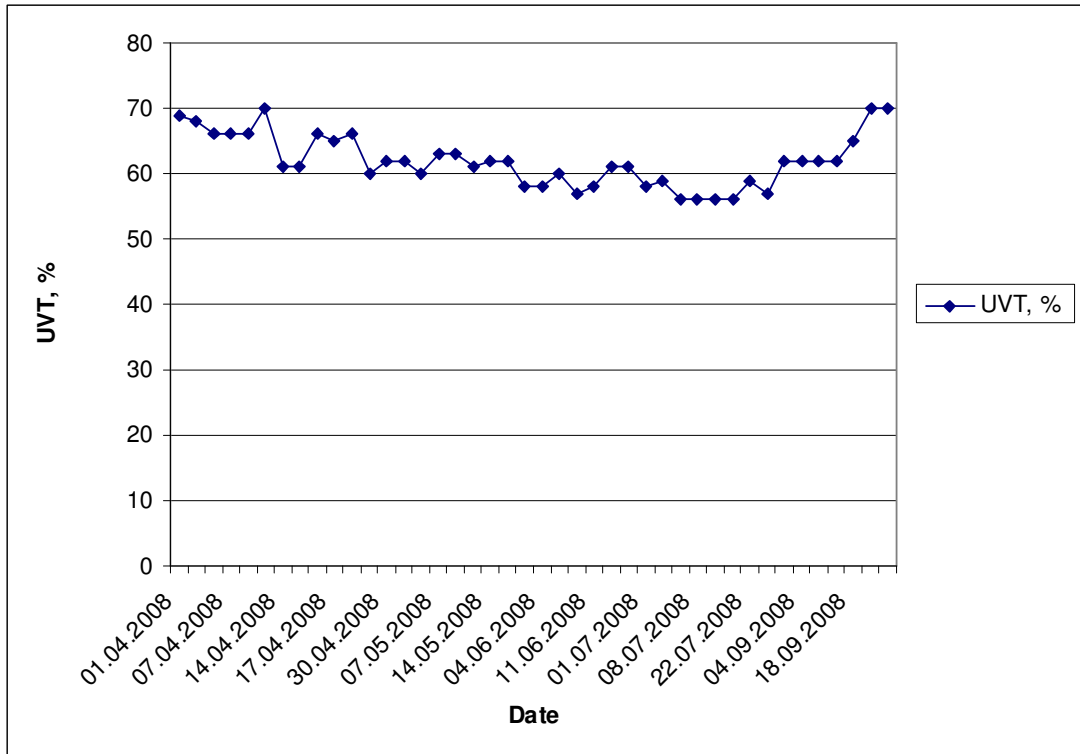


Figure IV.5. Variation of UVT (%) values of Paşaköy WWTP effluent

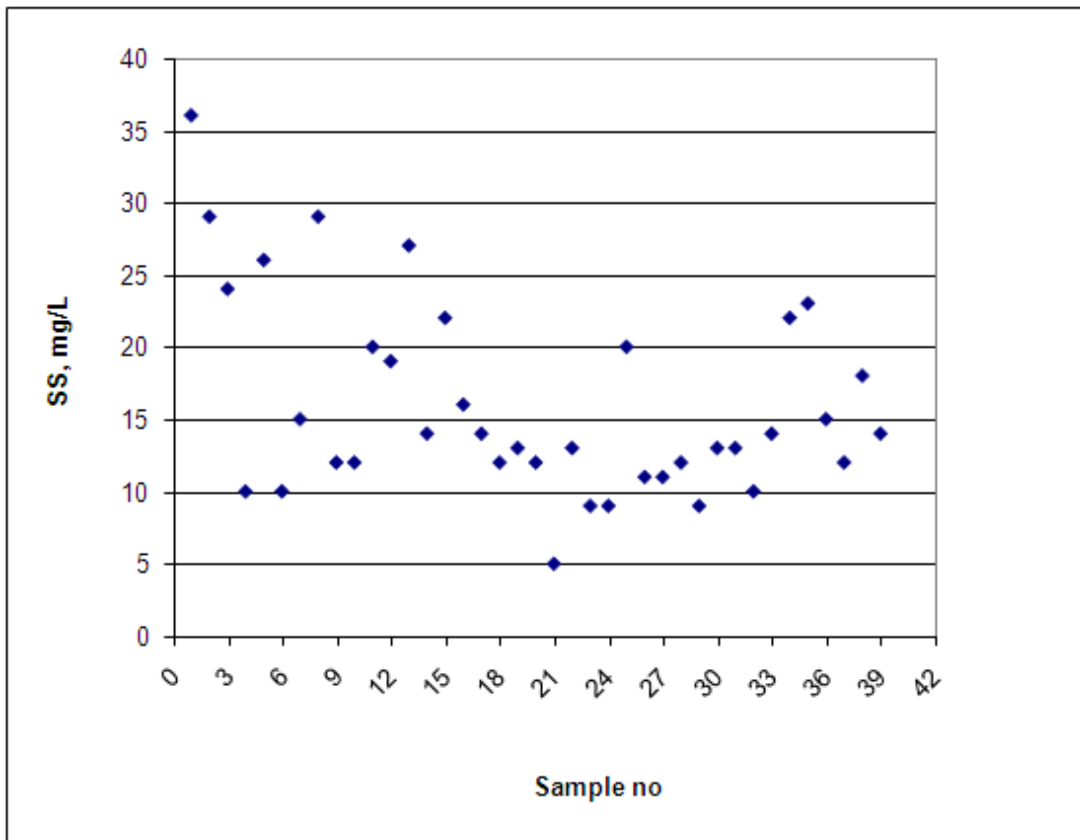


Figure IV.6. Variation of SS values of Paşaköy WWTP effluent

Table IV.2. Microbiological Characteristics of PaşaköyWWTP Effluents derived from the experiments

Date	TC / 100MI	FC / 100 mL	SS, mg/L	UVT, %
01.04.2008	360000	75000	36	69
02.04.2008.	360000	95000	29	68
03.04.2008	370000	90000	24	66
07.04.2008	150000	55000	10	66
08.04.2008	95000	30000	26	66
10.04.2008	95000	45000	10	62
14.04.2008	350000	100000	-	61
15.04.2008	227500	82500	-	61
16.04.2008	235000	90000	15	62
17.04.2008	225000	85000	29	61
21.04.2008	565000	105000	12	61
24.04.2008	820000	275000	12	59
30.04.2008	575000	155000	20	62
01.05.2008	435000	100000	19	62
05.05.2008	300000	90000	27	59
07.05.2008	150000	40000	14	63
12.05.2008	190000	28000	22	59
13.05.2008	60000	14000	16	61
14.05.2008	80000	22000	14	57
29.05.2008	130000	21000	12	62
03.06.2008	200000	62000	13	58
04.06.2008	218000	71000	12	58
10.06.2008	240000	64000	5	57
10.06.2008	366000	96000	-	-
11.06.2008	400000	135000	13	58
17.06.2008	415000	155000	9	61
19.06.2008	285000	100000	9	61
01.07.2008	245000	85000	20	58
03.07.2008	315000	85000	11	59
07.07.2008	300000	100000	11	56
08.07.2008	230000	97500	12	56
14.07.2008	230000	70000	9	56
15.07.2008	330000	60000	13	56
22.07.2008	210000	65000	13	59
29.07.2008	270000	-	10	57
28.08.2008	245000	50000	14	62
04.09.2008	740000	220000	22	62
11.09.2008	780000	115000	23	62
16.09.2008	2120000	200000	15	65
18.09.2008	1600000	340000	12	61
02.12.2008	130000	80000	18	70
03.12.2008	215000	60000	14	70

Table IV.3. shows the minimum, maximum and mean values of total coliform, fecal coliform, UVT and SS content of the effluent of Paşaköy WWTP.

Table IV.3. Minimum, Maximum and Mean Values of Microbiological Characteristics of the Paşaköy WWTP Effluent

Parameter	Minimum	Maximum	Mean
TC / 100 mL	60000	2120000	228193
FC / 100 mL	14000	250000	64597
UVT, %	56	70	61,19
SS, mg/L	5	36	16,02

IV.2. EFFICIENCY OF SAND FILTER

In order to monitor the removal efficiency of sand filter, bacteriological analysis were conducted in the inlet and outlet of filter. Total coliform removal efficiency of the sand filter varied between 20% and 62%, while fecal coliform removal was between 10% and 68%. Figure IV.7 and Figure IV.8 show the effect of sand filter on total and fecal coliform removals respectively.

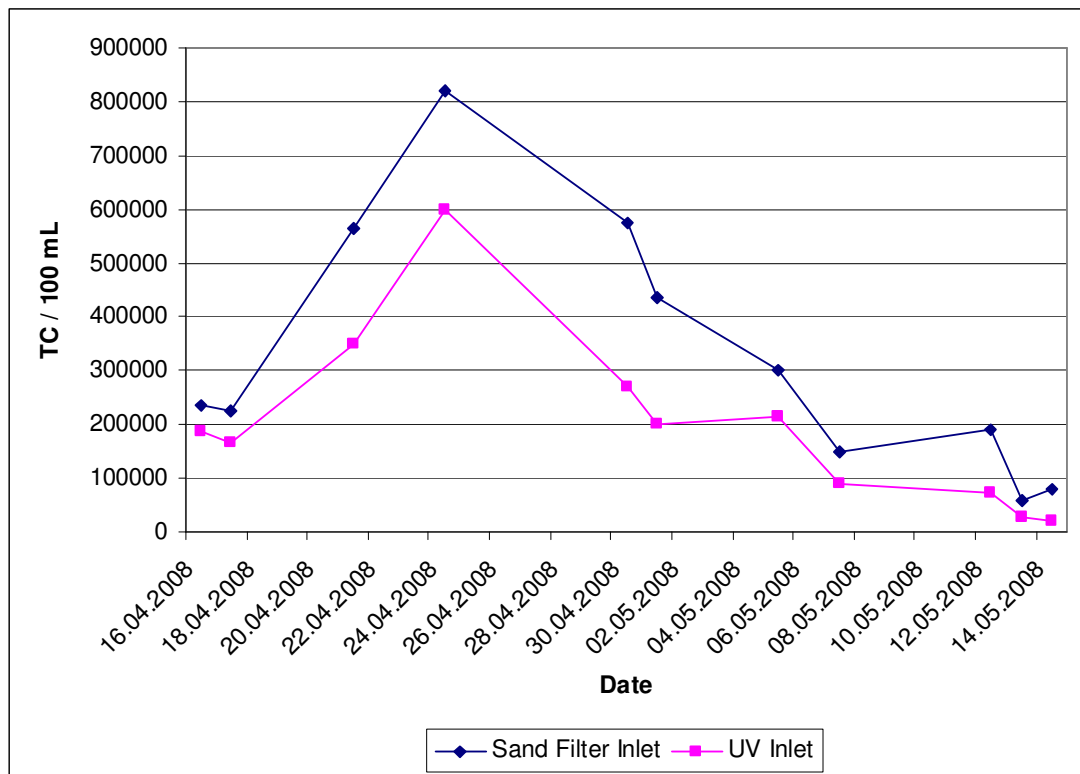


Figure IV.7. Total Coliform Removal Efficiency of Sand Filter

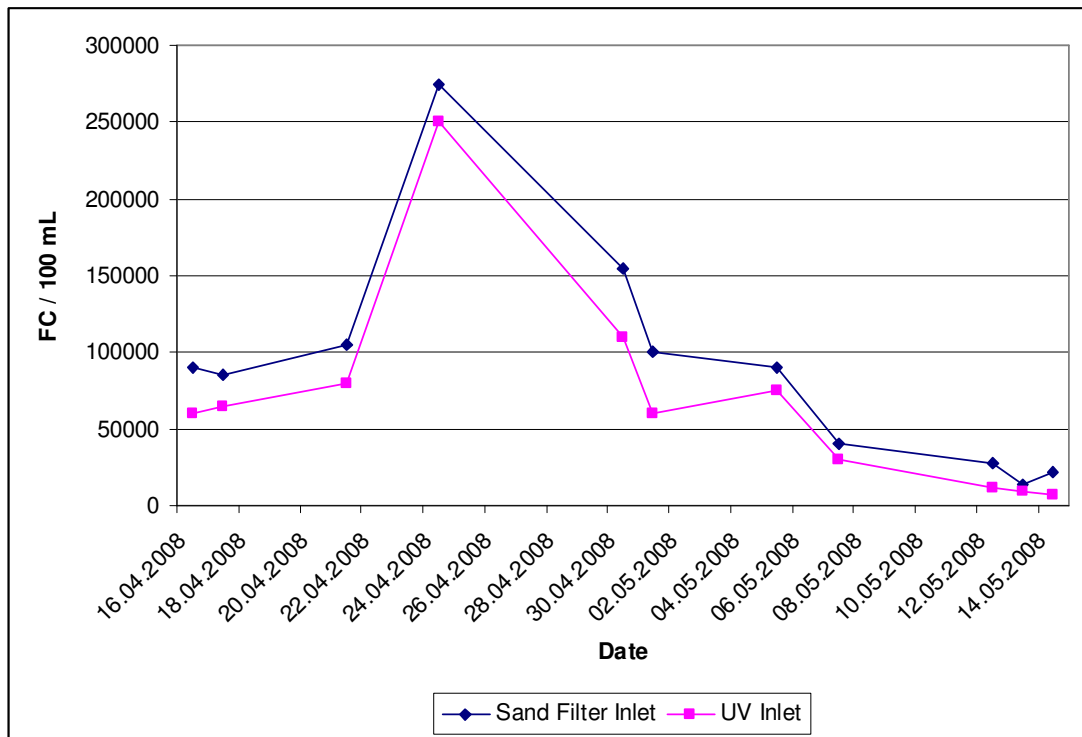


Figure IV.8. Fecal coliform Removal Efficiency of Sand Filter

Sand filter was also effective in SS removal. Figure IV.9 shows the efficiency of sand filter on SS removal. Up to 90% removal of SS was observed.

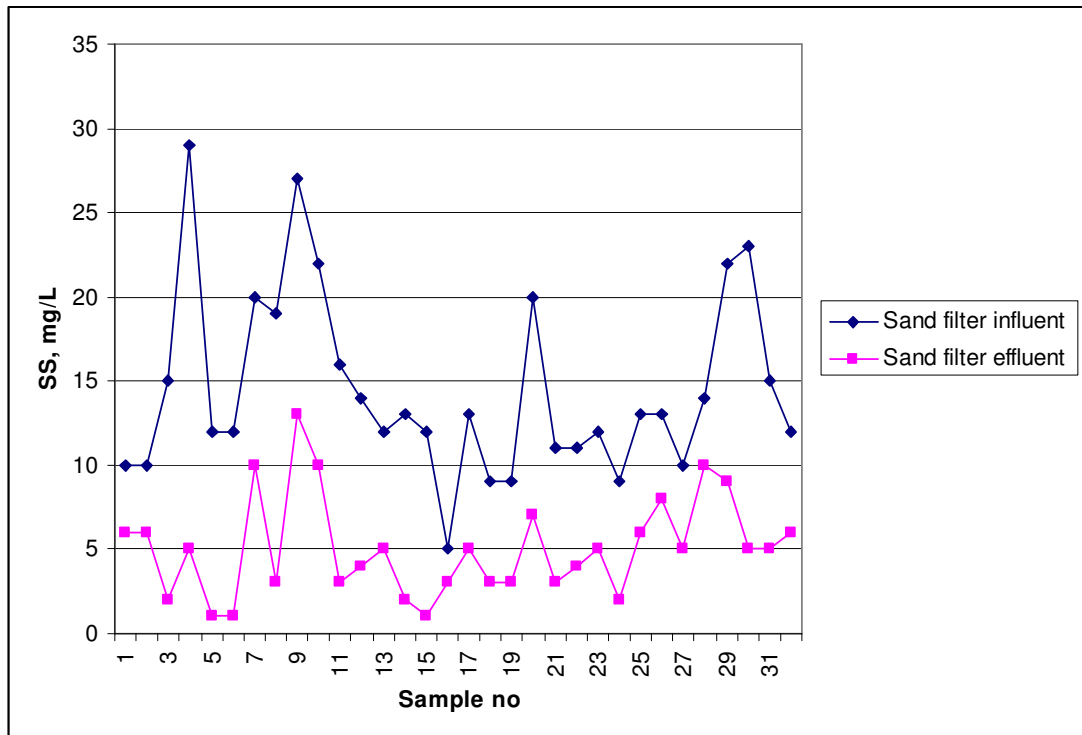


Figure IV.9 SS Removal Efficiency of Sand Filter

A slight improvement of UVT values was observed at the sand filter effluent. The wastewater going into sand filter had an average UVT of 60%, while the sand filter effluent had an average UVT of 64%. Figure IV.10 shows the UVT values of influent and effluent of the sand filter.

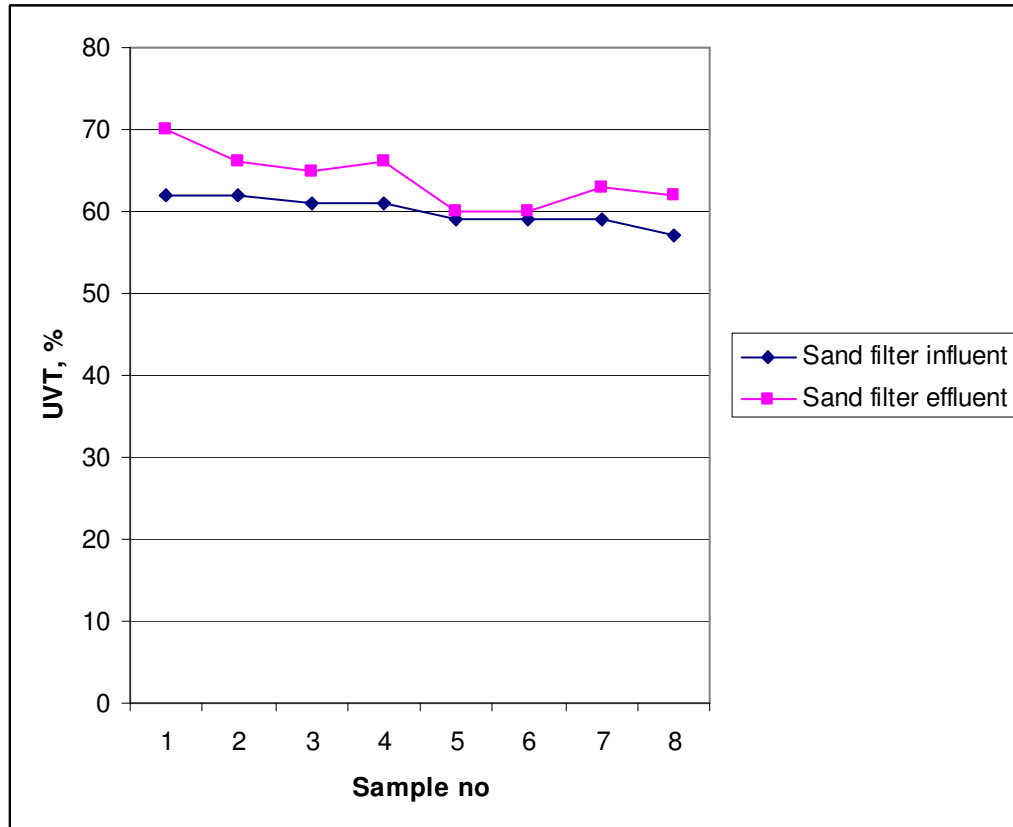


Figure IV.10 The effect of sand filter on UVT

In full scale applications, if sand filter is used before the UV disinfection, it can be assumed that the sand filter will remove the TC and SS at least %20 and 28% respectively. So this pretreatment before UV will decrease the load on the UV system.

IV.3. Dose-Response Curves for Total and Fecal Coliforms

Several experiments were made with different UV doses and different wastewater characteristics. The varying wastewater characteristics in these experiments were inlet TC and FC amounts, SS and UVT. Table IV.4 and Table IV.5 show the dose-response data for the total coliforms and fecal coliforms respectively.

Table IV.4 UV Dose - Total Coliform Response Data

Date	TC / 100 mL According to the Applied UV Dose (mWs/cm ²)												
	0	20	30	40	50	60	70	80	90	100	120	140	150
01.04.2008	360000						70	28					
02.04.2008	360000			730									
03.04.2008	370000			240				50					
07.04.2008	150000			460			60						
08.04.2008	95000	5250			600					100			
10.04.2008	95000				70				38	8			
14.04.2008	350000					125				26			
15.04.2008	227500				360	185				44	46		20
16.04.2008	187500		4560		125	50				12			
17.04.2008	167500			1630			70	60	28			4	2
21.04.2008	350000			190		55		70		22			
24.04.2008	600000	18900				565				56	36		
30.04.2008	270000		8400	1100	240	180		32			28		
01.05.2008	200000	600		120				5		6			
05.05.2008	215000	3140		500		75		30		28			
07.05.2008	90000					140				8			
12.05.2008	72000	2700		325		32		56	28	0			
12.05.2008	190000			3460		264		236		156			
13.05.2008	27000			585		64		45		8	2		<1
14.05.2008	22000				55	18		40		4			
29.05.2008	130000	4000		785		42		30		6			
03.06.2008	200000	5200		730									
04.06.2008	218000			1180		85		30		12			2
10.06.2008	240000			1435								22	
10.06.2008	366000			2520					38			4	
11.06.2008	400000	78500		4160		220	78			98	16		6
17.06.2008	415000	54400	6800	2560		280	70			74			
19.06.2008	285000	17000			620	280		190		42			
01.07.2008	245000		12300		480	365				84			
03.07.2008	315000	33600	7300	1925		165	166	160	60				
07.07.2008	300000		18000			1430							
08.07.2008	230000	47000		5350	520	190				60			
14.07.2008	230000	24000		2100				50	48	32			
15.07.2008	195000					50					10		
15.07.2008	330000					370					50	34	6
22.07.2008	210000	7000		1750			20			36			
29.07.2008	270000		12000		250				45		30		2
28.08.2008	245000		6400	1350	460	165		186			12		
04.09.2008	740000	77000	8400	6750		500	178			28	60		
09.09.2008										18	12	12	
11.09.2008	780000						300					35	12
16.09.2008	2120000	16800		4900	2040	190		46	38				
02.12.2008	130000						120						
03.12.2008	215000					120	35		28	24			

Table IV.5 UV Dose - Fecal Coliform Response Data

Date	FC / 100 mL According to the Applied UV Dose (mWs/cm)													
	0	20	30	40	50	60	70	80	90	100	120	140	150	
01.04.2008	75000		30				5							
02.04.2008.	95000			110				4						
03.04.2008	90000			120				5						
07.04.2008	55000						5							
08.04.2008	30000	1050			40	25				3				
10.04.2008	45000		50		10	5				6				
14.04.2008	100000		180			15	6			2				
15.04.2008	82500				70	20				4	12		2	
16.04.2008	60000		780		25	5				<1				
17.04.2008	65000			160	20			28	4			<1		
21.04.2008	80000			10		5		4		<1				
24.04.2008	250000	4000		500		20		24		4	<1			
30.04.2008	110000		2300	150	30	30		6						
01.05.2008	60000									2				
05.05.2008	75000	440		75		5		4		<1				
07.05.2008	30000					66				2				
12.05.2008	12000	300		35		4		0		<1				
12.05.2008	28000			230		10		10		6				
13.05.2008	9000			45		2		44		<1	<1			
14.05.2008	7000				5	2		2		<1				
29.05.2008	21000	800		50		6		2		<1				
03.06.2008	62000	1660		50										
04.06.2008	71000			130		15		<1		<1	<1			
10.06.2008	64000			135					14			<1		
10.06.2008	96000			440								4		
11.06.2008	135000			1300						9	4			
17.06.2008	155000	16500	2700	800		30	10			4				
19.06.2008	100000	3000			40	20		5		<1				
01.07.2008	85000		1800	320	60	25	5		<1	<1			<1	
03.07.2008	85000	4400	2300	280	180	<1		<1		2	<1			
07.07.2008	100000		2600											
08.07.2008	97500	12500		600		10				2			<1	
14.07.2008	70000	8500		340			5	<1		2				
15.07.2008	40000					<1	9				<1			
15.07.2008	60000					6					<1			
22.07.2008	65000	3500		200			5	<1		<1				
28.08.2008	50000		2400	700	<1	<1		<1			<1			
04.09.2008	220000	18000					14							
09.09.2008							10							
11.09.2008	115000							5				<1	<1	
16.09.2008	200000	2000	600	350	100	10		1	<1					
02.12.2008	80000						10	6	3	2	1	<1	<1	
03.12.2008	60000						10	8	6	5	<1			

The UV dose- response data are generally log-normally distributed. So the observed survival data presented in Table IV.4 and Table IV.5 were transformed to logarithmic values and presented in Table IV.6 and IV.7 respectively.

Table IV.6. Log Survival of Total Coliforms at Applied UV Dose

Date	Log Survival of TC at Applied UV Dose (mWs/cm ²)												
	0	20	30	40	50	60	70	80	90	100	120	140	150
01.04.2008	5,56						1,85	1,45					
02.04.2008	5,56			2,86									
03.04.2008	5,57			2,38				1,70					
07.04.2008	5,18			2,66			1,78						
08.04.2008	4,98	3,72			2,78					2,00			
10.04.2008	4,98				1,85				1,58	0,90			
14.04.2008	5,54					2,10				1,41			
15.04.2008	5,36				2,56	2,27				1,64	1,66		1,30
16.04.2008	5,27		3,66		2,10	1,70				1,08			
17.04.2008	5,22			3,21			1,85	1,78	1,45			0,60	0,30
21.04.2008	5,54			2,28		1,74		1,85		1,34			
24.04.2008	5,78	4,28				2,75				1,75	1,56		
30.04.2008	5,43		3,92	3,04	2,38	2,26		1,51			1,45		
01.05.2008	5,30	2,78		2,08				0,70		0,78			
05.05.2008	5,33	3,50		2,70		1,88		1,48		1,45			
07.05.2008	4,95					2,15				0,90			
12.05.2008	4,86	3,43		2,51		1,51		1,75	1,45	0,00			
12.05.2008	5,28			3,54		2,42		2,37		2,19			
13.05.2008	4,43			2,77		1,81		1,65		0,90	0,30		0,00
14.05.2008	4,34				1,74	1,26		1,60		0,60			
29.05.2008	5,11	3,60		2,89		1,62		1,48		0,78			
03.06.2008	5,30	3,72		2,86									
04.06.2008	5,34			3,07		1,93		1,48		1,08			0,30
10.06.2008	5,38			3,16								1,34	
10.06.2008	5,56			3,40					1,58			0,60	
11.06.2008	5,60	4,89		3,62		2,34	1,89			1,99	1,20		0,78
17.06.2008	5,62	4,74	3,83	3,41		2,45	1,85			1,87			
19.06.2008	5,45	4,23			2,79	2,45		2,28		1,62			
01.07.2008	5,39		4,09		2,68	2,56				1,92			
03.07.2008	5,50	4,53	3,86	3,28		2,22	2,22	2,20	1,78				
07.07.2008	5,48		4,26			3,16							
08.07.2008	5,36	4,67		3,73	2,72	2,28				1,78			
14.07.2008	5,36	4,38		3,32				1,70	1,68	1,51			
15.07.2008	5,29					1,70					1,00		
15.07.2008	5,52					2,57					1,70		0,78
22.07.2008	5,32	3,85		3,24			1,30			1,56			
29.07.2008	5,43		4,08		2,40				1,65		1,48		0,30
28.08.2008	5,39		3,81	3,13	2,66	2,22		2,27			1,08		
04.09.2008	5,87	4,89	3,92	3,83		2,70	2,25			1,45	1,78		
09.09.2008										1,26	1,08	1,08	
11.09.2008	5,89						2,48					1,54	1,08
16.09.2008	6,33	4,23		3,69	3,31	2,28		1,66	1,58				
02.12.2008	5,11						2,08						
03.12.2008	5,33					2,08	1,54		1,45	1,38			

Table IV.7. Log Survival of Fecal Coliforms at Applied UV Dose

Date	Log Survival of FC at Applied UV Dose (mWs/cm ²)												
	0	20	30	40	50	60	70	80	90	100	120	140	150
01.04.2008	4,88		1,48				0,70						
02.04.2008	4,98			2,04				0,60					
03.04.2008	4,95			2,08				0,70					
07.04.2008	4,74						0,70						
08.04.2008	4,48	3,02			1,60	1,40				0,48			
10.04.2008	4,65		1,70		1,00	0,70				0,78			
14.04.2008	5,00		2,26			1,18	0,78			0,30			
15.04.2008	4,92				1,85	1,30				0,60	1,08		0,30
16.04.2008	4,78		2,89		1,40	0,70				0,00			
17.04.2008	4,81			2,20	1,30			1,45	0,60			0,00	
21.04.2008	4,90			1,00		0,70		0,60		0,00			
24.04.2008	5,40	3,60		2,70		1,30		1,38		0,60	0,00		
30.04.2008	5,04		3,36	2,18	1,48	1,48		0,78					
01.05.2008	4,78									0,30			
05.05.2008	4,88	2,64		1,88		0,70		0,60		0,00			
07.05.2008	4,48					1,82				0,30			
12.05.2008	4,08	2,48		1,54		0,60		0,00		0,00			
12.05.2008	4,45			2,36		1,00		1,00		0,78			
13.05.2008	3,95			1,65		0,30		1,64		0,00	0,00		
14.05.2008	3,85				0,70	0,30		0,30		0,00			
29.05.2008	4,32	2,90		1,70		0,78		0,30		0,00			
03.06.2008	4,79	3,22		1,70									
04.06.2008	4,85			2,11		1,18		0,00		0,00	0,00		
10.06.2008	4,81			2,13					1,15			0,00	
10.06.2008	4,98			2,64								0,60	
11.06.2008	5,13			3,11						0,95	0,60		
17.06.2008	5,19	4,22	3,43	2,90		1,48	1,00			0,60			
19.06.2008	5,00	3,48			1,60	1,30		0,70		0,00			
01.07.2008	4,93		3,26	2,51	1,78	1,40	0,70		0,00	0,00			0,00
03.07.2008	4,93	3,64	3,36	2,45	2,26	0,00		0,00		0,30	0,00		
07.07.2008	5,00		3,41										
08.07.2008	4,99	4,10		2,78		1,00				0,30			0,00
14.07.2008	4,85	3,93		2,53			0,70	0,00		0,30			
15.07.2008	4,60					0,00	0,95				0,00		
15.07.2008	4,78					0,78					0,00		
22.07.2008	4,81	3,54		2,30			0,70	0,00		0,00			
28.08.2008	4,70		3,38	2,85	0,00	0,00		0,00			0,00		
04.09.2008	5,34	4,26					1,15						
09.09.2008							1,00						
11.09.2008	5,06							0,70				0,00	0,00
16.09.2008	5,30	3,30	2,78	2,54	2,00	1,00		0,00	0,00				
02.12.2008	4,90						1,00	0,78	0,48	0,30	0,00	0,00	0,00
03.12.2008	4,78					1,00	0,90	0,78	0,70	0,00			

The results of the series of experiments are presented in Figure IV.11 and Figure IV.12 as log survival of the total coliforms and fecal coliforms respectively,

according to the applied UV Dose. In these graphs, arithmetic averages of the effluent coliform concentrations for each dose were used to define the relation between the log survival and applied UV dose.

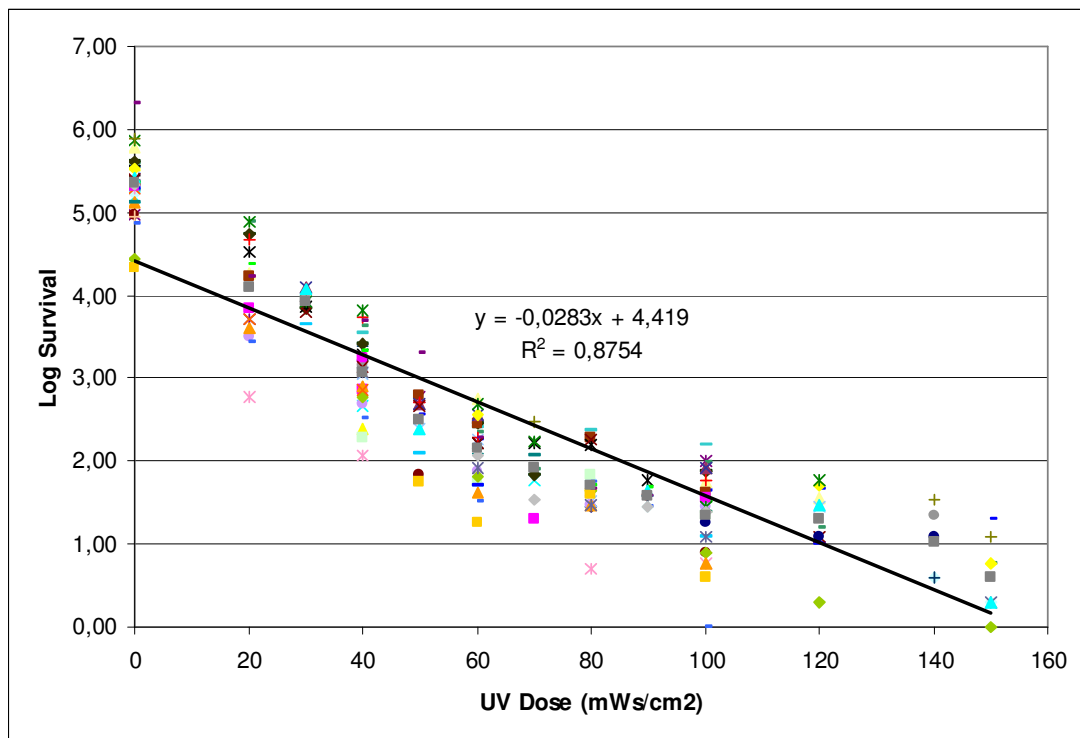


Figure IV.11. Log Survival of Total Coliforms According to the Applied UV Dose

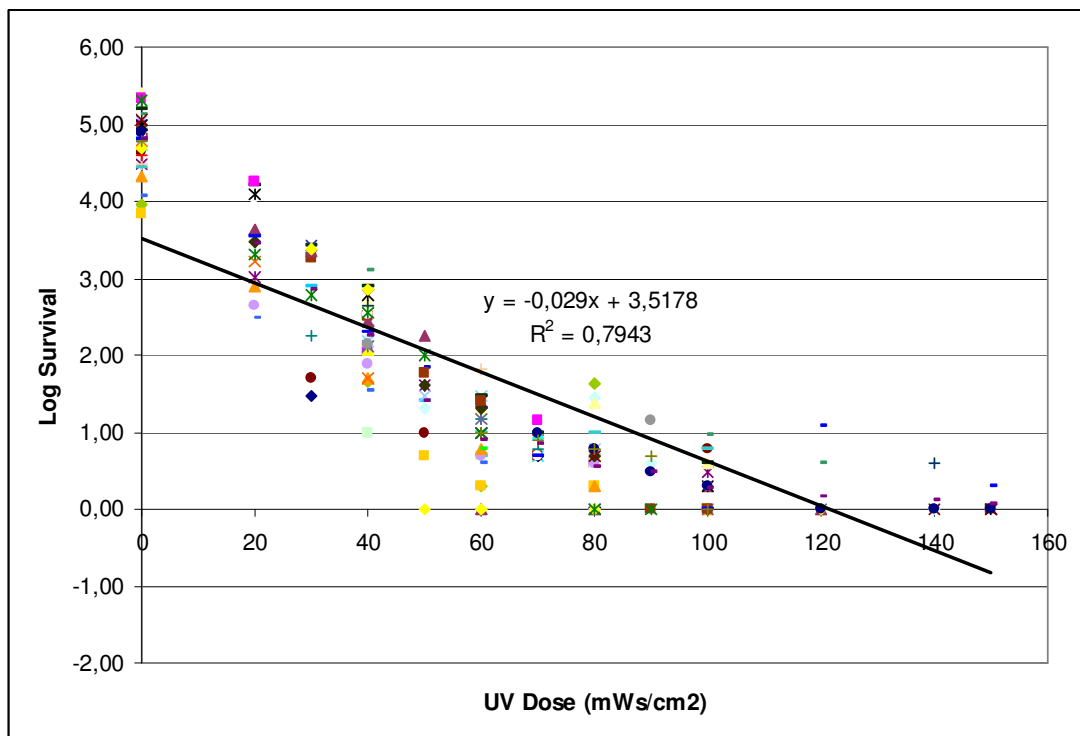


Figure IV.12 Log Survival of Fecal Coliforms According to the Applied UV Dose

The statistical analysis of the collected experimental data was made. The average and standard deviation for the log-transformed data for each investigated UV dose were determined. The following formula was used to calculate the standard deviation.

$$s = \sqrt{\frac{\sum_{i=1}^N (x_i - \bar{x})^2}{N - 1}} \quad (\text{IV.1.})$$

Where;

- s = Standard deviation,
- N = Number of analysis, and
- \bar{x} = Arithmetic mean of the values X_i .

Table IV.8 shows the average and standard deviation for the log-transformed data of total and fecal coliforms for each investigated UV dose presented in Tables IV.6 and IV.7.

Table IV.8. Average and standard deviation for the log survival of total and fecal coliforms at applied UV dose

UV Dose (mWs/cm ²)	Average		Standard Deviation	
	TC	FC	TC	FC
0	5,35	4,81	0,341	0,328
20	4,08	3,45	0,604	0,562
30	3,93	2,85	0,179	0,721
40	3,06	2,25	0,466	0,499
50	2,49	1,41	0,439	0,613
60	2,16	0,9	0,425	0,494
70	1,91	0,86	0,331	0,162
80	1,71	0,56	0,395	0,505
90	1,57	0,49	0,116	0,44
100	1,35	0,27	0,511	0,299
120	1,29	0,17	0,428	0,372
140	1,03	0,12	0,427	0,269
150	0,6	0,06	0,449	0,135

As shown in Table IV.8, log survival of both total and fecal coliforms decrease as the applied UV dose increases. The 4,81-log of initial fecal coliform content decreases quickly under 1-log at a UV dose of 60 mWs/cm².

Disinfection efficiencies can be expressed either as log reduction or log survival. The results of the series of experiments were compiled in Figure IV.13 according to the average logarithmic values. This graph shows the survival of both total and fecal coliforms according to the applied UV dose. In Figure IV.14, the same experiments are presented also as log reduction.

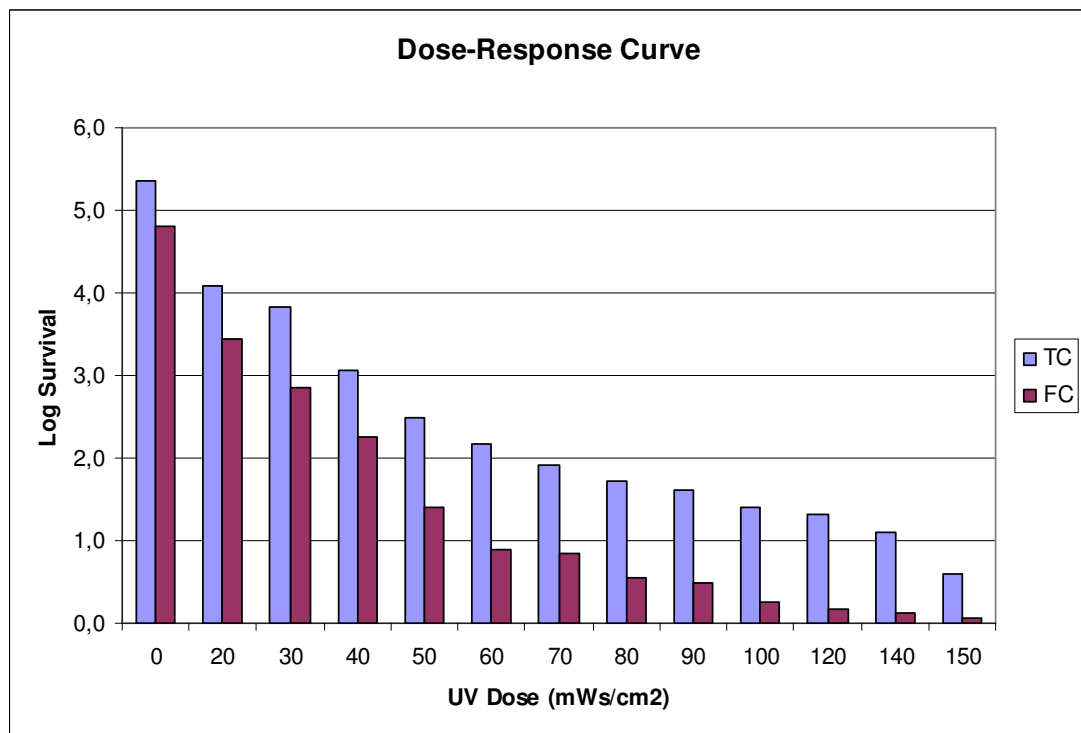


Figure IV.13. Log Survival of total and fecal coliforms according to applied UV Dose

Only average values are presented in these figures, while all of the collected data were presented in Figures IV.11 and IV.12.

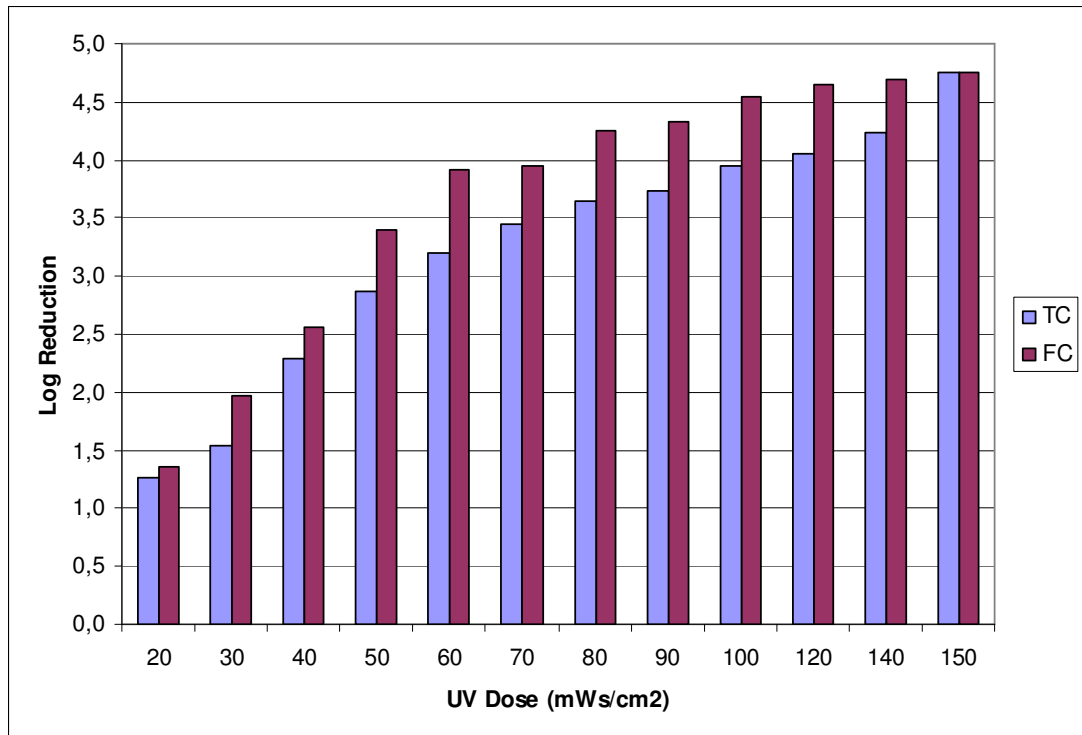


Figure IV.14. Log Reduction of total and fecal coliforms according to applied UV Dose

Figure IV.14. shows that, a UV Dose of 120 mWs/cm² is necessary to achieve a 4 log reduction of total coliforms. And to achieve a 4 log reduction of fecal coliforms, a UV Dose of 80 mWs/cm² is adequate.

The 75 percent confidence interval was determined for the data presented in Tables IV.6 and IV.7. The 75 percent confidence interval was calculated using the following expression:

$$75\% \text{ confidence limit} = \bar{x} \pm t_{0.125} \left(\frac{s}{\sqrt{n}} \right) \quad (\text{IV.2})$$

Where;

\bar{x} = Mean survival at a specific UV dose,

$t_{0.125}$ = student-*t* value associated with a 75 percent level of confidence. The values were obtained from t-statistical tables.

n = Number of replicates

s = Sample standard deviation

Table IV.9 shows the mean and confidence interval associated with each investigated UV dose.

Table IV.9. Survival coliform bacteria amount versus applied UV Dose

UV Dose (mWs/cm ²)	Surviving coliform per 100 mL					
	Average		Lower 75% C.I.		Upper 75% C.I.	
	TC	FC	TC	FC	TC	FC
0	228194	64597,6	197287	56086	263942	74401,1
20	12263	2833,2	8090	1868	18589	4297,5
30	8652	701,6	7371	381	10155	1292,6
40	1167	175,9	906	133	1503	232,0
50	314	25,9	220	16	447	42,5
60	145	7,9	116	6	181	10,3
70	82	7,2	62	6	109	8,2
80	52	3,6	40	3	68	4,9
90	38	3,1	34	2	43	4,7
100	22	1,8	17	2	30	2,2
120	20	1,5	14	1	29	2,1
140	11	1,3	6	1	18	1,9
150	4	1,1	3	1	6	1,4

The 75% confidence intervals indicate a 0.75 probability of containing the mean of a log inactivation for a set of data at a specified UV dose. For example, at a UV dose of 60 mWs/cm², there is 75% probability that the mean survival of total coliforms will be between 116 and 181 TC / 100 mL according to Table IV.9.

Average, lower 75% confidence interval and upper 75% confidence interval log survival of total coliforms and fecal coliforms are shown on Figures IV.15 and IV.16 respectively.

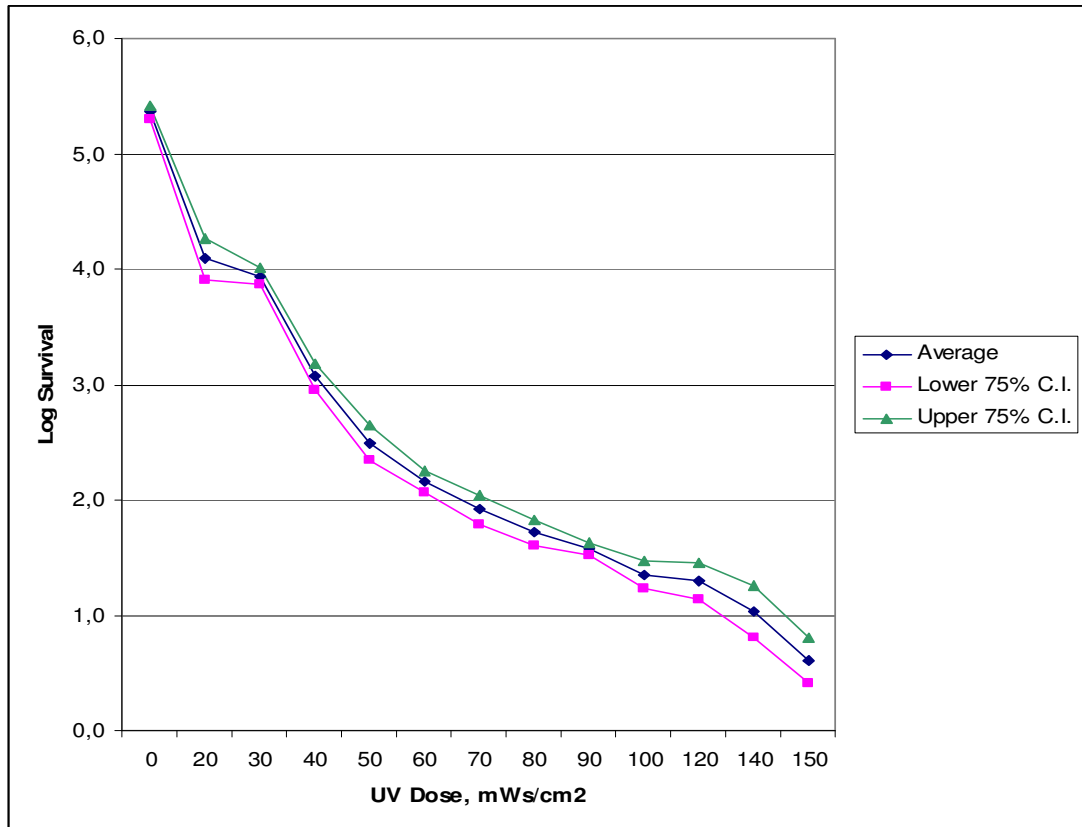


Figure IV.15. Average, Lower 75% C.I., and Upper 75% C.I. Log Survival of TC

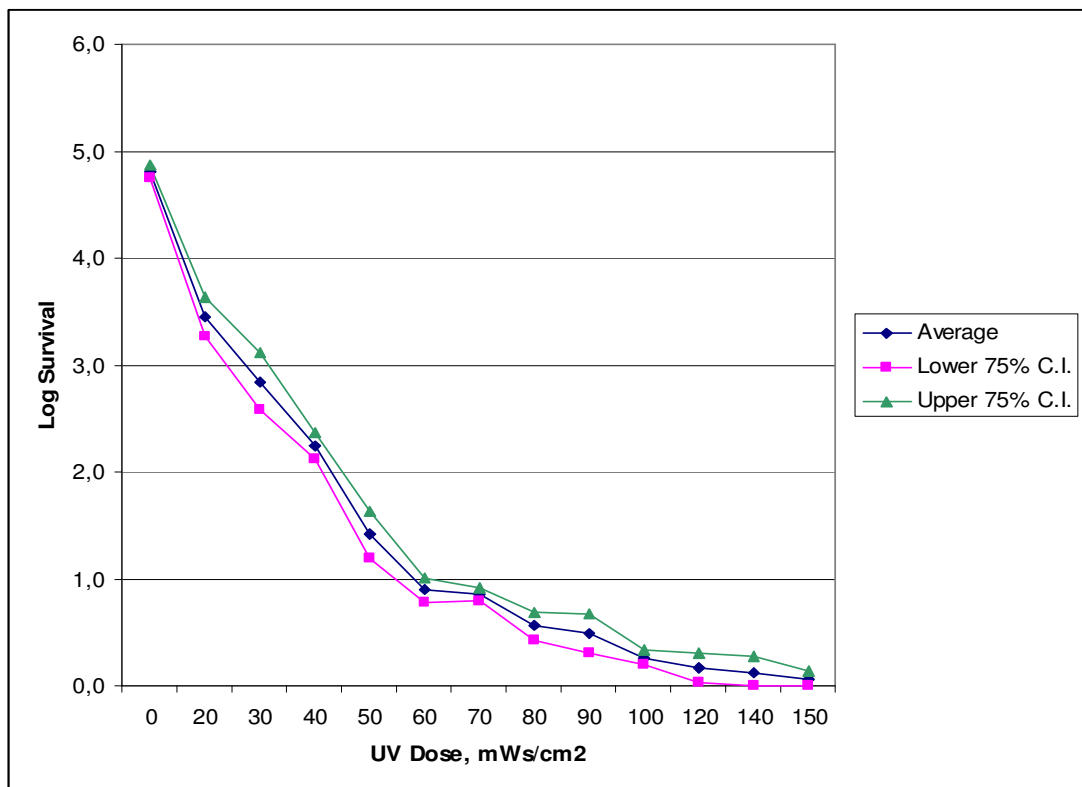


Figure IV.16 Average, Lower 75% C.I., and Upper 75% C.I. Log Survival of FC

The only microbiological parameter for agricultural reuse applications of wastewaters in Turkish Regulations is the fecal coliform content of the wastewater. The classification of irrigation waters based on fecal coliform counts were given in Table II.4. The experimental results were evaluated based on this classification. An inspection of upper 75% confidence intervals for fecal coliform amounts at table IV.9 leads to the conclusion that a minimum design UV Dose of 140 mWs/cm² is necessary to obtain Class 1 irrigation water and a UV Dose of 60 mWs/cm² is adequate to obtain Class 2 irrigation water. It is evident that Paşaköy WWTP effluent prior to UV disinfection is not suitable for agricultural reuse.

Table IV.10 shows the required UV doses to comply with fecal coliform permit values for irrigation water classes according to Turkish Regulations.

Table IV.10. Required UV Doses for Different Irrigation Water Classes

UV DOSE (mWs/cm ²)	Fecal Coliform / 100 ml	Class 1	Class 2	Class 3	Class 4	Class 5
		<2	2 – 20	20 – 100	100 – 1000	> 1000
		(excellent)	(good)	(permissible)	(doubtful)	(unsuitable)
0	74401,1					X
20	4297,5					X
30	1292,6					X
40	232,0				X	
50	42,5			X		
60	10,3		X			
70	8,2		X			
80	4,9		X			
90	4,7		X			
100	2,2		X			
120	2,1		X			
140	1,9	X				
150	1,4	X				

Experimental data were also analyzed in terms of the other reuse regulations (WHO, Californian). The requirements defined in these regulations were summarized in the previous chapters (Tables II.2, II.3 and II.5).

Figure IV.17 shows the appropriate UV doses for different regulations for wastewater reuse applications.

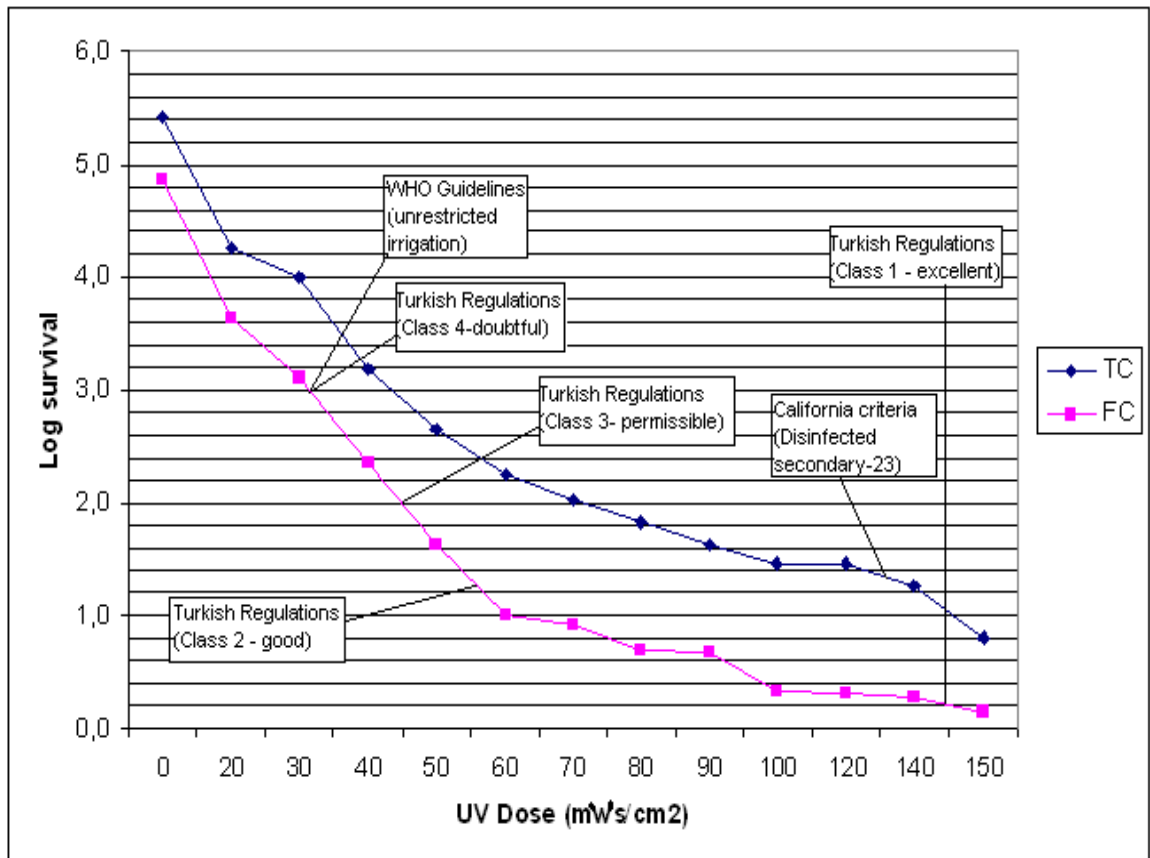


Figure IV.17. Upper 75% C.I. Log Survival of Total and Fecal Coliforms According to Applied UV Dose and the Appropriate UV Dose for Different Wastewater Reuse Regulations

Figure IV.17 indicates that a UV dose of 40 is adequate to comply with the unrestricted irrigation conditions of WHO Guidelines and also to achieve a Class 4 wastewater quality according to Turkish Regulations. A UV dose of 140 mWs/cm² is needed to comply with the California Water Recycling Criteria for disinfected secondary-23 category of reclaimed waters. However, an effluent that complies with disinfected secondary-2.2 category of reclaimed waters could not be obtained in the experiments. The highest UV dose applied was 150 mWs/cm². Even this dose was not sufficient. It should be kept in mind that the average SS content of wastewater used in these experiments were 16 mg/L. A better SS removal could be affective to reach the desired disinfection.

IV.4. Effect of Suspended Solids on Disinfection Efficiency

Throughout this research, the effect of suspended solids on UV disinfection efficiency was investigated. Since the experiments were conducted with the real wastewater on site, it was not possible to conduct controlled experiments by changing the SS content and keeping the other parameters (initial TC, FC, UVT) constant. The experimental results were classified into five groups based on the suspended solid content of the effluent. The experiments conducted with wastewater that contain less than 5 mg/L were gathered in one group. Those that contain suspended solids between 5 and 10 mg/L, 10 and 15, 15 and 20, and those that contain more than 20 mg/L were gathered together as the other four groups. Figure IV.18 shows the log survival of total coliforms for wastewaters with different SS values.

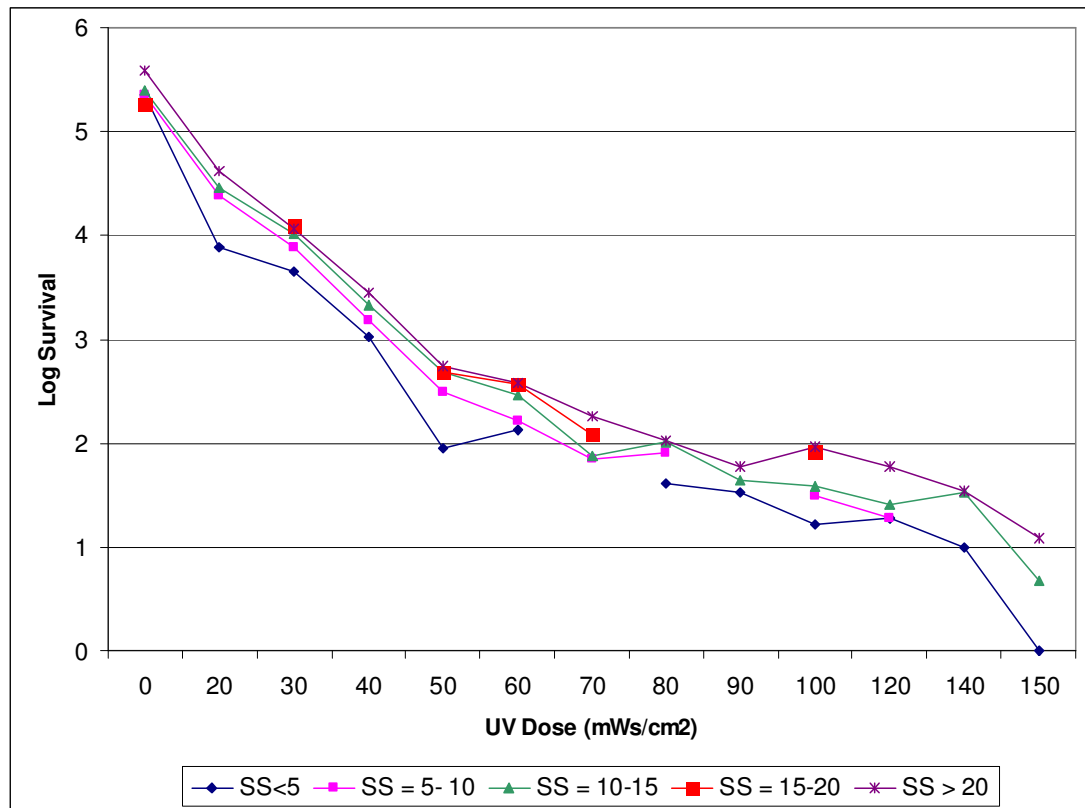


Figure IV.18. The effect of Suspended Solids on UV Disinfection Efficiency

Figure IV.18 indicates that greater log-reduction was achieved at the experiments that were conducted with wastewaters that contain less than 5 mg/L suspended solids. The coliform removal efficiency decreases as the suspended solids amounts increase.

IV.5. EFFECT OF UVT ON DISINFECTION EFFICIENCY

UVT is known to be one of the key parameters effecting the efficiency of UV disinfection and in most of the UV applications, UV dose is adjusted based on the UVT values of the incoming wastewater.

In this study, it has been clearly observed that, as the UV transmittance increases, the efficiency of the disinfection increases. As an example, average total coliform content of the effluents with UV transmittance higher than 65% which were exposed to a UV Dose of 20 mWs/cm² was 11025 TC/100 mL. Average total coliform of the effluents with UV transmittances between 55% and 60%, which were exposed to the same amount of UV Dose was 32550 TC /100 mL. Table IV.11 shows the total coliform content of effluents with different UV transmittance values. Figure IV.19 shows the effect of UVT on disinfection efficiency. During the research period, the measured UVT values varied between 56% and 70%. This cannot be described as a wide range. But even within this narrow UVT variations range, its effect on disinfection efficiency could be observed.

Table IV.11. Average total coliform content of effluents with different UVT values

UVT, %	Average Total Coliforms / 100 mL			
	Applied Uv Dose (mWs/cm2)			
	20	40	60	80
55-60	32550	2575	335	119
60-65	22218	1558	198	67
>65	11025	1358	104	51

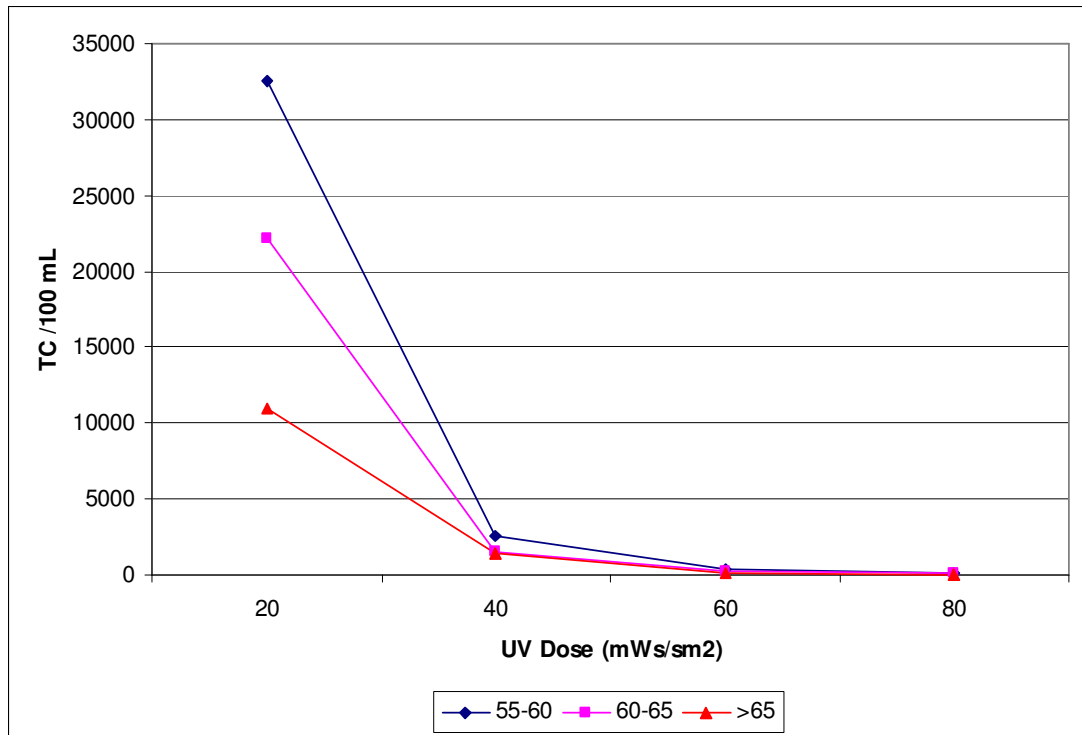


Figure IV.19. Effect of UVT on Disinfection Efficiency

Figure IV.19 indicates that almost 40 mWs/cm² of UV dose is necessary to achieve an effluent quality with less than 10000 TC / 100 mL with influents that have UVT values between 55 and 60 %, while approximately 20 mWs/cm² of UV dose is adequate to achieve the same TC content with wastewaters with a UVT value more than 65%.

CHAPTER V

CONCLUDING REMARKS AND RECOMMENDATIONS

Microbiological characteristics of Paşaköy WWTP effluent was monitored throughout the experiments. The results show that, with an average total coliform concentration of approximately 283000 TC/100 mL, and an average fecal coliform concentration of 78000 FC/100 mL, the effluent coliform concentrations of Paşaköy WWTP complies with the typical coliform bacteria levels of secondary treatment effluents given in the literature, and it is not suitable for agricultural reuse applications prior to disinfection.

The required UV dose to achieve a Class 4 wastewater quality according to Turkish Regulations for irrigation water standards was found to be 40 mWs/cm². The minimum required UV doses to achieve Class 3, Class 2, and Class 1 irrigation water quality were found to be 50 mWs/cm², 60 mWs/cm², and 140 mWs/cm², respectively.

Results of the experiments indicate that the applied UV dose, suspended solids and UV transmittance of water, and initial coliform concentrations are the most important factors affecting the UV disinfection efficiency.

UV disinfection efficiency decreased as the suspended solids values increased. The most effective coliform removal was achieved with wastewaters that contained less than 5 mg/L suspended solids.

Sand filter was observed to be effective in coliform and suspended solids removal. It also improves the UVT values. In full scale UV disinfection applications, a filtration unit would decrease the load on the UV system.

For further studies, it is aimed to include other wastewater quality parameters like sulfate and nitrate content that may also affect the UV disinfection efficiency. When these parameters are also monitored during the UV disinfection experiments, the results can be used for defining an empirical model that predict the UV disinfection efficiency for Paşaköy WWTP based on the wastewater quality parameters and applied UV dose.

The results of this experimental study was used as a guidance for the design of the full scale UV system that will be built in Pasaköy WWTP. In the full-scale UV system, the target effluent FC limit is determined as ≤ 2.2 FC / 100 mL, and the design UV dose is chosen as 90 mWs/cm². Although in this study, the appropriate UV dose to achieve such a wastewater quality was found to be 100 mWs/cm², it should be kept in mind that the majority of the experiments were conducted with unfiltered wastewater. In the full scale system there will also be sand filters prior to UV disinfection. Therefore it can be estimated that a UV dose of 90 mWs/cm² will be adequate to reach the desired disinfection target.

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CURRICULUM VITAE

Name & Surname : Serkan Evcimen
GSM : 0532 4306966
E-mail : serevcimen@hotmail.com
Date of Birth : 03.12.1982

EDUCATIONAL BACKGROUND:

MS: Marmara University, Institute for Graduate Studies in Pure and Applied Sciences, Environmental Engineering Programme
BS: Kocaeli University, Engineering Faculty, Environmental Engineering Department, 2006
High School: Körfez Oruç Reis Anatolian High School, 2000

FOREIGN LANGUAGES:

English: Advanced
German: Beginner

CERTIFICATE:

ISO 14001:2004 Çevre Yönetim Sistemi İç Denetçi, TMMOB ÇMO
AutoCAD 2004-2006, Avrupa İnsan Kaynakları Eğitim Merkezi
CNNA, Netron Bilgi İletişim Teknolojileri
CCNP, Netron Bilgi İletişim Teknolojileri

T.C.
MARMARA UNIVERSITY
THE INSTITUTE FOR
GRADUATE STUDIES IN PURE AND APPLIED SCIENCES

ACCEPTANCE AND APPROVAL DOCUMENT

The jury established by the Executive Board of the *INSTITUTE FOR GRADUATE STUDIES IN PURE AND APPLIED SCIENCES* on ^{26.01.2009, 2009/03-2} has accepted Mr. Serkan Evcimen's thesis titled "Application of UV Disinfection in Municipal Wastewater Treatment Plants for Agricultural Use of Reclaimed Wastewater" as Master of Science thesis in Environmental Engineering Programme.

Advisor : Assist. Prof. Aslihan KERÇ

1. Member of the jury: Assoc. Prof. Zehra CAN

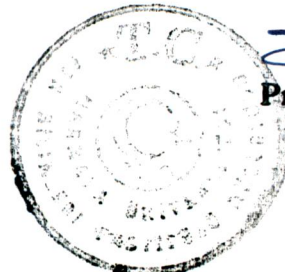
2. Member of the jury : Assoc. Prof. Nilgün CILIZ

Date : 02.02.2009

APPROVAL

Mr. Serkan Evcimen has satisfactorily completed the requirements for the degree of Master of Science in Environmental Engineering Programme at Marmara University. The Executive Committee approves that he be granted the degree of Master of Science on, ^{09.02.2009, 2009/04-3}

DIRECTOR OF THE INSTITUTE




Prof. Dr. Sevil ÜNAL
Müdür