ADVANCED MASTER OF SCIENCE IN 'TECHNOLOGY FOR INTEGRATED WATER MANAGEMENT'

ANDICOS^{TM}: A NEW APPROACH TO TREAT WASTEWATER AND WASTE IN THE GANGA RIVER BASIN

CASE STUDY IN KANPUR, INDIA

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Abstract

Ever since the onset of the demographic transition in the developing world, their cities have faced an overwhelming increase in production of wastewater and municipal solid waste. The development of treatment facilities and disposal sites has not caught up with the fast-growing waste and wastewater production, causing high loads of untreated sewage and municipal solid waste in the rivers and its banks with serious consequences for the urban river quality. In the near future, large efforts have to be made towards developing new wastewater technologies adapted to the scenery of the developing world, in order to increase water quality in this parts of the world. To address the dualistic waste problem of low-income countries in a sustainable way at low cost, the new conceptual waste treatment approach Andicos^{TM} could be used. The Andicos^{TM} technology combines wastewater treatment through membrane ultrafiltration to generate high-quality effluent and retentate processing via anaerobic digestion with biogas and organic fertilizer production. The membrane retentate is enriched with organic matter to allow efficient anaerobic digestion.

As the EU-India Horizon2020 project ‘Pavitra Ganga’ is setting up a pilot-scale Andcos^{TM} wastewater treatment plant at Kanpur, the research is set in the municipal area of Kanpur and analyzed the ultrafiltration performance response with regards to fouling, effluent quality and carbon recycling on several attributes for the location-specific condition. The main studied parameters are flux of filtration, backwash strength, origin of wastewater and water quality of retentate and influent including the concentration factor. The optimal filtration settings were defined to achieve the desired continuity in the membrane filtration process by reducing the negative effect of fouling, while sustaining a sufficient high permeate flux to reduce the overall costs of the Andicos^{TM} treatment plant. Moreover, an adequate balance between effluent quality and carbon concentration in the membrane tank had to be looked for to satisfy both ecological and economic incentives.

The results show that maximal permeate production with minimal fouling is obtained by the filtration flux of 25 $l.m^{-2}.h^{-1}$ with a backwash strength of $37.5 l.m^{-2}.h^{-1}$. For this flux, maximal carbon recycling can be achieved by the membrane tank COD concentration of 9096 $mg.L^{-1}$, while generating permeate with an COD concentration in agreement with the Indian discharge regulations. During the Jajmau wastewater filtration experiments, the IPC membranes retained efficiently organic carbon (91.4 ± 2.3 %) of which a considerable amount (32.3 ± 9.6 %) was lost, probably through biodegradation The concentrated retentate was co-digested with organic kitchen waste at a sludge retention time of 20 days and reached a stable biogas production of 380 ± 11 $mL/g_{CODadded}$. At a loading rate of 2 g $VS.L^{-1}.d^{-1}$, the recovered methane gas via anaerobic digestion equals 0.88 $m^3_{methane}/m^3_{sewage\ treated}$, yielding 3.66 $kWh/m^3_{sewage\ treated}$ at an electrical conversion of 40%, which is by far more than the expected power requirement for membrane filtration. Compared to the current Jajmau ASP facility, the implementation of a full-scale Andicos^{TM} (130-MLD) would be more efficient to decrease the contaminant load into the Ganges. The results imply that the implementation of a large-scale Andicos^{TM} facility (130 MLD) could improve drastically the Ganges river water quality during the low flow regime in summer season. Andicos^{TM} technology is an approach with great potential to be an economic and environmentally sustainable waste and wastewater treatment technology as it delivers an excellent effluent quality to resilience river systems while being a net-energy producer and reducing greenhouse gas emissions.

List of symbols

ASP	Activated Sludge Process
BOD	Biological Oxygen Demand
COD	Chemical Oxygen Demand
EQI	Effluent Quality Index
IIT	Indian Institute of Technology
JNNURM	Jawaharlal Nehru National Urban Renewal Mission
IPC	Integrated Permeate Channel
MBR	Membrane treatment
MLD	Million Litres per Day
MTC	Mass Transfer Coefficient
NGRBA	National Ganga River Basin Authority
N-TKN	Nitrogen-Total Kjeldahl Nitrogen
Rs	Rupees
STP	Sewage Treatment Plant
TMP	Transmembrane pressure
TSS	Total Suspended Solids
UASB	Upflow Anaerobic Sludge Blanket
VITO	Flemish Institute of Technology Development

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1. Introduction and objectives

The Ganges river flows through the North of India and supports one of the most densely populated areas of the world. Its river basin drains approximately 26% of the total surface area of India and is home to more than four hundred million Indian people. (water resource information system, 2017; Brown T., 2019) Melting water, originating from the Himalaya Mountains, and water provided by rain and tributary streams feed the Ganges river. It flows southbound into Uttarkhand (India) and winds its way through northern India, before discharging in the Meghna River. The fertile soils along the shores of the river have stimulated the development of civilizations along the waterway for centuries, such that millions of people live in this river basin. The river provides freshwater to all these people and is also considerably important for bathing, irrigation and fishing. However, the Ganges is a priceless natural resource on the decline because of the growing threats (Brown T., 2019).

Exponential growth of population combined with a rapid increase of industrialization led to a strong increased discharge of domestic and industrial wastewater into the Ganges with limited or no treatment. Therefore, the water quality of the Ganges collapsed over the last few decades resulting in the Ganges turning into the sixth most polluted river of the world (Agarwal, 2015; Heylen C., 2018).The highest pollution rates are identified in the river section between Kanpur and Varanasi (Heylen C., 2018). As Kanpur has a population of more than 3 million inhabitants (Census Organization of India, 2011) and an industrial area with approximately 400 tanneries (Central Leather Research institute, 2012), the city creates between 426 and 600 million liters per day (MLD) of wastewater (Administrative Staff College of India, 2013; Heylen C., 2018). Currently, only 100 MLD can be treated in Kanpur by the three operational sewage treatment plants. A shortage in treatment facilities, sewerage and energy are considered as the main causes of the insufficient wastewater treatment (Administrative Staff College of India, 2013; Heylen C., 2018).

To reduce the impact of the industries and the households on the quality of the Ganges, new sewage treatment facilities have to be built. Currently, the Activated Sludge Process and Upflow Sludge Anaerobic Reactor are the only used technologies in Kanpur (Heylen C., 2018). However, unsatisfactory removal efficiencies, high investment costs and energy demand of these technologies gave incentive to the Indian authorities to search for new wastewater treatment approaches (Heylen C., 2018; Indian Institutes of Technology, 2010). The new waste treatment approach Andicos^{TM}, integrating ultrafiltration of wastewater with anaerobic digestion of the carbon-rich retentate and organic municipal waste into one system, could cut down the disadvantages (Diels L., 2017). The increased wastewater discharge, as well as the growing municipal waste problem in Indian cities, all could be tackled by the implementation of the Andicos^{TM} technology while being a net-energy producer (Heylen C., 2018).

To examine whether the Andicos^{TM} technology is a concept that can provide a sustainable solution to the overwhelming waste problems in developing countries, we analyzed the potential of the Andicos^{TM} approach in terms of carbon recycling and contaminant removal, for this Kanpur was selected as case study. In the framework of an official partnership between the University of Antwerp and the Indian Institute of Technology of Kanpur as part of the EU-India Horizon2020-project “Pavitra-Ganga”, this manuscript tries to address several challenges faced during the implementation of the Andicos^{TM} technology in Ganges river basin to pave the way for the future pilot-scale Andicos^{TM} treatment facility in the municipal area of Kanpur. First, the optimal settings of this technology have to be sought with respect to the constraints prevailing at the Kanpur wastewater treatment site. Then, the impact of the optimized Andicos^{TM} technology on the wastewater quality will be investigated and compared to the current technologies. The comparison between the treatment technologies is based on the contaminant removal efficiencies, the sustainability and the overall costs. To draw valid conclusions from this research project, the efficiency of the technologies was evaluated for location-specific conditions (e.g. wastewater feed characteristics, climate, etc.) of the Kanpur metropolitan region.

This MSc thesis aims to answer the following questions:

- What are the optimal filtration settings to achieve a continuous filtration process with the highest treatment capacity as possible?
- Where lies the optimal equilibrium between effluent quality and carbon up-concentration to satisfy both ecological and economic incentives?
- How much organic carbon of the carbon-rich stream and food waste can be degraded in the anaerobic digestion process? Is the capital withdrawal from the methane production sufficient to make Andicos^{TM} a profitable investment?
- What is the removal efficiency of the Andicos^{TM} treatment technology for Kanpur wastewater? Is the overall effluent quality after treatment through the Andicos^{TM} technology for wastewater coming from Kanpur sufficient?
- Which treatment technology is the most suitable to treat the wastewater of Kanpur with regards to the effluent quality and the overall costs?

To determine the optimal filtration settings, the flux of filtration and backwash strength were evaluated with regards to their capacity to reduce the negative effects of concentration polarization/fouling while assuring a high treatment capacity. Moreover, the effect of influent and retentate quality on the permeate quality was investigated by the daily sampling of the different fractions during long-term filtration tests. The biodegradability of the yielded retentate and food waste was tested by setting up different digestors and monitoring its biogas production.

For various filtration settings, the removal efficiency of the filtration process was evaluated by analyzing several water quality parameters of the influent and the effluent. To make a comparison with the current used technologies, the effluent quality of the Activated Sludge Process (ASP) facility was investigated. Finally, the capital and operational costs of the different technologies were estimated based on values found in the literature. For the Andicos^{TM} technology, the earnings from methane production via the digestion of food waste and retentate were included in this cost assessment (Heylen C.,2018).

2. Context

2.1 General scenery

Environmental contamination owing to wastewater discharge and solid waste dumping is a growing issue in low-income countries (Ferronato & Torretta, 2019). The development of treatment facilities and disposal sites has not caught up with the fast population growth and rapid urbanization rate in developing countries, causing high loads of untreated sewage in rivers and open dumping of solid waste in uncontrolled sites with huge consequences for urban river water quality (Xu et al. 2019). As untreated sewage contains high concentrations of organic matter and nutrients, the municipal discharges poses a significant risk of eutrophication-related problems to the receiving rivers (Norah et al. 2015). The decay of organic material leads to the consumption of a substantial amount of the dissolved oxygen in the river water, resulting in a life threatening situation for many aquatic species (Norah et al. 2015). In addition, leachate of solid waste dumping sites in close proximity of rivers may contaminate its water by increasing the organic matter, nutrient and total coliform load. It can be concluded that the high average concentration of total coliform, biochemical oxygen demand and low dissolved oxygen found in the rivers of some developing countries are primarily the result of the considerable discharge of untreated sewage and solid waste leachate into urban rivers (Chamara & Koichi, 2017).

To restore the river quality in developing countries, there is an urgent need to increase the treatment capacity of the existing sewage treatment facilities and waste disposal sites. However, the expansion of the conventional facilities for wastewater treatment is associated with some major drawbacks, namely high investment costs, intensive land occupation, large energy demand and high greenhouse gas emissions (Diels L., 2017). To put things into perspective, a traditional activated sludge plant requires almost one squared meter surface per cubic meter of sewage per day (Institute of technology Kanpur, 2011), consumes 0.3-1.9 kWh per cubic meter sewage (Tuyet et al. 2016) and contributes to 2% of the global greenhouse gas emissions (Diels L. 2017). Besides, traditional solid waste management (e.g. landfilling, burning or composting) is not satisfactory in ecological and economical perspective (e.g. leaching, flue gasses. energy demanding, etc.) (Diels L.2017).

The new waste treatment approach Andicos^{TM} may be an adequate solution to the dualistic waste problem of developing countries. Andicos^{TM} combines wastewater filtration by ultrafiltration (UF) membranes with anaerobic digestion of the concentrated retentate to produce energy (Pavitra ganga, 2020). As the anaerobic digestion processes need a sufficient high organic load to be profitable, food waste is added to the concentrated retentate. This carbon-rich product has a high potential for anaerobic digestion and methane production (Heylen C., 2018). The membrane based treatment technology can reduce the land requirement by a factor of 4 in comparison to the conventional activated sludge process (Institute of technology Kanpur,2011), while being a net energy-producer instead of an energy consumer (Diels L., 2017). Moreover, a reduced emission of the greenhouse gasses CO_2 and N_2O can be expected for the Andicos^{TM} technology due to the absence of aeration (Heylen C., 2018). In addition, the Andicos^{TM} technology may be helpful against the threatening nutrient scarcity in the future. As Andicos^{TM} does not consume phosphorus or nitrogen, these nutrients can be recycled from the system in the form of irrigation water and digestate to be reused for agriculture purposes. Another major advantage of the Andicos^{TM} technology is the possibility to spread investment costs due to the modular nature of this technology, which allows a step-by-step implementation (Diels L., 2017).

To evaluate the suitability of the Andicos^{TM} technology to solve the growing waste problem in developing countries, the technology was tested for the city of Kanpur located in the Ganges River basin, an illustrative example of river degradation by the dualistic waste problem.

2.2 The Ganges

The Ganges-Brahmaputra-Meghna (GBM) river basin comprises a contributory area of 1.7 million km³, distributed between India (64%), China (18%), Nepal (9%), Bangladesh (7%) and Bhutan (3%) (Figure 2.1) (FAO, 2011; Heylen C., 2018). Although the three rivers of this system are characterized by different flows and morphology through very distinct areas for the majority of their river streams, the GBM river basin is regarded as one system (FAO, 2011). The Ganges is the main river of this basin, covering 63,5% of the total surface area whereof 860,000 km² is located in India (FAO, 2011; Heylen C., 2018).

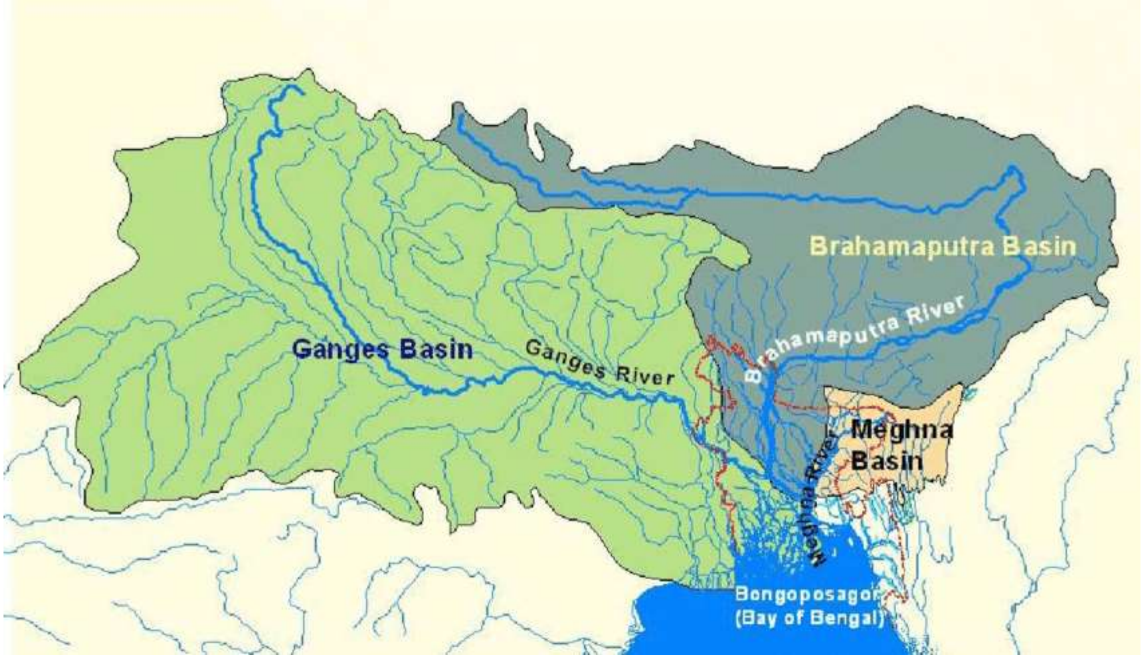

Figure 2.1 *Plan of the Ganges-Brahmaputra-Meghna (GBM) river basin (Palash W., 2005).*

The headwaters of the Ganges find their origin in the Himalayan mountain range in China and flows South into India. The river turns to the Southeast in the Indian province Uttar Pradesh, before flowing into Bangladesh (FAO, 2011). The Ganges, Brahmaputra and Meghna rivers merge in Bangladesh and jointly leave the continent as the Meghna river (FAO, 2011). Throughout its 2,525 km long flow, many tributary streams flow into the Ganges (Heylen C., 2018). The main tributary streams are Gomti, Ghaghara, Gandaki, Yamuna, Son and Pupun (FAO, 2011; Heylen C., 2018).

The annual precipitation in the Ganges river basin averages 110 cm and varies between 39cm to 200cm (Heylen C., 2018). The upper Gangetic plain (Uttar Pradesh) is characterized by an average annual rainfall of 76 to 102 cm (FAO, 2011). The majority (80%) of the annual rainfall takes place in the Monsoon season (June to October) (Heylen C. 2018). The intra-annual precipitation variability causes a high variance in discharges of the Ganges river throughout the year. A maximum discharge of approximately 60000 m³/s is observed during August and September, while the discharge drops to values under 4000m³/s from December to June (Heylen C., 2018).

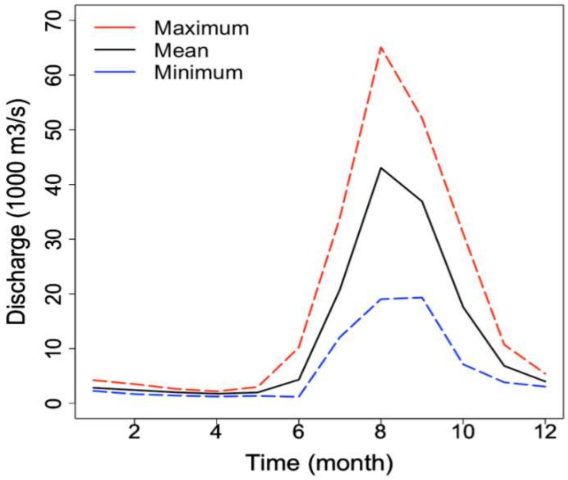

Figure 2.2 The annual hydrograph in Farakka shows that the Ganges is a tropical monsoon river with a high seasonality (Heylen C., 2018)

The Ganges river basin is home to approximately 600 million people and more than 40% of the Indian gross domestic product is generated in this basin (WHO, 2015). One-third of India's surface water originates from the Ganges basin, of which 90% is used for irrigation (WHO, 2015. The majority of the land is used for agricultural purposes. Nevertheless, a wide range of industrial activities are carried out in the proximity of the Ganges river (WHO, 2015).

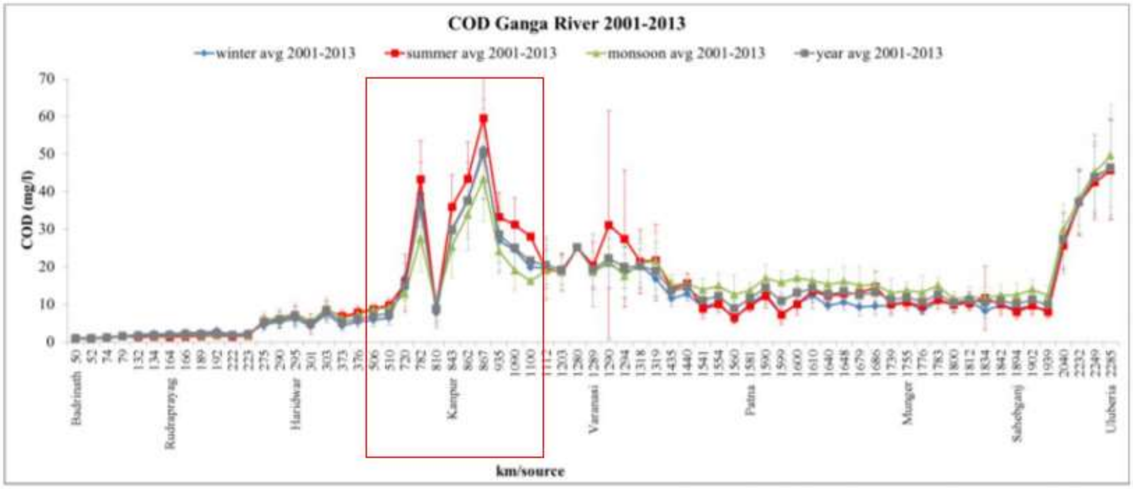

***Figure 2.3** The mean average COD along the Ganges river for the three seasons between 2001 and 2013. The Ganges river trajectory near Kanpur is marked by the red square. (Diels L. 2017)*

Figure 2.3 shows the average Chemical Oxygen Demand (COD) concentration for the Ganges river between 2001 and 2013. The high population size in combination with the increasing industrial activities are putting pressure on the water quality of the Ganges, because of high domestic and industrial wastewater discharges. The sewage load of about 6,087 MLD exceeds the existing treatment capacity of 1,208 MLD (Central Pollution Control Board, 2013; Heylen C., 2018). Along the Ganges river there are 138 open drains identified originating from channels to carry storm water (Central Pollution Control Board, 2013; Heylen C., 2018) Between Varanasi and Kanpur, the Ganges river experiences the most pollution (Heylen C., 2018; Troch M., 2018). Figure 2.3 illustrates that Kanpur is the main contributor to the deteriorated state of the Ganges river, due to high discharges of untreated wastewater near the city of Kanpur. As the metropolitan area of Kanpur is the main polluter along the Ganges river, this manuscript focused on the pollution pressure of this city.

2.3 Kanpur

Kanpur is a major urban agglomeration situated in the state of Uttar Pradesh (Northern India). The city covers an area of 260km² with an average population density of 830 persons/km². The population size of Kanpur district was estimated to 5,035,730 in 2020 (Census Organization of India, 2011; Troch M., 2018). However, according to the 15th National census survey, Kanpur district had a population of 4,581,268 in 2011 with a decennial increase of 9.92% (Census Organization of India, 2011; Heylen C., 2018). The world population review estimates that the population of the metropolitan area will be equal to 3,124,000 in 2020 (World population review, 2020). Based on the current population and the expected growth, the Indian Institute of Technology (IIT) expects a population increase to 7.394.319 inhabitants in 2050 (Heylen C., 2018; University of Ontario, Institute of Technology, 2018). Kanpur is the second largest city of Uttar Pradesh and belongs to the top 12 most populous cities of India (Heylen C., 2018). However, Kanpur ranks amongst the poorest regions of India with an average GDP per capita of 18,279 rupees (218.0 euro) and a poverty rate of 33.9% (Roberts M., 2016) . This illustrates that the economic performance not always meets the economic potential (Roberts M., 2016).

Nevertheless, Kanpur is an economic hotspot of India because of its highly developed industrial sector. The leather industry is responsible for the primary economic activity, which is mainly located in the Jajmau district (Troch M., 2018) . The Jajmau array of tanneries contains more than 400 factories (Pavitra Ganga, 2020). The major part of the leather industry practices chrome tanning resulting in 50 MLD of highly concentrated tannery effluent, which makes up 8 to 14% of the total wastewater discharge (NGRBA, 2017; Heylen C., 2018). The tannery effluents contain 30 to 50% of the used chromium and are often illegally discharged in the Ganges river via open drains (Troch M., 2018). The high chromium concentrations in the Ganges are harmful to aquatic fauna and flora and humans (Beg &Ali, 2008; Troch M., 2018). Besides the leather industry, about 5100 other industries are identified in Kanpur mainly producing chemicals, paints, detergents and fertilizers (Heylen C., 2018).

However, the major volume of wastewater discharge has a domestic origin. The domestic wastewater production in Kanpur is estimated between 376 MLD and 550 MLD, of which 326 MLD to 500 MLD is discharged without any treatment into the Ganges via open drains (Heylen C., 2018; Narain, 2014). In Kanpur city, 15 open drains are identified with each a flow above 1 MLD. Although it is expected that a considerable amount of the open drains are not classified (Heylen C., 2018; Troch M., 2018). The largest open drain Sisamau Nala has a discharge between 130 and 143 MLD (Heylen C., 2018; NGRBA, 2017). Based on the population census and discharge rates, each inhabitant produces between 130 and 200L per day (Heylen C. 2018). Because of the expected population growth in India, the Administrative Staff College of

India estimates that the domestic discharges will increase from 426 MLD in 2010 to about 1000 MLD in 2040 (Administrative Staff College of India, 2013; Heylen C., 2018).

No data was found on the exact quantity of food waste generated in Kanpur. According to World bank (2012), the average food waste generation in India is 0.7kg solid waste per capita, of which 58% is organic waste (Silpa et al. 2018). Therefore, the total organic waste production of Kanpur is estimated to be around 2044 tons. However, the current solid waste management in Kanpur appears to be highly ineffective (Zia & Devadas, 2008). The solid waste management system only includes primary and secondary collection, transportation and open dumping (Zia & Devadas, 2008).

The flow of the Ganges in Kanpur varies between 21m³/s in the dry season and 10.483m³/s in the monsoon season with an average discharge of 895m³/s (Global Runoff Data Center, 2014; Heylen C., 2018). Three different discharge patterns can be distinguished throughout the year because of the three climatic seasons. The average discharges are 173m³/s (summer), 434m³/s (winter) and 2.918 m³/s (monsoon) (Heylen C., 2018). In Kanpur, the temperature varies between 2°C and 48°C and has an annual average of 26°C. (Heylen C. 2018; Singh, M. 2007)

The large pollution pressure of the industrial sector and the concentrated population in combination with low dicharges of the Ganges river are resulting in a critical environmental situation. Therefore, new treatment facilities have to be built to reduce the negative impact on the environment and health (Heylen C., 2018 ; Troch M., 2018).

2.4 Existing treatment facilities

In order to reverse the degraded state of the Ganges River, the Mission for Clean Ganga has been launched by the National Ganga River Basin Authority (NGRBA) under the supervision of the Ministry of Water Resources (National Mission for Clean Ganga, 2018). In the framework of the Mission for Clean Ganga, the NGRBA has to develop a River Basin Management Plan with the focus on regulation, prevention, control and reduction of pollution in order to increase the water quality and restore the river ecology (National mission for clean Ganga, 2018; Heylen C., 2018).The Indian Institute of Technology of Kanpur operates as a main research center to provide continuous data on Ganges water quality, which will be reported by the Centre for Ganga River Basin Management and Studies (Heylen C., 2018;).

Currently, three sludge treatment plants (STPs) are operational and four new STPs are under construction in Kanpur. The three treatment facilities together only have a capacity of 171 MLD, therefore only 28% to 40% of the total wastewater volume can be treated (Administrative Staff College of India, 2013; Heylen C., 2018). Due to inappropriate management, a lack of stable electricity and sewerage, the STPs do not work at full capacity resulting in an actual treated volume of 100 MLD (Heylen C. 2018). Enhancing the treated volume can be accomplished by increasing the number of STPs and developing a more comprehensive sewage network (Heylen C. 2020). Currently, the sewerage network covers only 29% of the city area (Pavitra Ganga, 2020).

The three operational STPs are situated on the same ground, but all have unique treatment mechanisms and design characteristics. The treatment volume of the distinct STPs are 5 MLD, 36 MLD and 130 MLD (Heylen C., 2018).

The 5-MLD treatment facility dates from 1989 and is currently still working at total capacity. The plant was built to treat domestic water only, but currently it is also receiving an unquantified amount of tannery wastewater because of illegal dumping in the sewerage (Heylen C. 2018). The treatment facility anaerobically degrades organic matter by using an Upflow Anaerobic Sludge Blanket (UASB) reactor. Before entering the UASB reactor, the water goes through a screen and grit chamber. Afterwards, the water enters the polishing pond to enhance the effluent quality. The sludge of the UASB is evacuated to a sludge drying bed and the produced gas is flared (Heylen C. 2018). The treatment scheme is shown in figure 2.4.

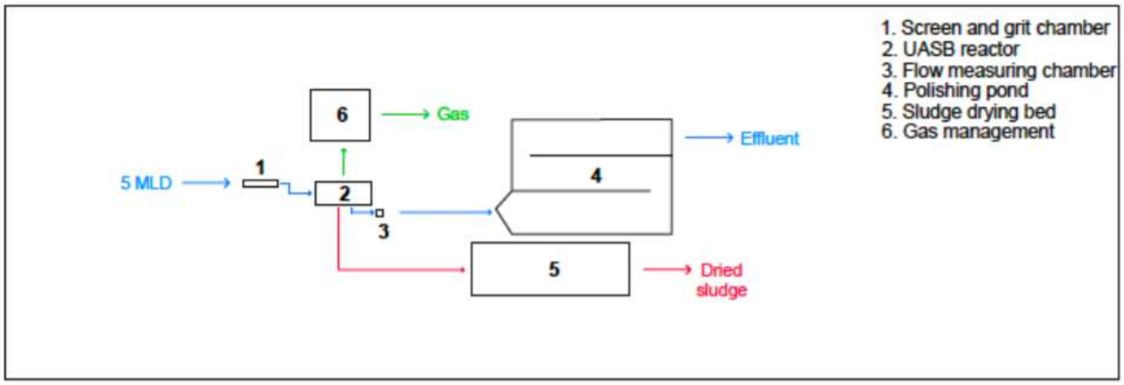

Figure 2.4 *Treatment scheme of the 5 MLD wastewater treatment plant. (Blue: water line, green: gas line and red: sludge line). (Heylen C., 2018)*

In 1994, the 36-MLD treatment plant was constructed based on the UASB concept. The treatment facility receives 27 MLD of wastewater with domestic origin and 9 MLD of process water originating from the leather industry (Heylen C. 2018). Figure 2.5 shows the treatment process of the 36MLD plant. Pretreated (screen and grid chamber) industrial wastewater is standardized in two parallel equalization tanks. Subsequently, the industrial wastewater is mixed with domestic wastewater and is pumped into two parallel UASB reactors. After aeration of the anaerobically treated water, it is collected in two clariflocculators. The sludge is stored in drying beds and the produced gas is flared (Heylen C., 2018).

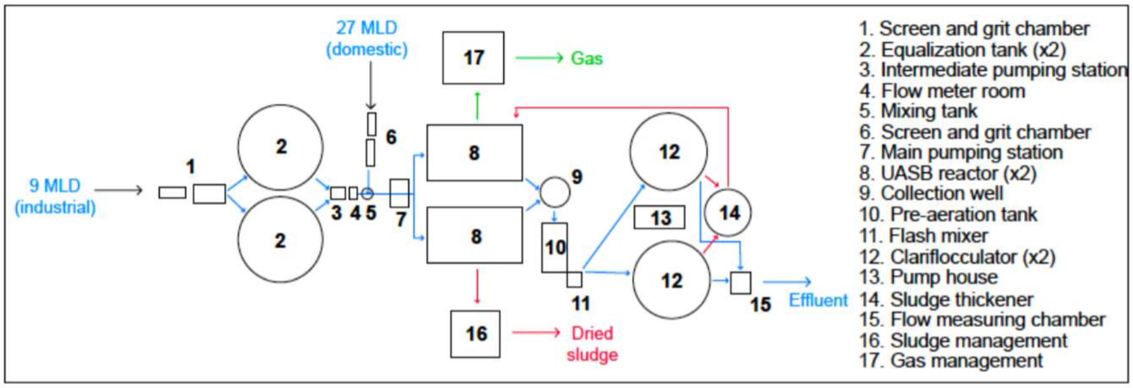

Figure 2.5 *Treatment scheme of the 36 MLD wastewater treatment plant. (Blue: water line, green: gas line and red: sludge line). (Heylen C., 2018)*

The 130-MLD treatment plant dates from 1999 and should only receive domestic wastewater (Heylen C., 2020). Although, the domestic wastewater is contaminated by industrial wastewater because of illegal discharges in the sewage. The facility is based on the activated sludge process. The wastewater goes respectively through pretreatment facility, primary settling tank, aeration tank and clariflocculator, shown in figure 2.6 (Heylen C., 2018).

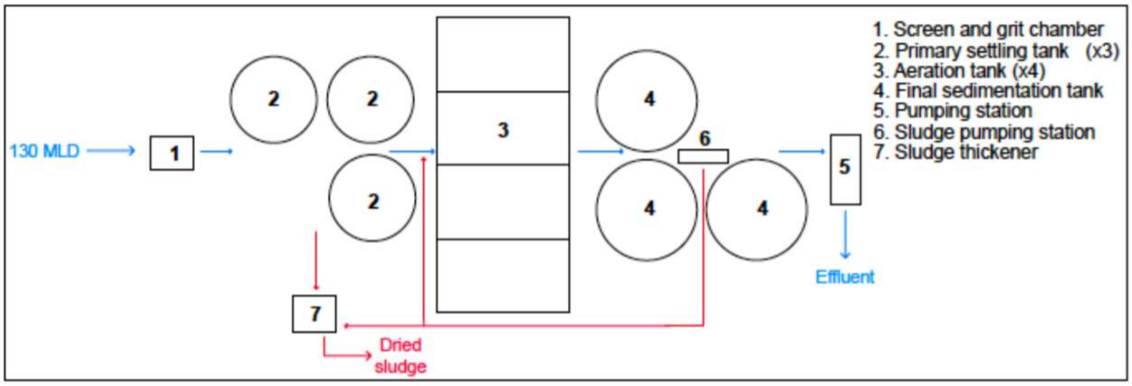

Figure 2.6 *Treatment scheme of the 130 MLD wastewater treatment plant. (Blue: water line and red: sludge line). (Heylen C., 2018)*

The representative of STPs is not satisfied by the UASB based reactors. The UASB reactors are not suitable for the variable organic and hydraulic loads. The effluent of this treatment process still contains high loads of Biological Oxygen Demand (BOD) and chromium, therefore the effluent should require further treatment. Because of the low removal efficiency in the prevailing conditions, the technology will not be used in future projects (Heylen C., 2018). The activated sludge based STP records better treatment efficiencies, but the effluent quality results are still unsatisfying as they are not in agreement with the Indian regulations (Diels L., 2020). However, the ASP technology is still considered for future projects (Heylen C., 2020).

The effluents of the 130-MLD and 36-MLD treatment facilities are combined after treatment and used for irrigation purposes, because the “inland surface effluent standards” (100 mg/L of Total Suspended Solids (TSS) and 30 mg/L of biological oxygen demand) are not fulfilled (Central Pollution Control Board, 2020; Pavitra ganga, 2020). The “land for irrigation effluent standards” (200 mg/l of TSS and 100 mg/L of BOD) are less strict and therefore easier to fulfill (Central Pollution Control Board, 2020). Nevertheless, local stakeholders have doubts about the effluent quality and its suitability for irrigation. Lower yields are reported for the agricultural fields irrigated with the mixed effluents. The main concern of the farmers is the high chromium concentration of this mixture, which is mainly originating from the effluent of the 36-MLD treatment facility. To increase the irrigation water quality, both effluents should not be mixed (Pavitra ganga, 2020). The effluent of the 5-MLD treatment facility complies with the “inland surface effluent standards” and is therefore directly discharged into an open drain (Heylen C., 2018).

The existing STPs provide treatment capacity for only 30% of the produced wastewater, therefore large amounts of untreated wastewater flow directly in the Ganges River. Because of the degraded state of the Ganges River, the government is incentivized to strive for a “zero liquid discharge” in the future (Heylen C., 2020). New treatment facilities have to be installed to reach this “zero liquid discharge” goal. Currently, the Jawaharlal Nehru National Urban Renewal Mission (JNNURM) and the NGRBA are facilitating projects to enhance the coverage of the sewage network, renovate the existing STPs and built new treatment facilities. (Heylen C., 2018; The Energy and Resources Institute, 2014)

Under JNNURM program, it is planned to increase the treatment capacity with 310 MLD by implementing four new STPs at various location, namely at Bingawan (210 MLD), Jajmau (43 MLD), Sajari (42 MLD) and Baniapur (15 MLD) (The Energy and Resources Institute, 2014). The construction of the Bingawan STP is already completed and was based on the UASB concept. The Bingawan facility is still under trail run and is only receiving little sewage. In addition, another ASP unit (43 MLD) is yet to be commissioned at the Jajmau site to achieve an augmentation of the treatment capacity of the Jajmau ASP (Pavitra ganga, 2020). In the frame of the JNNURM program, an STP of 15 MLD at Baniapur and an STP of 43 MLD at Sajari are going to be built in the future (The Energy and Resources Institute, 2014).

It was approved by the JNNURM to renovate and rehabilitate the exiting STPs of Jajmau. To enhance the flow into the Jajmau STP, the trunk sewer to the Jajmau STP was renovated and its capacity was enhanced at the start of 2020. Through the trunk sewer renovation, the infamous Sisamau drain, which discharges approximately 140 MLD into the Ganges river, was trapped and the flow was partially diverted to the Jajmau STPs (± 60 MLD). The rest of the Sisamau drain (±80 MLD) will be diverted to the Bingawan STP (Tare V., personal communication, May 29, 2020). As consequence of the changed situation, the influent wastewater characteristics are altered since February 2020. Historical data on the influent characteristics are therefore not representable.

The ongoing projects are still not sufficient to process all generated wastewater, therefore it was decided to launch a new umbrella program by the NGRBA. To achieve the “zero liquid discharge” goal, the NGRBA program aims to implement two additional sewage treatment plants with a total capacity of 110 MLD and to increase the coverage of the sewerage network (Heylen C, 2018). However, the plan is not yet approved and the proposal is not ambitious enough to tackle the future increment in wastewater discharge.

Currently, it is not determined which type of treatment technology they plan to implement in Kanpur. As mentioned, conventional treatment technologies (e.g. ASP and UASB) are not satisfying with regards to energy demand, investment costs and effluent quality. Due to the warm Indian climate and high municipal solid waste production, the implementation of an anaerobic based conversion technology could be the most advantageous for the city of Kanpur as it has the smallest economic and environmental impact.

2.5 Aerobic versus anaerobic treatment

The treatment of both solid and soluble organic waste can be performed in aerobic or anaerobic conditions (Deseau I., 2020). These conditions refer to the presence or absence of oxygen. During aerobic degradation, organic matter is converted into new cells, carbon dioxide and water. Anaerobic conditions result in a fermentation process defined by the conversion of organic matter into biomass and biogas (Deseau I., 2020). The main components of biogas are methane (50-75%) and carbon dioxide (25-50%). Figure 2.7 shows the energy and carbon flows for both aerobic and anaerobic conversion.

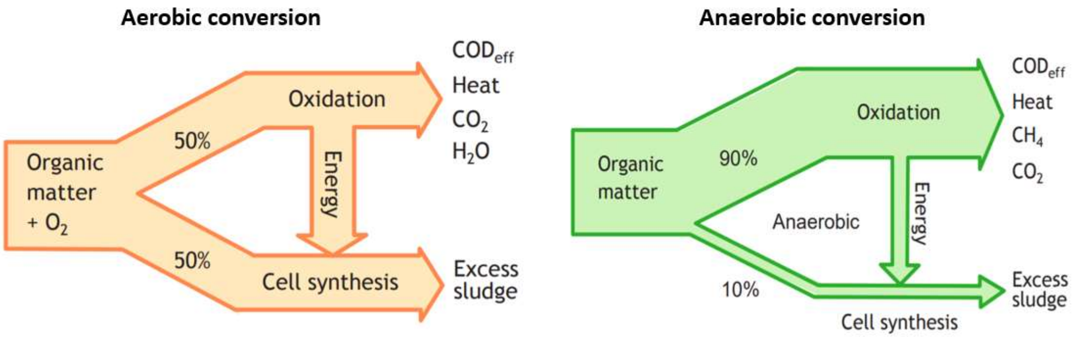

Figure 2.7 *Fate of carbon and energy in aerobic (left) and anaerobic (right) organic matter conversion (Diels L. 2017)*

In aerobic treatment, microorganism convert organic matter (carbon) and mineral nutrients (nitrogen and phosphorus) from the wastewater to carbon dioxide and new biomass in the presence of oxygen (Deseau I., 2020). The bonds of organic matter are broken by the microorganisms to generate ATP-molecules which are later used to build up new biomass (up to 50% of the original organic load) with a part of the biodegraded material (Diels L. 2017; Deseau I. 2020). As oxygen is the most efficient electron acceptor to produce ATP for the aerobic bacteria, oxygen-rich conditions are required to establish an efficient conversion process (Deseau I., 2020). To create this oxygen-rich conditions, continuous aeration is required resulting in an energy-demanding process (1.5 kWh for oxidation of 1kg COD) with a high biomass production creating a huge sludge waste stream (Diels L. 2017). Today the most commonly used aerobic wastewater treatment technology for municipal sewage is the conventional Activated Sludge Process (ASP), which is also used at Kanpur (Hernalsteens.,2015). The ASP consist of a three-stage treatment train, containing primary, secondary and tertiary treatment technologies (Hernalsteens M.A.,2015). In the primary treatment process, particulate solids are settled as the major part of these solids are non-biodegradable for aerobic bacteria. Primary settling is followed by secondary or biological treatment, which has the largest contribution to the improvement of the water quality (Hernalsteens M.A.,2015). Finally, the new formed biomass during aerobic conversion is eliminated from the water during tertiary treatment.

In an anaerobic environment, other electron acceptors are used by the metabolism of microorganisms resulting in a synergism of reactions and finally the production of carbon dioxide, methane and new biomass (Vingerhoets R,. 2019). As anaerobic microorganism achieve smaller energy yields due to the energetic unfavorable electron acceptors, the energy investment in cell synthesis is rather low resulting in a low new biomass production (10% of original organic matter) (Diels L., 2017). A more detailed description of the anaerobic digestion process can be found in section 2.6.3. By degrading organic matter in an oxygen-free environment, microorganism will produce biogas which can be used as an alternative energy source (Deseau I., 2019). The anaerobic reactors are mainly used to treat water with high organic strength (e.g. agricultural, industrial and food processing wastewaters) (Hernalsteens M.A.,2015). For instance, the Upward-flow Anaerobic Sludge Blanket Reactor (UASB), the most conventional anaerobic bioreactor, is composed of a sludge bed containing microorganism that form granules (Hernalsteens M.A., 2015). Due to their high sedimentation velocities (up to 100 $m.h^{-1}$), these granules are not washed out during treatment (Hernalsteens M.A.,2015).

Anaerobic conversion has some major advantages in comparison to aerobic conversion. Due to the absence of aeration, the anaerobic digestion process demands a lower energy input and produces less biomass (Deseau I., 2019). The reduced sludge production decreases costs of sludge processing and abduction (Deseau I., 2019). Moreover, methane-rich biogas is produced during anaerobic digestion, which is a valuable energy source reducing operational costs and environmental footprint (Deseau I., 2019).

However, the anaerobic treatment can exclusively be used to treat concentrated waste streams, while aerobic treatment is more adapted to treat domestic sewage with low organics (0.1-0.5g/L) (Deseau I., 2019). Furthermore, anaerobic systems need to be heated to mesophilic conditions (25°C-40°C) which can increase the operational costs (Deseau I., 2019). In contrast to aerobic systems that easily operates at colder temperatures. In addition, the conventional anaerobic systems tend to realize a lower effluent quality in comparison to ASP because of the slow growth rates of the microorganisms (Deseau I., 2019).

Despite the major advantages of anaerobic treatment and the warm Indian climate that supports anaerobic treatment, conventional anaerobic systems are not readily applicable for domestic sewage treatment due to the low organic load of domestic wastewater and bad effluent quality. The new waste treatment approach Andicos^{TM}, integrating ultrafiltration of wastewater with anaerobic digestion of the carbon-rich retentate and organic municipal matter into one system, could overcome these problems and facilitate the implementation of anaerobic conversion to save money and environment. Through ultrafiltration, the Andicos^{TM} can generate an excellent effluent quality and produce a more concentrated retentate in the tank. The anaerobic digestion process however requires a high organic matter concentration, therefore municipal organic waste is added to the retentate resulting in the production of a carbon-rich stream highly suitable for anaerobic digestion. Due to the high solid municipal waste production with a high fraction of organics in India, this technology is highly suitable for India. This alternative water treatment system thus also contributes to settle the municipal waste problem of India. The high biowaste fraction of municipal Indian solid waste suggests a high potential for anaerobic digestion and makes this an interesting waste-to-energy option (Breitenmoser L., 2019). Through the incorporation of municipal organic waste in the anaerobic digestion process, the Andicos^{TM} technology could contribute to the transition into a more sustainable solid waste management in Kanpur as currently the major part is landfilled, burned or composted. Therefore, VITO, Ion Exchange and IIT Kanpur are working on a promising project to demonstrate a pilot-scale Andicos^{TM} treatment plant at the existing Jajmau site (Pavitra Ganga, 2020).

2.6 Andicos^{TM}: A new treatment technology

Andicos^{TM} technology (Anaerobic Digestion by Combining Organic Waste and Sewage) combines ultrafiltration of wastewater to generate excellent effluent quality, with anaerobic digestion of the concentrated retentate to produce biogas (figure 2.8). The technology aims to create an energy-neutral sewage water treatment system (Diels L., 2017, Heylen C.,2018). As the filtration process is retaining organic matter of the influent, the retentate is rich in carbon. Efficient anaerobic digestion however requires a high concentration of organic matter, therefore food waste is added to the system before the anaerobic digestion stage (Heylen C, 2018). The carbon-rich mixture is anaerobically digested to provide biogas and an organic fertilizer (Diels L., 2017). To secure an efficient functioning of the system, an optimal equilibrium between effluent quality, membrane fluxes, concentration factor of the retentate and organic matter loss have to be sought.

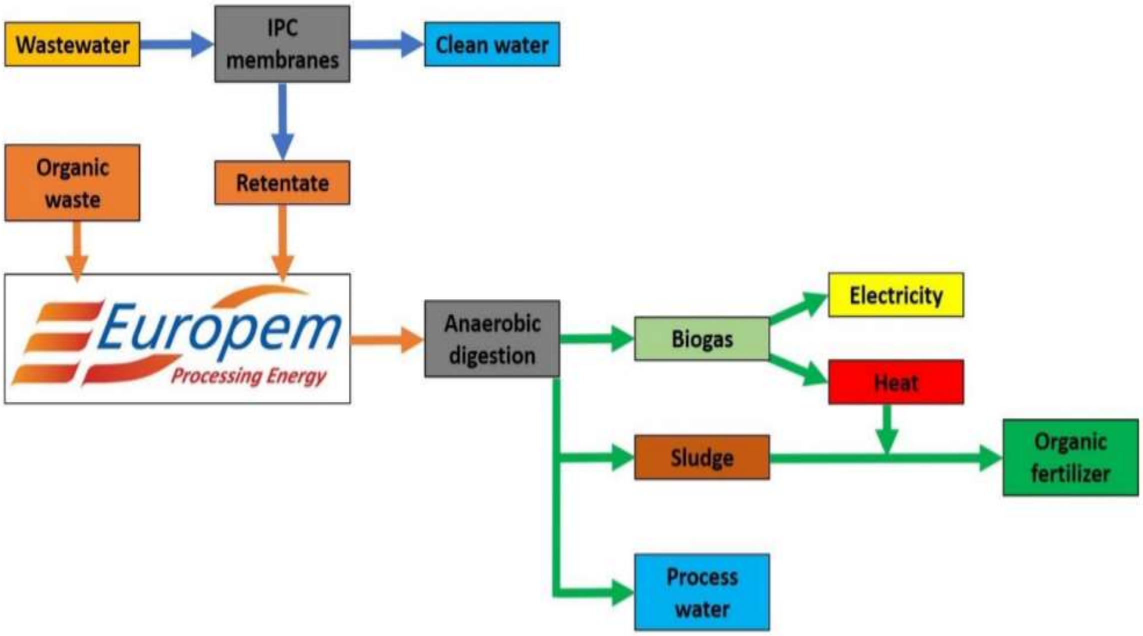

Figure 2.8 *Operation scheme of Andicos^{TM} technology concept (Diels L., 2017; Troch M., 2018)*

The high energy consumption and land occupation are major financial and environmental disadvantages of the current wastewater treatment facilities. The Andicos^{TM} technology can overcome these hurdles by treating water on a relatively small surface, while being a net energy producer instead of a net energy consumer (Diels L., 2017; Heylen C., 2018). Combining both energy production and water treatment is a model example of how green technology can transform an environmental problem into a valuable resource (Heylen C., 2018)

The different system processes will be extensively described in the following sections to increase the reader's understanding of the Andicos^{TM} technology.

2.6.1 Ultrafiltration

During the first step of Andicos^{TM}, wastewater is treated by ultrafiltration. The membrane tank is filled with sewage, in which the ultrafiltration membranes are submerged. Water is sucked through the membranes by a pump. The small pores of the membranes prevent the major part of suspended solids leaving the tank and thus these particles are retained in the membrane tank. Consequently, ultrafiltration is producing at the same time a purified effluent and concentrated retentate in the membrane basin (Heylen C., 2018). As membrane ultrafiltration is retaining particles with a larger diameter compared with the pore size, no bacteria will be present in the effluent. This can be a major advantage for human health as many waterborne diseases have a bacterial origin (Van Damme S., 2020). When the effluent is used as irrigation water, the removal of pathogenic bacteria out of the wastewater is crucial to avoid infections entering the crop production systems.

Compared with other traditional treatments, the membrane technique has some major advantages. The technology can easily be upscaled and linked with other processes, because the membrane only acts as a barrier and thus does not consume the present organic matter (Heylen C. 2020). However, as barrier-based technology the process is prone to fouling and concentration polarization by the accumulation of particles in the pores and on the surface of the membranes (Heylen C., 2018). The accumulation of the retained particles on the membrane will increase the resistance of the membrane and thereby decrease the system's performance (Heylen C., 2018; Verliefde, 2017). To overcome the increased resistance and maintain the desired permeate flux, the transmembrane pressure (TMP) has to increase. For the same flux through the membrane, more energy will be consumed. In other words, the flux will decline over time if the same TMP is maintained (figure 2.9) (Heylen C., 2018; Verliefde, 2017).

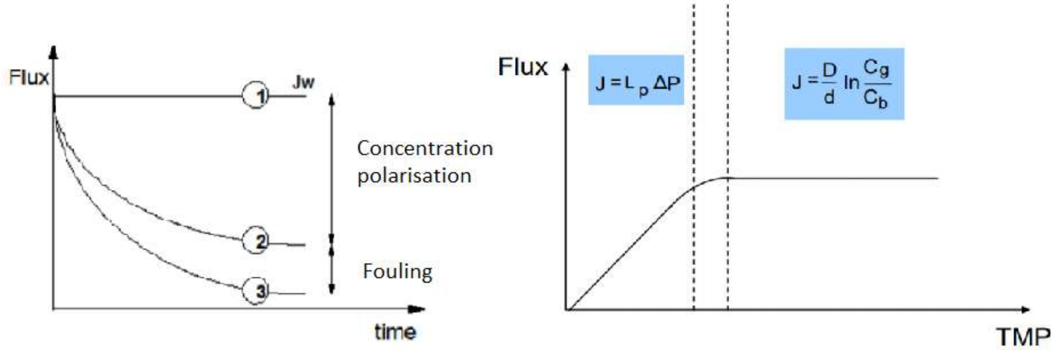

Figure 2.9 *Left: Evolution of flux over time for a constant TMP. The graph illustrates that the flux declines as a result of concentration-polarization and fouling. Right: The evolution of flux by an increasing TMP. (Diels L., 2020; Heylen C., 2018)*

According to ability to remove fouling by physical cleaning, membrane fouling can be categorized in reversible and irreversible fouling (Diels L. 2020). Reversable foulants are loosely attached to the membrane surface and associated to cake layer formation. The cake layer is formed of particles with larger size in comparison to the pore diameter, therefore these particles accumulate on the membrane surface and increase the resistance of the permeate flow (Deseau I., 2019). The deposited substances onto the membrane surface can be eliminated by backwashing and relaxation. The deposition of small particles and macromolecules inside the membrane pores can cause irreversible fouling. The irreversible fouling cannot be removed by backwashing and relaxation (Deseau I., 2019).

As the TMP increases in the pressure-controlled region, the flux will increase with a declining rate and finally a plateau will be reached at high TMPs (mass-transfer controlled region) (Heylen C. 2018). This is shown in figure 2.9. The maximal flux depends on the particle concentration and temperature (Heylen C., 2018; Verliefde, 2017). The negative effects of fouling and concentration polarization are reduced by applying physical backwash and chemical cleaning. However traditional flat sheet membranes are not able to withstand backwash pressure above 0.3 bar and therefore their physical cleaning potential is rather low

(Heylen C. 2018). Integrated Permeate Channel (IPC) membranes were developed by VITO to counter this problem. The IPC membrane is shown in figure 2.10. The IPC membrane envelope consists of two polyvinylidene fluoride based ultrafiltration membranes spaced apart by monofilament thread forming an open 3D fabric structure which serves as drainage channel for the extracted permeate water (Blue Foot Membrane, n.d.). The different membrane layers of the IPC membrane are strongly attached to the spacer, which increases the maximal applicable backwash pressure to more than 2 bar. The average pore size of this IPC membrane is 80nm (Dotremont C., 2011; Heylen C., 2018).

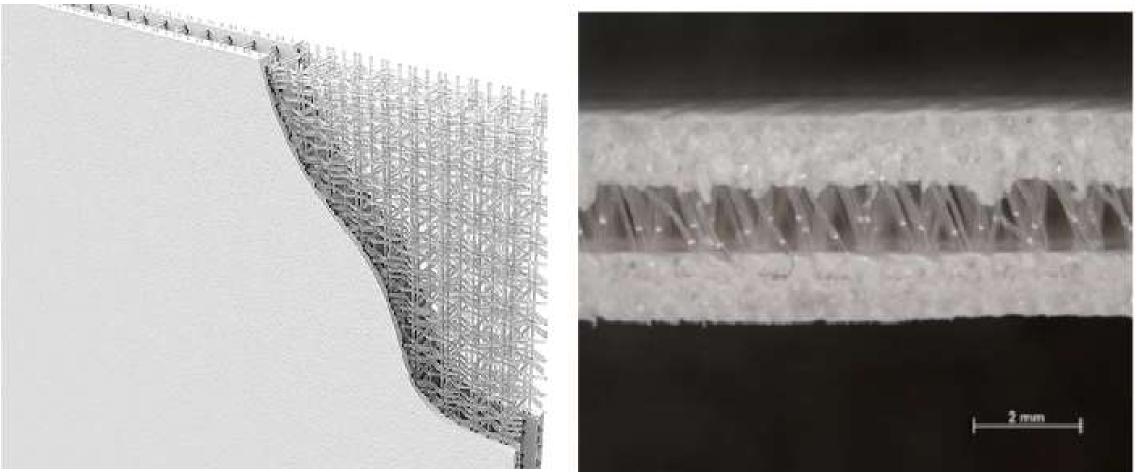

Figure 2.10 *Intergrated Permeate Channel membranes (Blue Foot Membrane, n.d.)*

2.6.2 Carbon-rich stream

The major part of the organic matter is retained in the membrane tank resulting in a carbon-rich stream. However, the organic matter concentration of the retentate is not sufficient to guarantee an economic sustainable anaerobic digestion process. To reach an optimal carbon concentration, processed organic waste is added to the system (Diels L., 2017). According to Kumar K.N. (2009), Indian organic waste is defined by a COD content of 0.16 gram COD per gram food waste (Kumar K.N, 2009; Heylen C., 2018). The solid food waste and sewage sludge are processed to a homogenous feed material for the anaerobic digester by a pretreatment technology of Europem. Applying this technology before digestion results in increased biogas yields. Other major advantages of this technology are its compactness and its capacity to execute upstream sorting (Diels L., 2017; Heylen C., 2018).

2.6.3 Anaerobic digestion

In an oxygen-free environment, other electron acceptors are used by the metabolism of micro-organisms resulting in the production of methane. Therefore, anaerobic degradation of organic matter results in the production of energy (Mes T.Z.D., 2003; Heylen C.,2018). The anaerobic digestion process is a synergism of reactions, whereby the end-product of one group of bacteria is the substrate for another group of bacteria. The digestion process consists of four phases: hydrolysis, acidogenesis, acetogenesis and methanogenesis. (Wett at al. 2014) Figure 2.11 gives a simplified schematic scheme of the anaerobic digestion process.

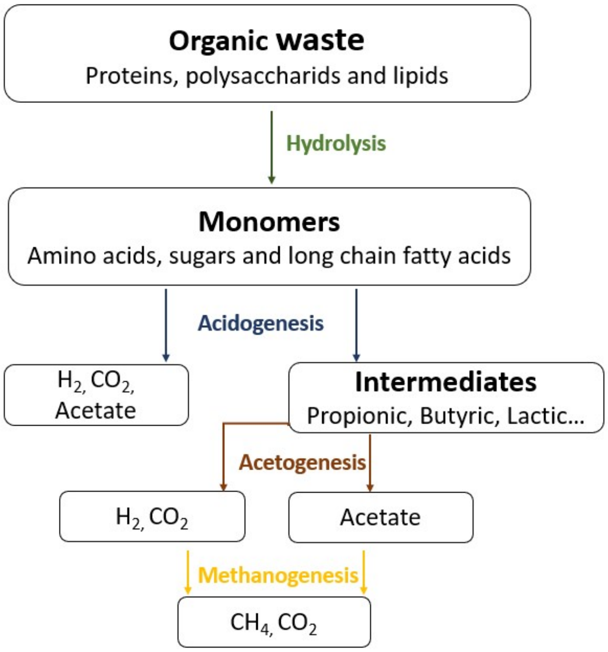

Figure 2.11 *The digestion process with its four phases: hydrolysis, acidogenesis, acetogenesis and methanogenesis.*

The digestion processes finally lead to the creation of liquid digestate, solid digestate and biogas. The biogas is a mixture of carbon dioxide (25%-45%) and methane (55-75%), which can be used to generate both electricity and heat or to derive natural gas. Multiple factors influence the methane yield such as pH, temperature, retention time, mixing, nutrient concentrations, toxic compounds and feed characteristics (Mes T.Z.D., 2003; Heylen C., 2018). Before methane formation can take place, large polymers have to be hydrolyzed to their building stones (sugars, amino acids, glycerol and long chain fatty acid). Subsequently acidogenic bacteria transform the organic compounds to higher organic acids, which are further degraded to acetate and hydrogen during acetogenesis. The formed acetic acid and hydrogen are the substrate for the methanogenic bacteria. Acetate acid and carbon dioxide accept the electrons of hydrogen during the anaerobic respiratory of methanogens, which results in the formation of methane. (Vingerhoets R., 2019)

Microorganisms are not able to hydrolyze all organic matter due to the molecular structure and inaccessibility of some carbon molecules and thus not all organic carbon is converted to biogas (Mes T.Z.D., 2003; Heylen C. 2018,). The total anaerobic biodegradability is defined by the quantity of methane produced after 50 days. The total biodegradability of tannery wastewater is only 15%, whereas the organic fraction of wastewater can be degraded for 90%. (Mes T.Z.D., 2003; Heylen C.,). The highest biodegradability is recorded at a temperature of 37°C (Vingerhoets R., 2019). Process deterioration may occur in anaerobic digestion due to reactor acidification. Overloading the reactor can result in the build-up of volatile fatty acids which are assembled by the acidogenic and acetogenic bacteria and implies on a kinetic disbalance between acid consumers and producers (Franke-Whittle et al., 2014). An excessive volatile fatty acid concentration results in a pH-drop and reduces the productivity of the methanogens.

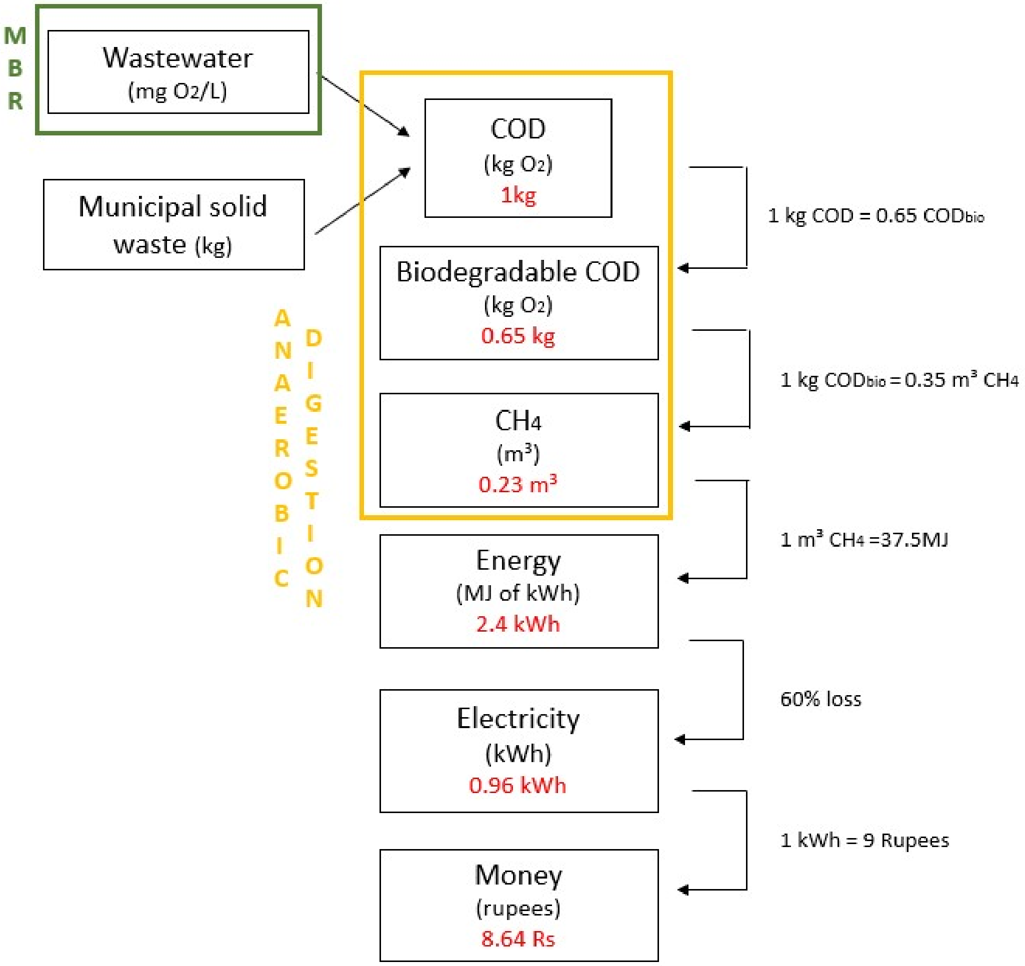

Figure 2.12 *Schematic representation of the validation of organic matter to money.*

Figure 2.12 shows a schematic representation of the validation of organic matter to money (Heylen C., 2018). Anaerobic digestion is only economically feasible in countries with a sufficient high ambient temperature, because of a higher methane yield per amount of organic matter (Diels L. 2017). Along with this, Indian wastewater is characterized by high COD concentrations, which is favorable for the production of the carbon-rich retentate (Heylen C. 2018). These factors combined with the modular form of the Andicos^{TM} could incentify the Indian government to invest in this treatment technology (Heylen C., 2018; Strybos, 2017).

3. Materials and methods

The Andicos^{TM} treatment technology was optimized to the Indian constraints during a test period of 6 weeks at the Engineering Department of Indian Institute of Technology Kanpur. Moreover, a comparison between the efficiency of the Andicos^{TM} technology and the current ASP facility was made.

3.1 Wastewater sampling

The research project aims to find the optimal operational settings of the Andicos^{TM} technology for the Indian constraints to facilitate the implementation of the future pilot-scale Andicos^{TM} treatment facility. As mentioned before, the pilot-scale treatment facility is planned to be built on the existing Jajmau water treatment site. Due to recent sewer trunk renovations, the Jajmau STPs receive a considerable volume of wastewater from the Sisamua drain. As membranes are sensitive to damage from sharp objects, the pilot project will use the primary effluent of the activated sludge STP. Samples of the primary effluent and tertiary effluent treated by the ASP of Jajmau were taken on February 18th, February 27th and March 7th. The primary effluent was pumped into 80L-vessels and transported by a minivan to the IIT campus (2 hours' drive). (Figure 3.1). After transportation, the vessels were placed in a cold storage room (10°C) to prevent the decomposition of the organic matter. The collection of the Jajmau STP wastewater was time and cost intensive, therefore pretesting of the Andicos^{TM} system was done by using IIT Campus wastewater. During the pretests, the campus wastewater was sampled at a daily base from a local sanitary block. (Figure 3.1)

Figure 3.1 *The wastewater sampling at the Jajmau STP (left) and at the IIT sanitary block (right).*

3.2 Optimization of the parameter settings of the Andicos^{TM} technology

The membrane unit of the IIT laboratory consists of a membrane tank with three IPC membranes. The membranes are fixed into a metallic holder to keep them submerged in the membrane tank of 42.7L. A perforated tube at the bottom of the membranes provides a continuous transmembrane airflow over the flat-sheet membranes, which prevents the accumulation of organic matter on the outside of the membrane and thus reduces the fouling and concentration polarization (Heylen C., 2018). The continuous airflow, generated by a compressor with a flow range from 0.2 to 1.1N.m³/h, also functions as a mixing device. A peristaltic pump sucks the wastewater through the membrane. The generated pressure and flow are respectively measured by an in-line pressure transmitter and an in-line flow meter. Finally, the produced permeate was captured and stored in a 40L-vessel. The sewage level in the membrane tank is held constant by means of a tuning fork. When the level drops below the tuning fork, sewage is pumped into the tank. The laboratory-scale filtration system is shown in figure 3.2.

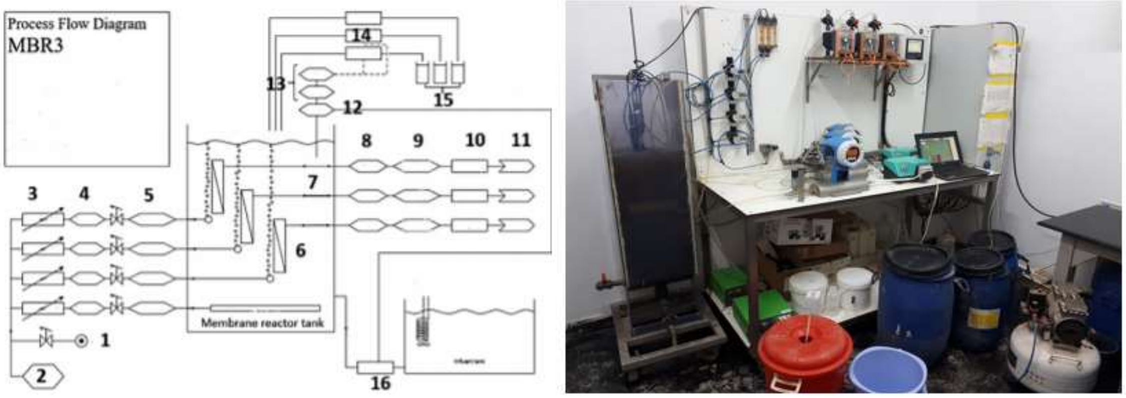

Figure 3.2 *Schematic (left) and photographic (right) representation of the laboratory-scale filtration set-up: The filtration installation is composed by: (1) the pressed air, (2) the pressure monitoring, (3) the reduced valve, (4) the pressure measurement, (5) the flow measurement, (6) the membranes, (7) membrane tank, (8) pressure meter, (9) flow meter, (10) pump, (11) permeate, (12) tuning fork, (13) pH probe, (14) temperature probe, (15) anti-foam probe, (16) influent tank. (Heylen C., 2018)*

The measurement and pumping devices were connected to a computer with the software program Mefias (Figure 3.3). Mefias co-ordinates filtration, backwash and relaxation by controlling parameters such as flow, flux and TMP (Heylen C., 2018). The user can define these control parameters through a graphical user interface. Each membrane can be controlled independently. A test run consists of an undefined number of cycles because it remains working until switched-off. However, as a membrane reaches a TMP above 0.5 bar, it is stopped automatically (Heylen C. 2018). One cycle lasts 10 minutes (9 minutes of filtration, 40 seconds of backwash and 20 seconds of relaxation).

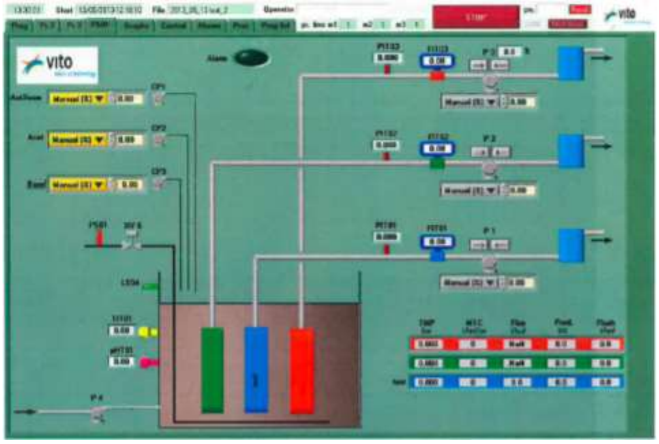

Figure 3.3 shows the Mefias interface. The results of the automatically measured parameters are shown on this interface. Besides, various settings of the three membranes (blue (membrane A), green (membrane B) or red (membrane C)) could be changed independently through the Mefias program. (Heylen, C. 2018; Vito, 2015).

The first 2 weeks of the research project were used as the pretesting phase to investigate some key parameters of the system, while using IIT wastewater as influent. The main process parameters that were investigated were flux of filtration, backwash strength, sewage water characteristics (influent, membrane tank and effluent), loss of organic matter and TMP. Airflow was set constant at 0.7 Nm^3/h because this parameter was hard to change. Nevertheless, the importance of this parameter on the operational cost (electricity consumption) and concentration polarization cannot be underestimated (Heylen C. 2018). The tested parameter settings can be found in table 3.1. The flux of filtration ranged between 10 and 15 $L.h^{-1}.m^{-2}$, while the backwash strength was set between 15 and 30 $L.h^{-1}.m^{-2}$ during the long-term experiments. Worth mentioning is that the short-term critical flux was assessed by the Kevin Young-June Choi method.

Afterwards, another 3 weeks of testing was carried out with the primary effluent of the Jajmau ASP. The process parameters of this experiment were selected building on experience of the first experiment. Again, the main settings that were investigated were flux of filtration, backwash strength, sewage water characteristics (influent, membrane tank and effluent), loss of organic matter and TMP. The assessed parameters settings can be found in table 3.1. For the long-term Jajmau experiments, the flux of filtration ranged between 10 and 30 $L.h^{-1}.m^{-2}$ and the backwash strength had a value between 15 and 45 $L.h^{-1}.m^{-2}$. Besides, the short-term critical flux was assessed by the Kevin Young-June Choi method.

A data file on the system parameters (temperature, pH, pump debits, fluxes, TMP, Mass Transfer Coefficient for a given temperature (MTC), etc.) was generated by Mefias. Every 10 seconds, the program measured all system parameters .

Table 3.1 *Summary of the filtration experiments executed at IIT Kanpur. Experiments tagged with the same color had a continuous retentate built-up.*

Origin	Sample date	Test date	Water sample	(s)COD	TSS	TKN	NH_4^+	SO_4^{2+}	Cr	Filtration flux (L.m².h^{-1})			Backwash strength (L.m².h^{-1})			Membrane tank Volume (L)	Retentate removal (L)
										Memb A	Memb B	Memb C	Memb A	Memb B	Memb C		
IIT	6/02/2020	6/02/2020	I, R, (3X) E	x	x					10-35	10	15	15-52.5	15	22.5	42.7	-
IIT	10/02/2020	10/02/2020	I, R, (3X) E	x	x					10	10	15	15	20	22.5	42.7	-
IIT	11/02/2020	11/02/2020	I, R, (3X) E	x	x					10	10	15	15	20	22.5	42.7	-
IIT	12/02/2020	12/02/2020	I, R, (3X) E	x	x					10	10	15	15	20	22.5	42.7	-
IIT	13/02/2020	13/02/2020	I, R, (3X) E	x	x					10	10	15	15	20	22.5	42.7	-
Jajmau	18/02/2020	19/02/2020	I, R, (3X) E	x	x				x	10	10	15	15	20	22.5	42.7	-
		20/02/2020	I, R, (3X) E	x	x				x	10	10	15	15	20	22.5	42.7	-
		21/02/2020	I, R, (3X) E	x	x				x	10	10	15	15	20	22.5	42.7	-
		22/02/2020	I, R, (3X) E	x	x				x	10	10	15	15	20	22.5	42.7	9.2
		23/02/2020	I, R, (3X) E	x	x					10	10	15	15	20	22.5	42.7	9.2
		24/02/2020	I, R, (3X) E	x	x					10	10	15	15	20	22.5	42.7	9.2
		25/02/2020	I, R, (3X) E	x	x					10	10	15	15	20	22.5	42.7	-
Jajmau	27/02/2020	27/02/2020	I, R, (3X) E	x	x					15	20	25	22.5	30	37.5	42.7	14.1
		28/02/2020	I, R, (3X) E	x	x					15	20	25	22.5	30	37.5	42.7	14.1
		29/02/2020	I, R, (3X) E	x	x					15	20	25	22.5	30	37.5	42.7	14.1
		1/03/2020	I, R, (3X) E	x	x					15	20	25	22.5	30	37.5	42.7	14.1
		2/03/2020	I, R, (3X) E	x	x					15	20	25	22.5	30	37.5	42.7	6.7
		3/03/2020	I, R, (3X) E	x	x					15	20	25	22.5	30	37.5	42.7	6.7
		4/03/2020	I, R, (3X) E	x	x					15	20	25	22.5	30	37.5	42.7	-
Jajmau	7/03/2020	8/03/2020	I, R, (3X) E	x	x					30	25	-	45	37.5	-	32.3	6.2
		9/03/2020	I, R, (3X) E	x	x	x	x	x		30	25	-	45	37.5	-	32.3	6.2
		10/03/2020	I, R, (3X) E	x	x	x	x	x		20	25	-	30	37.5	-	32.3	6.2
		11/03/2020	I, R, (3X) E	x	x	x	x	x		20	25	-	30	37.5	-	32.3	6.2
		12/03/2020	I, R, (3X) E	x	x	x	x			20	25	-	30	37.5	-	32.3	6.2
		13/03/2020	I, R, (3X) E	x	x					20	25	-	30	37.5	-	32.3	6.2
		14/03/2020	I, R, (3X) E	x	x					20	25	-	30	37.5	-	32.3	-

3.3 Digestion unit

Three digestors were built to evaluate the anaerobic digestibility of the retentate and food waste. Each digestion installation consisted of a 2L-digestion bottle with a sludge inlet, a sludge outlet and a gas channel, which was connected to a gas measuring apparatus based on a water displacement mechanism (Figure 3.4). Three different feeds were used to fill the digestors: retentate, food waste dissolved in water and food waste dissolved in retentate. On February 27th , the digestors were started with 300mL inoculum, 1300mL of their respectively feed and 400 mL headspace. The starting feeds contained a lower concentration of food waste to prevent overloading. Afterward, every day 80 mL digestate was removed from each digestor and 80 ml feed was added to each digestor. To secure a volatile solid load of 1.5 $g.L^{-1}.day^{-1}$ for the ‘kitchen waste’ digestor, its feed contained 175 grams of IIT campus kitchen waste diluted in 1L water. For the feed of the ‘kitchen waste + retentate’ digestor, the same dilution ratio was used. The gas formation was continuously measured with an interval of 24 hours.

Figure 3.4 *The digestor set-up (left) and the different feeds (right).*

3.4 Chemical analyses

During the membrane experiments, five samples (influent, retentate and 3X effluent) were taken every day. For each sample, the total suspended solids (TSS), total chemical oxygen demand and soluble chemical oxygen demand were assessed. Kjeldahl-Nitrogen, ammonia, sulfate and total chromium were only measured several times because of time and equipment limitations. The scheme of the chemical analyses is shown in table 3.1 and the used analytical methods can be found in appendix A. Besides, all mentioned contaminants were analyzed for the samples of the tertiary effluent of the Jajmau ASP.

The feed of the different digestors was made in batches of 2 liters. Every time a new batch was created, the batch was tested on COD, volatile solids and total solids. As acidity can become a major problem by food digestion, the pH of the digestate was measured every day. Besides pH, COD and alkalinity of the digestate were occasionally measured.

3.5 Statistical Analysis

Anova tests were performed on the generated data to examine the significance of the influence of several factors on the TMP or/and the water quality. Anova is a statistical method, which compares means of more than two groups by assessing the relative size of variance among group means to the average variance within groups (Kim H.Y., 2014). As the null-hypothesis of Anova assumes no impact of the factor, a low p-value indicates a significant impact of this factor on the assessed parameter. The analyses of variances presume similar variances between groups and normal distribution of the data (Heylen C. 2018).

Besides, different effect tests evaluated the independent and/or mixed impact of multiple factors on the TMP and effluent quality. The investigated parameters included the origin of wastewater, type of membrane, influent quality (multiple factors), retentate quality (multiple factors), flux of filtration and backwash strength.

3.6 Derived system characteristics

The performance of the membrane technology was assessed by means of removal efficiency towards TSS, (s)COD, Total Kjeldahl Nitrogen (TKN), NH_4^+, SO_4^{2-} and total chromium. Besides, the carbon concentration efficiency was evaluated and the Effluent Quality Index (EQI) was estimated based on the samples of the effluent.

The removal efficiency is the ratio of the amount of the pollutant removed from the wastewater to the total amount of pollutant that enters the water treatment system (Heylen C., 2018):

$$removal\ efficiency\ (\%) = \frac{C_{influent} - C_{effluent}}{C_{effluent}} * 100$$ Equation 3.1

The concentration efficiency is the ratio of the amount of pollutant in the retentate to the amount of pollutant that enters the wastewater treatment system. This parameter illustrates the ability of the system to concentrate the influent (Heylen C., 2018):

$$Concentration\ efficiency\ (\%) = \frac{C_{retentate} - C_{influent}}{C_{influent}} * 100$$ Equation 3.2

The Effluent Quality Index quantifies the effluent pollution load to a receiving water body into a single term. It includes loads of TSS, COD, Kjeldahl-N (NH_4^+ and organically bound nitrogen), NO_3^+ and BOD_5 of the produced effluent. In addition, the index takes into account the ecological impact of each contaminant by including a weight factor in the formula (Heylen C. 2018):

$$EQI\ = 2 * TSS\ + 1 * COD + 30 * TKN + 10 * NO_3^+$$ Equation 3.3

The contaminant concentrations (mg/L) are multiplied with the volume of wastewater per day (L/day) to yield the EQI (tons/day) (Heylen C., 2018).

3.7 Economic feasibility

To evaluate the economic feasibility of the Andicos^{TM} system, a cost estimation was performed which takes into consideration both investment and operational costs. The investment cost analysis determines the monetary inputs (expressed in Rs) required for land acquisition and infrastructure building (Heylen C., 2018). The operational costs take into account the costs of energy use, chemicals and maintenance to properly operate the treatment facility (Heylen C., 2018). In order to get an adequate estimation of the costs per treated volume (Rs/MLD), the long-term stable flux of the membranes had to be determined (Heylen C., 2018).

The anaerobic digestion generates energy and therefore reduces the overall costs. The energy production of the anaerobic digestion is estimated by using some theoretical assumptions. First, it is assumed that 1 m^3 of produced gas contains 0,65 m^3 methane. One cubic meter of methane contains 37.5 MJ of chemical energy. However, the low conversion efficiency of methane to electric energy results in an energy loss of about 60% to heat. Consequently, 1 m^3 of digestor gas yields 9.75 MJ of electric power which has a value of 24.38 rupees (2.5 Rupees/MJ electricity) (Heylen C. 2018).

4. Results

4.1 Membrane filtration settings assessment

The main objectives of the membrane filtration experiments were to find an adequate filtration flux and COD concentration factor to ensure a stable membrane functioning, an adequate effluent quality and a high carbon recycling. Different filtration settings were assessed during the testing period. Every ten seconds a data line was generated in the Mefias file, which contained information about temperature, pH, pump debits, fluxes, TMP and MTC. A matrix containing all parameters (mean and standard deviation) per cycle was generated to facilitate the data analysis. Next to the automatic measurement of these data, the (soluble) COD and TSS of each fraction (influent, retentate and effluent) were measured with a 24-hour interval. The results of the filtration experiments can be found in Appendix B.

4.1.1 Factors influencing the TMP

Currently, no relevant data exist on wastewater treatment by Blue Foot Membranes, therefore stable filtration settings have to be looked for from scratch. Concentration polarization and fouling are the main disadvantages of the filtration process. As the optimal system has a flux as high as possible with little to no concentration polarization/fouling, it was key to find this most favorable flux. The impact of the flux of filtration (from 5 to 35 $L.h^{-1}.m^{-2}$) is assessed with regards to their short-term and long-term effects on the TMP. These results will be discussed in the next sections. However, some other factors as membrane efficiency, strength of backflush, Total Suspended Solids concentration and origin of wastewater can influence the filtration process as well. The impact of these parameters will be evaluated in this section.

An effect test on 10297 lines of data revealed that membrane A and membrane B had a similar effect on the TMP, while membrane C acted differently. As all other parameters were kept constant, membrane C would have a significantly higher TMP than the other two membranes. The higher TMPs for membrane C cannot be explained by its intrinsic properties but are due to a deviating airflow. While the flux of air was fixed for membrane A and B (0.7 Nm^3/h), the airflow of membrane C was uncontrollable and probably lower. The effect test also revealed that the flux was positively correlated with TMP ($p=<0.0001$).

Pairwise comparison between the TMPs of the two tested backwash strengths, 150% and 200% of the filtration flux, indicated that there was a significant difference according to backwash strength. The backwash strength of 150% averaged the highest TMP (mean: 0,063 bar), compared to the backwash strength of 200% (mean: 0,055 bar). However, a stronger backflush also results in a lower production of effluent (29.8$L.day^{-1}$ vs 30.9$L.day^{-1}$).

To assess the influence of TSS concentration on the filtration process, another Anova-test was performed. For a fixed flux (15 $L.h^{-1}.m^{-2}$), membrane (MBR A), backwash strength (150%) and wastewater type (Jajmau), the TMPs for a high TSS concentration (8557 mg/L) were compared to the TMPs for a low TSS concentration (2454 mg/l). The test indicated that the TMP increased significantly with an increase of TSS concentration ($p=<0.0001$). However, the difference averaged only 0.009 bar.

Finally, the impact of wastewater origin (IIT or Jajmau) was evaluated. The type of wastewater played a significant role in the TMP of the three membranes. ITT wastewater provoked a stronger transmembrane pressure increment than the Jajmau wastewater for the same fluxes.

4.1.2 Optimization of filtration flux

To minimize the impact of concentration polarization/fouling on the filtration process, the maximum permeate flux that can be sustained without significant fouling has to be defined. High variation in TMP levels within one filtration cycle indicates on increased importance of fouling (Heylen C, 2018). Experimentally, a flux stepping protocol can be used to evaluate the critical flux (Miller et al., 2014) . The flux was gradually increased for one-hour, constant flux intervals from 10 to 35 L.h^{-1}·m^{-2}, while the TMP was continuously measured (Figure 4.1) (Miller et al., 2014). The variation of TMP within a filtration cycle increased remarkably from flux 25 L.h^{-1}.m^{-2} for both types of wastewater. For the IIT wastewater, the increment was considerably higher. The measured critical fluxes for the IIT and Jajmau wastewaters are respectively 29.42 and 28.15 L.h^{-1}.m^{-2} .

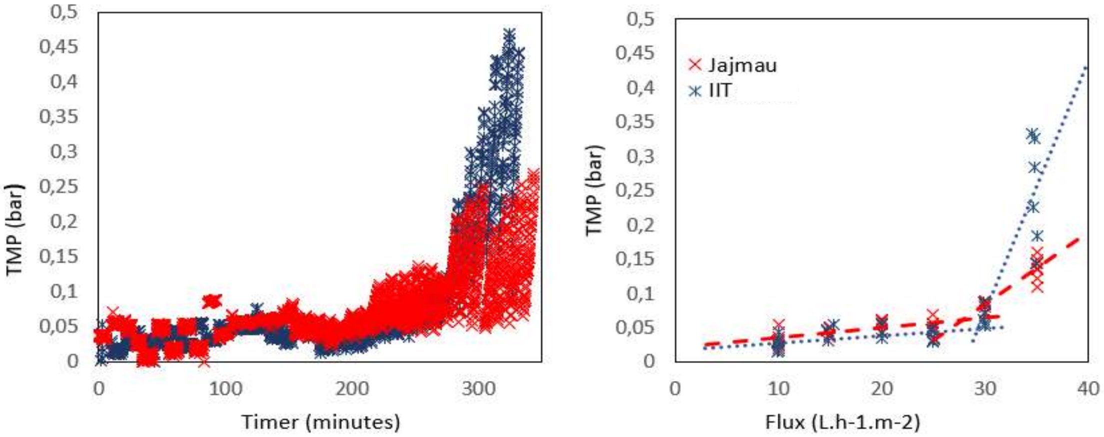

Figure 4.1 Evolution of TMP over time by an increasing filtration flux (from 10 to 35 L.h^{-1}.m^{-2}) for IIT and Jajmau wastewater (left).To assess the critical flux, the average TMP per cycle was plotted against the filtration flux (right)

Since each flux-step is sustained only for an interval of 1 hour, the flux stepping protocol is unusable to forecast fouling rates for long-term filtration processes (Le Clech et al. 2003). To overcome this drawback, long-term experiments have been executed for both ITT and Jajmau wastewater. To secure a continuous filtration process, the first long term experiment (96 hours) was carried out with rather low fluxes. The fluxes of filtration for membranes A, B and C were respectively 15, 15 and 10 L.h^{-1}.m^{-2}. Membrane A and C both had a backwash strength of 150% compared to the filtration flux, while the backwash flux of membrane B was set to be two times the filtration flux. The evolution of TMP over time for water coming from the ITT sanitary block is shown in figure 4.2. The TMP increased with a nearly constant rate for all membranes. The increment rates in TMP of membranes A, B and C were respectively 0.0015, 0.0011 and 0.0004 bar/hour. As membranes A and B have similar TMPs for the same process settings, the slower increase of TMP for membrane B can be attributed to its stronger backwash flux. Although membrane C is characterized by higher TMPs than the other membranes, the lower flux of membrane C during this test caused a more stable filtration process.

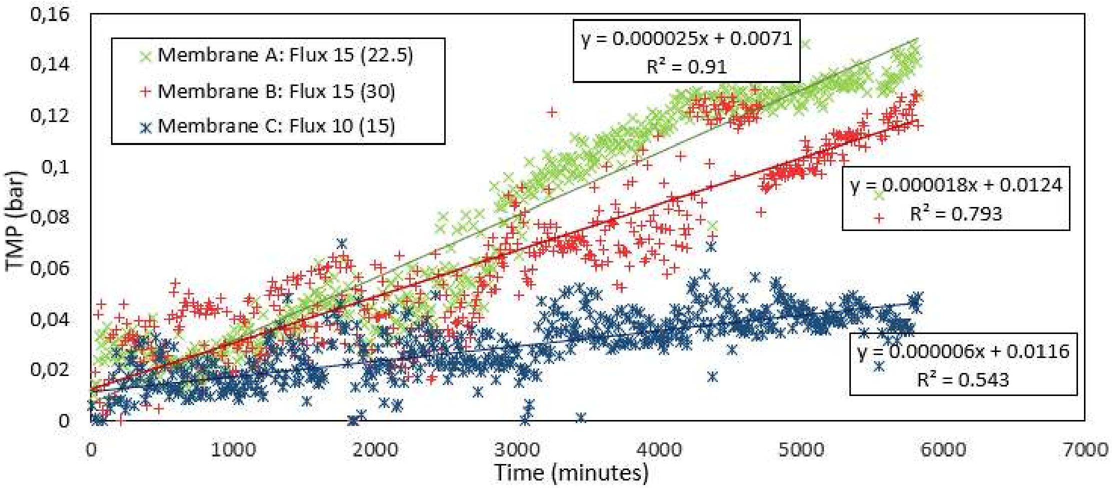

Figure 4.2 *Evolution of TMP per membrane for IIT wastewater.*

During the long-term filtration test on the IIT wastewater, low TMPs with a continuous increase were recorded. Because of these decent results, a long-term filtration test with the same process settings was executed on the Jajmau wastewater. However, this experiment was operated for 150 hours instead of 96 hours. Figure 4.3 shows the development of the TMP over time for membrane (A, B and C) for water coming from the Jajmau wastewater treatment plant and with an average membrane tank TSS concentration of 5601 ± 2006 mg/L. The membranes (A, B and C) were respectively operating with a flux of 15, 15 and 10 $L.h^{-1}.m^{-2}$ and a backwash flux of 22.5, 30 and 15 $L.h^{-1}.m^{-2}$. Compared to the IIT wastewater experiment, similar TMPs (between 0 and 0.05 bar) were recorded at the start of the experiment. However, the TMPs were not experiencing a constant increment during the filtration process of Jajmau wastewater but were fluctuating around a nearly constant value. The TMP of filtration for membrane A, B and C averaged 0.047, 0,040 and 0.003 bar. Although the fluxes were fluctuating, a small increase of TMP over time could be found for all membranes. The increment in TMP over time is $3.6.\ 10^{-4}$ bar/hour for membranes A and C, while the increase of TMP averaged $4.2.10^{-5}$ bar/hour for membrane B.

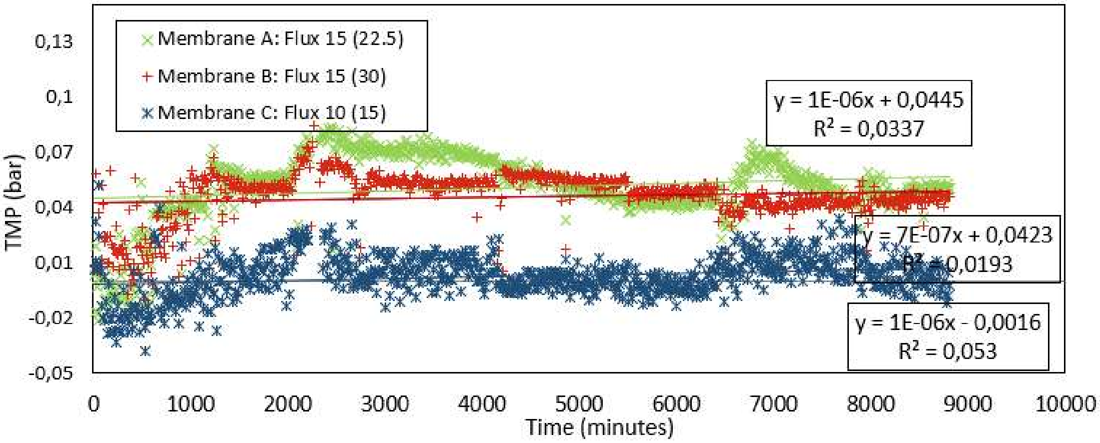

Figure 4.3 *Evolution of TMP per membrane for Jajmau wastewater.*

During the first test run on wastewater from the Jajmau treatment plant, the TMP of filtration did almost not increase for the fluxes 10 and 15 L.h^{-1}.m^{-2}. Therefore, higher filtration fluxes were tested during a new long-term filtration experiment. During this experiment, the flux of filtration was 15 L.h^{-1}.m^{-2} for membrane A, 20 L.h^{-1}.m^{-2} for membrane B and 25 L.h^{-1}.m^{-2} for membrane C. This test had an operation time of approximately 137 hours and was characterized with a TSS concentration in the membrane tank ranging between 7074 and 8557 mg/L. The mean TMP averaged 0.040, 0.034 and 0.088 bar with a slope of 1.8.10^{-3}, 3.10^{-4} and 1.8.10^{-2} (linear part) bar/hour for membranes A , B and C, respectively. For membrane C, two phases were distinguished in the evolution of the TMP over time . First, the increment in TMP followed a linear pattern, while the TMP increased exponentially during the second half of the experiment. The stronger increase of TMP for membrane C is probably due to the lower air flux causing excessive fouling.

Finally, the last filtration experiment was performed by using only membrane A and B while the membrane tank TSS concentration averaged 9276 ± 327 mg/L. At the start of this experiment, the flux of filtration of membrane A was 30 L.h^{-1} .m^{-2}. This high flux caused an exponential increase in TMP (= 8.10^{-6}e$^{0.0005.minute}$) and therefore the TMP reached the maximum level of 0.5 bar too fast. After a chemical cleaning, the membrane filtration was resumed with a flux of 20 L.h^{-1}.m^{-2}. Throughout this experiment, membrane B ran with a constant flux of 25 L.h^{-1} .m^{-2}. The membrane filtration was carried out as a continuous operation of 182 hours. Membrane A had a mean TMP of 0.051 bar, while the TMP of membrane B averaged 0.054 bar. For both membranes, the TMP increased with a nearly constant rate of a 1.8.10^{-3} bar/hour.

It can be concluded that the maximum stable filtration flux for Jajmau wastewater with a high membrane tank TSS concentration is 25 L.h^{-1}.m^{-2}. For this flux, a minimum of membrane cleaning is required while a big volume of permeate can be produced. Figure 4.4 shows the evolution of the TMP and the flux of filtration over time per membrane (A, B and C) for Jajmau wastewater during the three weeks of testing.

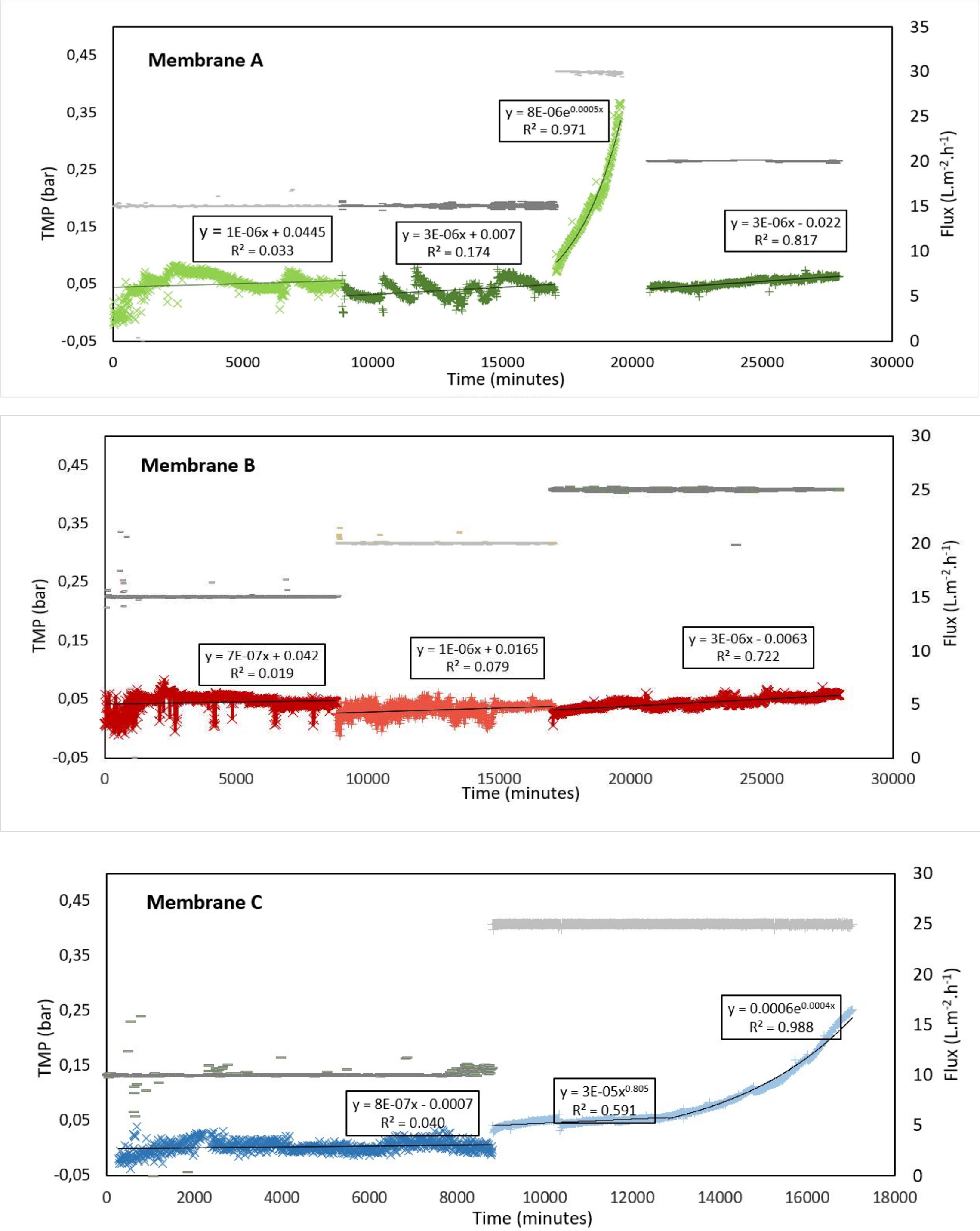

Figure 4.4 *Evolution of TMP and flux per membrane during the filtration experiments on Jajmau wastewater. A color change indicates a cleaning event*

4.2 Effluent quality assessment

This passage focusses on the water quality of the effluent after membrane filtration with regards to the influent and retentate characteristics. Then, a comparison is made between the effluent quality of the MBR experiment and the operational ASP treatment facility in Jajmau. A schematic representation of the treatments is shown in figure 4.5.

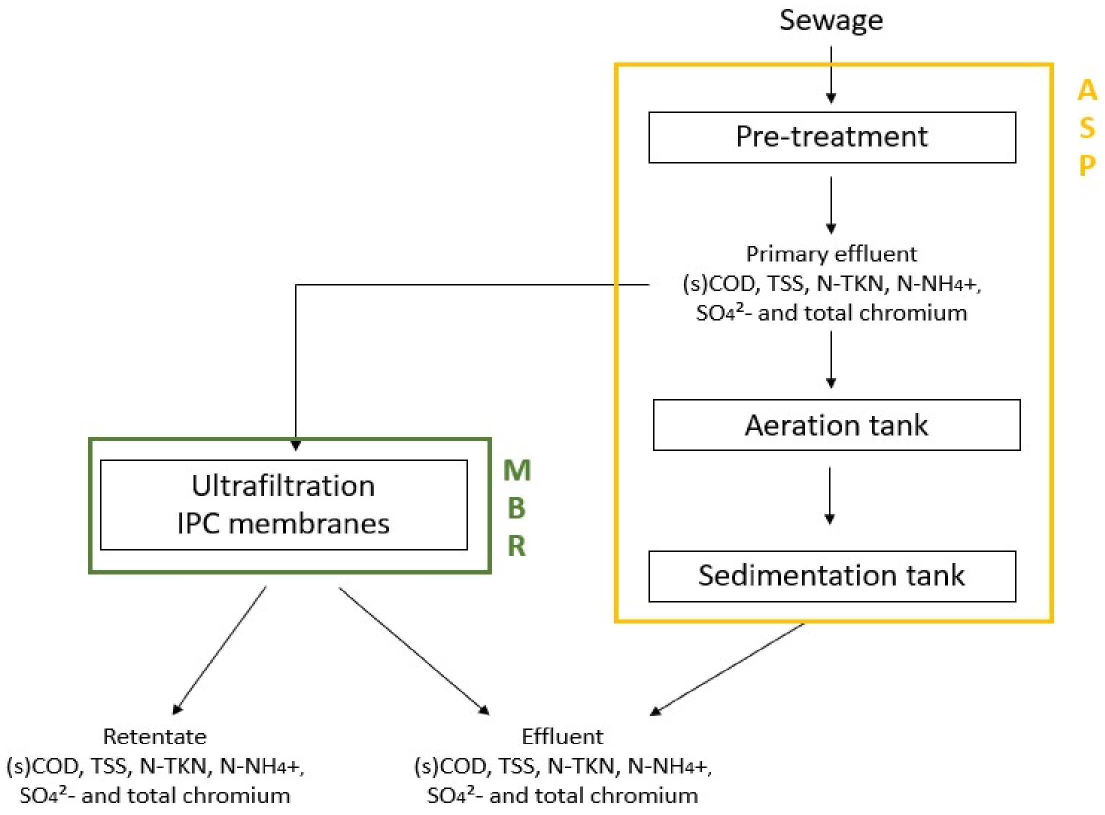

Figure 4.5 *Schematic representation of the treatment processes of the MBR and ASP technologies. The quality parameters that were analyzed for the different fractions are also shown in this figure.*

The assessed parameters included COD, sCOD, TSS, TKN, ammonium (NH_4^+) , sulphate (SO_4^{2-}) and total chromium. COD, sCOD and TSS were sampled every day of testing, while the other parameters were only measured a few times. The water quality measurements for the filtration experiments and the Jajmau ASP can be found in Appendix B and C, respectively.

First, the effectiveness of filtration was tested for the different quality parameters by assessing the influence of the stage on the sample (influent, effluent or retentate). Afterwards, the effect of sampling time, membrane efficiency (membrane A, B and C), filtration flux, influent and retentate characteristics on the effluent quality were evaluated.

4.2.1 Factors influencing the water quality

The average concentrations of the influent, retentate and effluent measured during the membrane filtration experiments with their standard deviations are shown in table 4.1. It was found that the stage had a significant effect on the COD, sCOD, TSS ,TKN and total chromium concentrations, while its effect on NH_4^+ and SO_4^{2-} was neglectable. The retentate was on average characterized by higher concentrations for COD, sCOD, TSS, TKN and total chromium than the effluent. It can be concluded that the membrane filtration had a significant positive impact on the effluent concentrations of large-sized particles but had not a significant beneficial effect for small-sized particles.

Table 4.1 *Quality parameters by stage after working with the ultrafiltration membranes (average ± standard deviation)*

	Influent	**Retentate**	**Effluent**	**P-value**
COD (mg O_2/L)	1138.8 ± 164	7240.1 ±2182.1	96.9 ± 26.5	<0.0001
sCOD (mg(O_2/L)	433.6 ± 61.5	1707.4 ± 584.3	96.9 ± 26.5	<0.0001
TSS (mgSS/L)	979.4 ± 134.5	7515.7 ± 1781.3	4.3 ± 2.7	<0.0001
N-TKN (mgN/L)	52.85 ± 2.2	373.1 ± 10.7	20.2 ± 0.7	<0.0001
N-NH_4^+ (mgN/L)	17.7 ± 1.5	17.8 ± 1.3	14.8 ± 1.1	0.2830
SO_4^{2-} (mg/L)	116 ± 12	128 ± 19	114 ± 9	0.4360
Total Cr (mg/L)	6.6 ± 0.3	31.1 ± 11.8	<0.1	<0.0001

The membrane filtration averaged a removal efficiency of 90.6% for COD, 75.4% for sCOD and 99.5% for TSS. The average nutrient removal efficiency of the ultrafiltration process is respectively 61.9% for TKN, 16.3 % for NH_4^- and 1.7% for SO_4^{2-}. The heavy metal chromium was removed with an efficiency of 100%.

Model analysis revealed that the time of sampling and membrane identity did not affect either COD or TSS concentration in the permeate. The type of wastewater (IIT or Jajmau) had a significant impact on the results. As mentioned before, the first filtration experiment was carried out with wastewater coming from the sanitary block of the IIT campus. Despite the lower concentrations of COD (442.5 ± 158.3mg/L) and TSS (181.0 ± 27.1 mg/L) in the raw IIT wastewater than in the Jajmau water, the effluent of the IIT test contained a higher amount of COD (100.4 ± 16.6 mg/L), probably through a higher share of soluble COD (224.3 ± 15.9) in the influent. It is expected that the fresh wastewater coming from the IIT campus contained a higher share of readily biodegradable COD in comparison to the mature sewage from Jajmau. It can be concluded that the efficiency of ultrafiltration as treatment technology varies according to the wastewater characteristics. Stable and mature wastewater is a more favorable influent for ultrafiltration than fresh and unstable wastewater.

Also, it was found that the filtration flux and the COD concentration in the membrane tank influenced significantly the permeate COD concentration during the Jajmau test. The effluent COD concentration was linearly related with the membrane tank COD concentration per flux. An increase in flux provoked a positive vertical translation of the correlation line. Figure 4.6 shows the relation between permeate COD concentration and tank COD concentration per flux. As the COD concentration in the tank increased, the amount of COD in the permeate increases as well. The linear relationship undergoes a positive translation by an increasing flux. It is expected that 95% of the single permeate COD measurements will not exceed the Indian municipal discharge standards (<120 mg/L) as the tank COD concentration equals 9096 mg/L for a flux of 25 $L.h^{-1}.m^{-2}$ (maximum stable flux), while the maximum average permeate COD concentration is scheduled to not exceed 116 mg/L for these operational settings with a confidence of 95%.

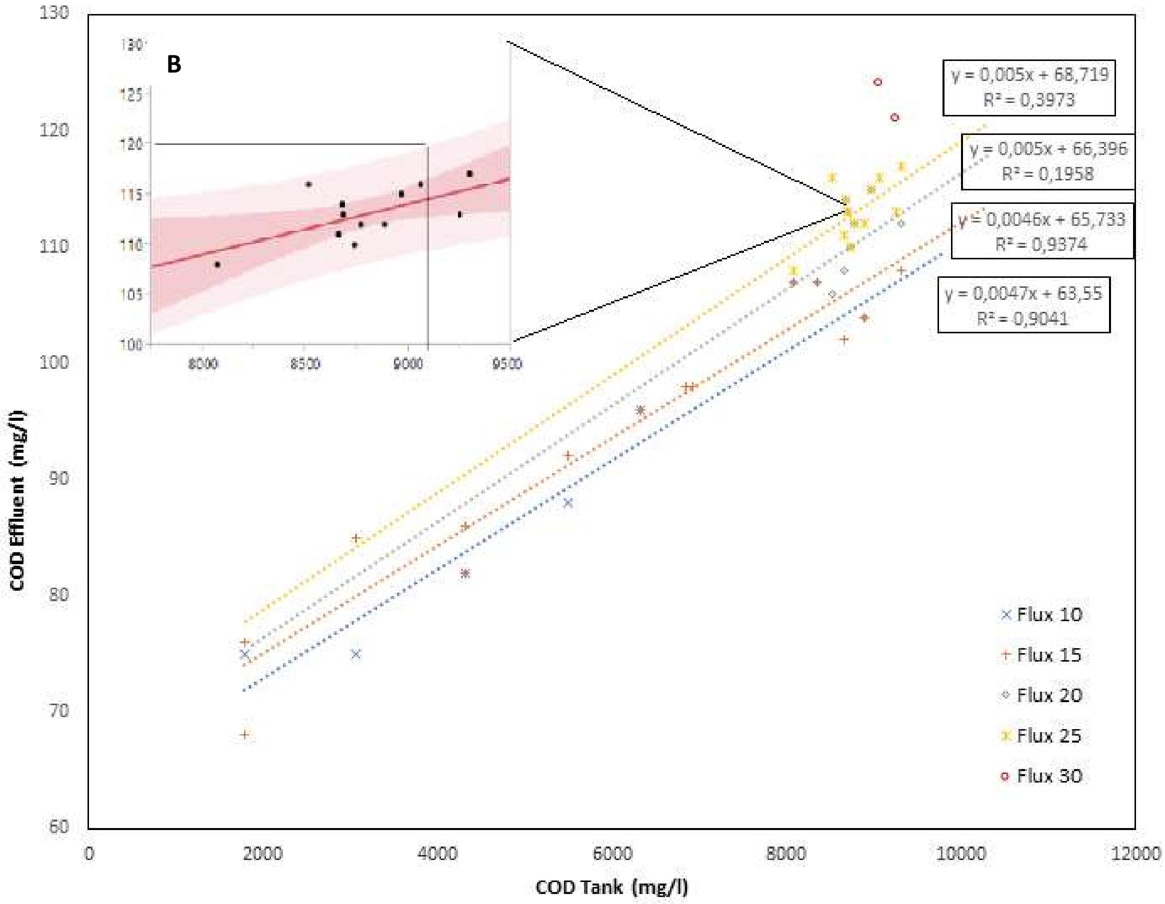

Figure 4.6 *the relation between permeate COD concentration and tank COD concentration per flux. Figure 4.6 B shows the 95%-interval of a single permeate COD measurements (light red) and the mean permeate COD measurements (dark red) for a flux of 25 L/h^{-1}m^{-2}.*

4.2.2 Comparison between the MBR and ASP technology

After assessing the effect of several parameters on the effluent quality of membrane filtration, the treatment efficiency of membrane filtration was compared with the efficiency of the existing ASP facility of Jajmau. Each time primary effluent was collected at the Jajmau ASP for the membrane filtration tests, the tertiary effluent was sampled as well to evaluate the efficiency of the operational ASP. For the permeate quality data of the filtration experiment, a distinction was made between two data groups. The first data group contains all quality measurements gathered during the three weeks of filtration, while the second data group only contains the removal efficiencies collected during the period of day 20 till day 25 (operation by recommended settings: filtration flux of 25 L.h^{-1} .m^{-2} and membrane tank concentration of around 9g/L).

First, the effluent quality of the ASP technology was compared with the permeate quality of the filtration experiment gathered during 3 weeks of testing. As the influent was the same for both treatment technologies, the effluent quality parameters of both groups could be compared directly. It was found that ultrafiltration generated an effluent with significantly less COD, sCOD, TSS, NTKN and total chromium than the ASP treatment technology. However, higher values for ammonium were recorded in the membrane filtration experiments.

Nevertheless, not all effluent quality results of the filtration experiment are representative for the desired operational filtration strategy, due to the too low membrane tank COD concentration and the unrepresentative filtration fluxes. Therefore, a data set with the permeate quality parameters for the desired operational settings (flux 25 $L.h^{-1}.m^{-2}$ and tank COD concentration around 9096 (8700-9100) was generated. However, a significant distinction in influent COD concentrations was found between this group and the other two data groups. In order to evaluate the effluent quality parameters independently of the influent characteristics, the removal efficiencies of the different treatment technologies are compared for several quality parameters. The average removal efficiencies are shown in table 4.2.

Table 4.2 *Removal efficiency of the MBR technology (all measurements and only for optimal settings) and ASP facility of Jajmau (average ± standard deviation %).*

	MBR technology	**MBR technology (operational settings)**	**ASP**
COD	90.6 ± 2.1	87.8 ± 0.3	57.4 ± 10.5
sCOD	75.4 ± 5.5	67.9 ± 0.5	61.8 ± 7.3
TSS	99.5 ± 0.03	99.5 ± 0.3	81.3 ± 5.9
N-TKN	61.9 ± 1.1	61.9 ± 1.1	23.2 ± 4.9
N-NH_4^+	16.3 ± 5.1	16.3 ± 5.1	42.9 ± 1.1
Total chromium	100 ± 0	100 ± 0	77.1 ± 4.3

The removal efficiencies of the membrane filtration adjusted to the desired settings equal 87.8% for COD, for 67.9% for sCOD and 99.5% for TSS, while the ASP removal efficiencies only reached values of 57.4%, 61.8% and 81.3% , respectively. As predicted, the MBR technology was the most efficient treatment strategy for large particles. However, the current ASP facility reached higher removal rates for the nutrient NH_4^+, namely 42.9%. For ammonium, it was found that the MBR technology only retained a neglectable fraction (maximum 16.3%). It can be concluded that the particle size of this nutrient is too small to be blocked by the membrane barrier.

Based on the observed removal efficiencies and the average influent quality, the EQI for the daily discharge of a 130 MLD-treatment facility is estimated with equation 3.3. To estimate the BOD_5 load, it was assumed that the influent BOD_5 concentration equaled 57% of the total influent COD concentration and the removal efficiency was set to be 81.2% for the MBR technology and 83.5% for the Jajmau ASP facility (Heylen, C. 2018). Both removal efficiencies were measured during a test campaign in 2018 at Kanpur. Nitrate was not included in the EQI estimation. However, the nitrate concentration in the effluent of the MBR technology was expected to be neglectable, due to the lack of aeration. Table 4.3 shows the estimated EQI values for the ASP and MBR technology. The impact of the wastewater discharge into the Ganges could be strongly reduced by installing the MBR technology.

Table 4.3 *The EQI of the different treatment facilities*

	EQI (tons/day)
MBR technology	127.8
MBR technology (operational settings)	128.3
ASP technology	303.4
Without treatment	786.2

4.3 Carbon up-concentration

The COD evolution during the concentration experiment of Jajmau wastewater is showed in Figure 4.7. Three batches of primary effluent were collected at the wastewater treatment plant of Jajmau on February 18th, 27th and March 7th. The COD of these sewages averaged 1169 ± 36 mg/l, 1319 ± 38 mg/l and 930 ± 22 mg/l, respectively. Despite the primary settling in the wastewater treatment plant of Jajmau, the COD concentrations of the wastewater were rather high. With one batch of wastewater, the filtration process could be sustained for approximately one week. During the first days of the experiment, the COD in the membrane tank increased continuously. The major part of COD was not able to pass the membranes and was therefore accumulating in the membrane tank.

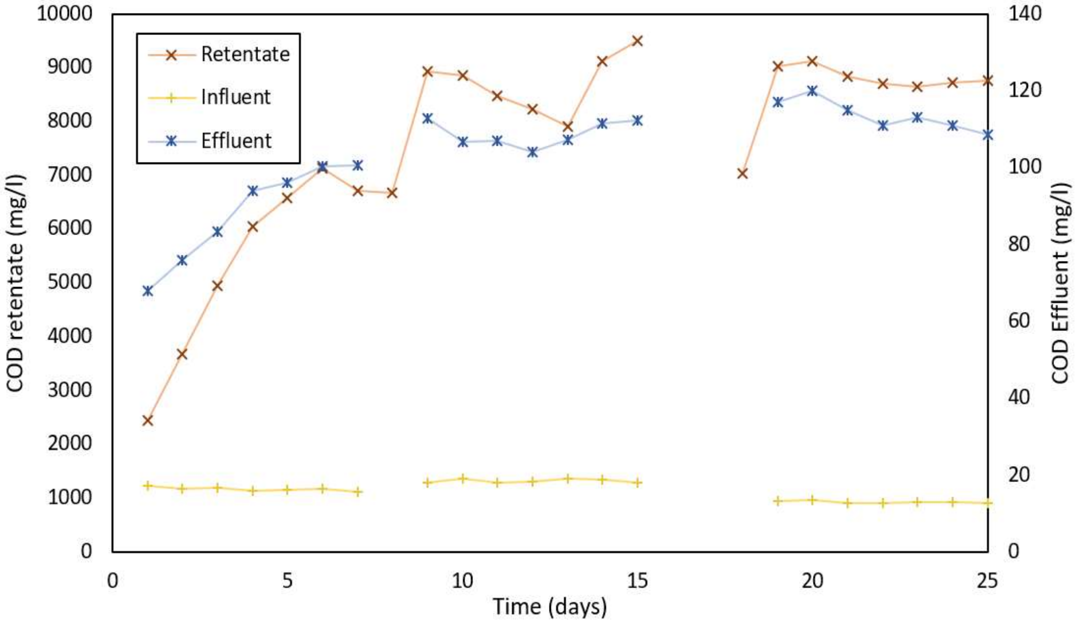

Figure 4.7 *Evolution of the COD concentration per fraction (influent, retentate and effluent) over time for the filtration experiment of Jajmau wastewater.*

The first 4 days no retentate was yielded from the reservoir. Based on the volume, a 9.5-fold concentration could be expected after four days of filtration. Nevertheless, in reality only a 5.1-fold concentration of COD was achieved after four days. The fact that the theoretical concentration factor was not reached, indicates that biodegradation occurred in the membrane reservoir (Tuyet et al. 2016). The importance of biodegradation was examined by estimation of cumulative COD in the concentrate and effluent and compared to the COD in the wastewater feed (Tuyet et al. 2016). The cumulative COD balance of the first four days of the filtration process is shown in figure 4.8. Figure 4.8 also shows the cumulative COD balance of the filtration process with IIT wastewater. After one day of filtration, the recovery rate was 75% in the Jajmau test, which is much higher than the 53% obtained in the ITT test. The higher recovery rate was the result of the higher COD retention by the UF membranes (97 % in the Jajmau test vs 87.5% in the IIT test) and less biodegradation in the membrane tank (22% in the Jajmau experiment vs 34.5% in the IIT test). These differences in COD loss between both experiments can be explained by the fact that the IIT experiment was carried out with freshly produced wastewater, while the Jajmau experiment operated with more matured sewage (Tuyet et al. 2016). The freshly produced IIT wastewater probably contains a larger fraction of readily biodegradable COD prone to degradation in the membrane tank in comparison to the sewage of the Jajmau treatment plant.

As expected, the COD loss by bio-decomposition steadily increased throughout both filtration experiments. After 4 days, a COD loss of 34% for the Jajmau experiment and a COD loss of 42% for the ITT test were observed. The cumulative COD found in the effluent fraction almost doubled for the Jajmau test to 5.7% while the IIT test also had a steady increase in cumulative COD to 17%. During the IIT wastewater experiment, the lower percentual increment in cumulative effluent COD lies in line with the lower increase of COD concentration in the membrane tank.

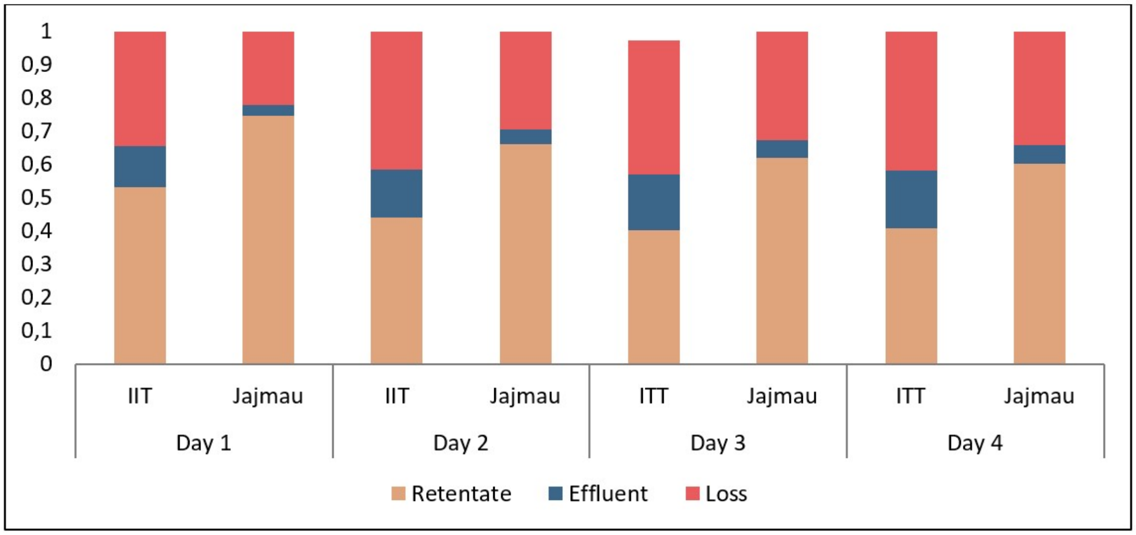

Figure 4.8 *Comparison between the cumulative COD balances of IIT and Jajmau filtration experiments*

After 96h of filtration, every day 9.2 liter of retentate was removed from the tank till the end of the first filtration period. The retentate removal resulted in a stabilization of the membrane tank COD concentration between 6500 mg/L and 7120 mg/L. In line with the COD increase in the membrane tank, it was found that the effluent COD concentrations raised from 70 mg/L at the start of filtration to 101 mg/L at the end of the first week. The removal of retentate from the tank also halted the increment in COD loss by biodegradation. This is revealed by the daily COD balance shown in figure 4.9. The daily COD balance was calculated by estimation of COD changes in the tank, COD of retentate removal and cumulative effluent COD compared to the cumulative COD in the wastewater feed. The 7th day of testing was cut short because the system ran out of wastewater, therefore the retentate removal accounted for a large portion of the COD day balance, which resulted in a COD decrease in the membrane tank.

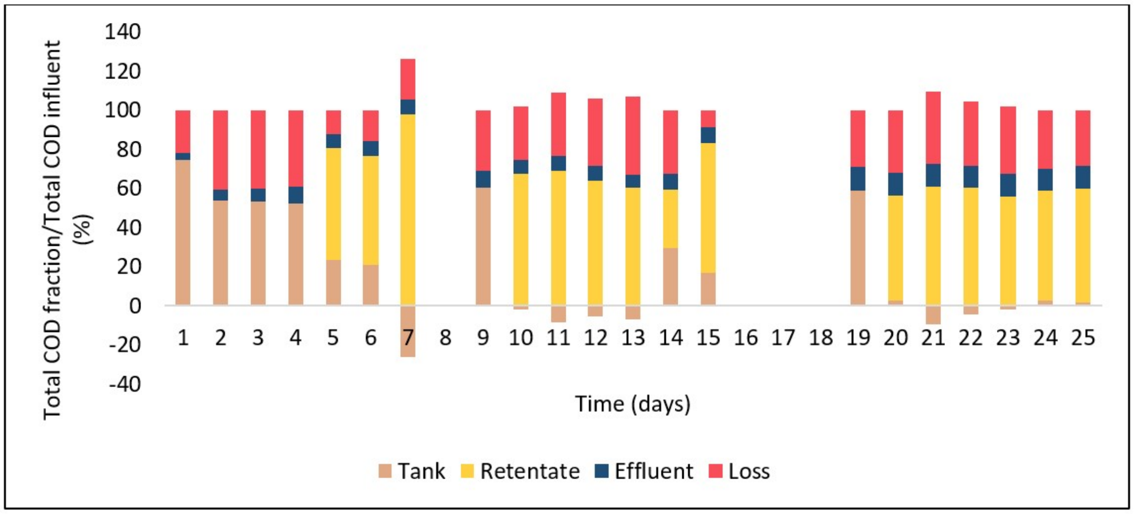

Figure 4.9 *Daily COD balance: Cumulative COD in a fraction/Cumulative COD in influent per day.*

After 24 hours of inactivity, the filtration process was restarted where the stored concentrate of the previous filtration test was reused. The higher filtration fluxes resulted in a permeate volume of 126.8 ± 3.7L each day. Throughout the first day, no retentate was removed resulting the increased membrane tank COD concentration. During the next four days, every 24 hours 14.1 liter of retentate was removed out of the tank to halt the increment in COD concentration in the tank. During this period, the average COD concentration in the tank was 8367 ± 283 mg/l while the average permeate COD concentration equaled 107.6 ± 2.7 mg/l. Based on the results of the daily COD mass balances, the mean daily COD yield (retentate) was 65.2 ± 3.4%, the mean cumulative permeate COD was 7.3 ± 0.2% and the mean COD loss equaled 33.4 ± 4.6% of the daily cumulative influent COD, which resulted in a decrease of membrane tank COD concentration with a mean rate of 5.8 ± 2.5% to the daily cumulative influent COD. Therefore, a lower amount of retentate (6.7 liters) was removed from the tank during the last two days of the second test run resulting in an increasing COD concentration in the tank.

In the membrane tank, the COD concentration decreased from 9490mg/L to 7030mg/L due to three days of inactivity. Therefore, no retentate was removed during the first day of the third test run resulting in the increased COD concentration in the tank. Afterwards, a stable process was achieved by using a constant daily influent volume (102.9 ± 2.4 liter) and a constant daily retentate removal rate (6.2 liters) for a membrane tank volume of 32.3 L. Accordingly, every day a permeate volume of almost 96 liters was produced which counts for 94% of the influent volume. During the test period with these settings, both membrane tank COD (8796.7 ± 150.3 mg/l) and permeate COD (112.4 ± 2,9 mg/l) remained nearly constant.

The mean daily cumulative COD balance of this period is shown in figure 4.10. The membrane filtration averaged a COD retention of 89% of the influent COD, whereof 64% was yielded as retentate and 36% was lost due to biodegradation. Because of the high membrane tank COD concentration and the strong filtration flux during this period, the cumulative permeate COD was rather high. The high COD losses through biodegradation may be due to the long hydraulic retention time (7.5 hours) and the long sludge retention time (5.2 days). Short SRT and HRT are crucial components to reduce the impact of microbial decomposition of COD during up-concentration (Tuyet et al., 2016).

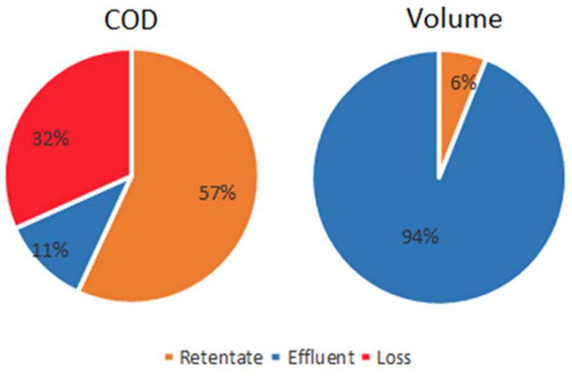

Figure 4.10 *The mean daily COD balance and water volume balance of the membrane filtration experiment from day 20 till day 25 (membrane tank COD concentration between 8700-9100mg/L).*

To gain insights into the impact of membrane filtration on the particle distribution, the soluble and particulate COD concentrations in the membrane tank were evaluated overtime during the filtration experiment (Tuyet et al. 2016). At the start, the soluble COD concentration was 472 mg/L, equal to 38% of the total COD. Both particulate and soluble COD concentrations increased during the first 4 days. However, the percentage share of soluble COD decreased over time. As result of retentate removal, the share of soluble COD increased from 17% at the end of the 4th day to 24% at the end of the 7th day. The highest soluble COD values (up till 2600 mg/l; 29% of total COD) were recorded during the first part of the second test week, when the system operated with the shortest SRT (3 days). As the SRT was increased at the end of the second test week, the percentage share of soluble COD decreased again. From day 20 till day 25, the soluble COD concentration was stable and averaged 1948 ± 71 mg/L, equal to 22.5% of the total COD. These results illustrate that the average particle size increased with the sludge retention time. It can be concluded that the dissolved organic matter clustered together in the membrane reservoir, which could be due to bio-flocculation (Tuyet et al. 2016). As dissolved organic matter is characterized by higher digestion rates in comparison with particulate organic matter and hence the requirement of a lower retention time during anaerobic digestion, a high soluble COD concentration in the retentate is preferred (Tuyet et al. 2016). Thus, the retention time should be short enough to reduce the impact of bio-flocculation and long enough to maximize up-concentration (Tuyet et al., 2016).

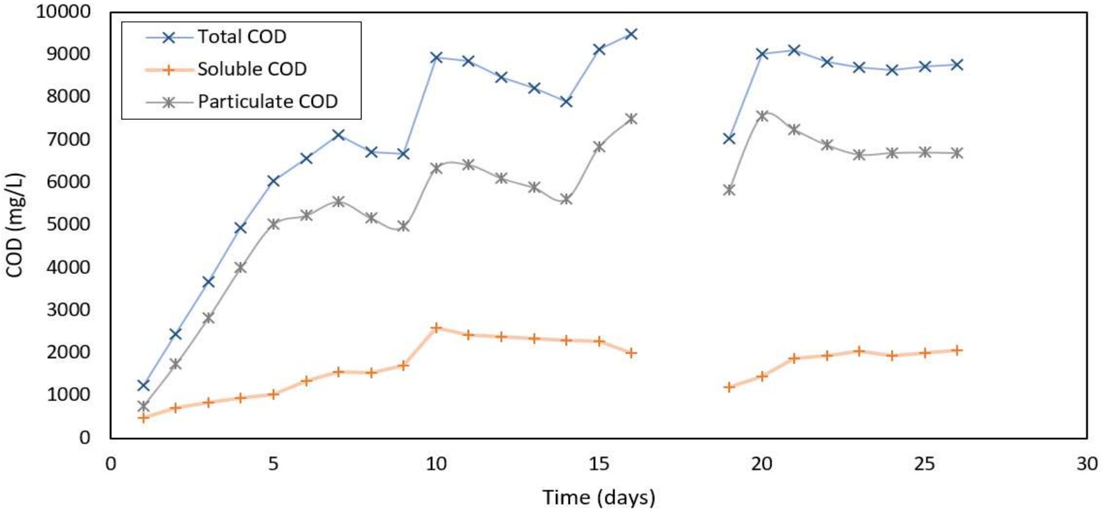

Figure 4.11 *Evolution of the total COD, particulate COD and soluble COD fractions over time.*

The filtration membrane acts as a barrier for various substances, therefore not only COD is retained in the tank. It was found that the influent total chromium concentration averaged 6.6 ± 0.4 mg/l, which indicates that tannery effluents were illegally discharged in the municipal wastewater. After membrane filtration, no chromium was found in the permeate water. As no chromium could pass the membrane, chromium was concentrated over time in the membrane tank. To understand the evolution of membrane tank total chromium concentration, the total chromium concentration was monitored throughout the first 96 hours of the Jajmau test (table 4.4). As predicted, the total chromium concentration increased in the membrane tank according to the volume concentration factor. After four days, the total chromium concentration reached a value of 46.6 ppm, equal to 90% of the estimated total chromium input. Unequal distribution in the influent wastewater or retentate could have resulted in this small error.

Table 4.4 *Chromium up-concentration in the membrane tank*

	Day 1	**Day 2**	**Day 3**	**Day 4**
Influent (mg/L)	7.1	6.5	6.2	6.4
Permeate (mg/L)	<0.1	<0.1	<0.1	<0.1
Retentate (mg/L)	15.1	25.9	36.7	46.6

4.4 Anaerobic digestion

The stored bio-energy in the concentrated sludge can be revaluated by anaerobic decomposition to methane and carbon dioxide. The Andicos^{TM} technology foresees the addition of organic waste to the carbon-rich sewage stream to increase the efficiency of the anaerobic digestion process (Heylen C., 2018). As municipal organic waste consists mainly of food waste, the retentate was enriched with IIT campus kitchen waste during the lab-digestor tests. In order to test the digestibility of the concentrated retentate, local kitchen waste and the mixture of both, three digestors were established and monitored during a period of 40 days. The results of digestor tests can be found in Appendix D. The feed to the digestors included respectively retentate from the membrane tank (Retentate digestor -RD), mixed kitchen waste from the IIT campus and tap water with ratio 175g kitchen waste to 1L of tap water (Kitchen waste digestor - KD) and mixed kitchen waste of the IIT campus diluted in retentate with the same ratio as the kitchen waste/water digestor (Kitchen waste + Retentate digestor - KRD). Table 4.5 summarizes the average characteristics of the organic feed in the digestors. The feed characteristics in terms of VS:TS ratio (retentate: 0.46 and kitchen waste: 0.83), COD:N ratio (retentate: 19.5 and kitchen waste: 52), COD:S ratio (retentate: 6) were for all feeds appropriate for anaerobic digestion (Tuyet et al. 2016). It was found that 1kg kitchen waste contained 187 gram COD, which is slightly higher than the COD content of Indian food waste (e.g. 0.16kg/kg food waste) found by Kumar (2009). The digesters in this study ran under mesophilic conditions at a constant temperature in a sealed room, ranging from 35 to 38 °C.

Table 4.5 *characteristics of retentate and kitchen waste for digestion process (average ± SD).*

	pH	**T, °C**	**COD (g/kg)**	**TS (g/kg)**	**TVS (g/kg)**	**NH_4-N (g/kg)**	**TKN (g/kg)**	**SO_4 (g/kg)**
Retentate	7.6 ± 0.4	27.6 ± 2.0	7.8 ± 1	13.6 ± 2	6.2 ± 0.9	0.04 ± 0.01	0.4 ± 0.01	0.13 ± 0.02
Kitchen waste	5.4 ± 0.3	28.1 ± 1.7	187.4 ± 6.2	207.4 ± 4	171.5 ± 7	3.2 ± 0.8	3.6 ± 0.8	*

Figure 4.12 shows the evolution of the pH for the three digestors. All digestors experienced a pH drop during the first days of operation, probably through excessive production of volatile fatty acids. The kitchen waste-digestor reached the lowest pH (4.52) and alkalinity (2800) during the pH drop. Also, the combined digestor experienced a pH drop, although the pH (5.4) and alkalinity (400) remained higher. The pH of the digestors (RD, KD and KRD) were restored into the favorable range for the anaerobic digestion (6.5-8) by adding 23.8, 47.04 and 58.8 gram sodium bicarbonate, respectively. Afterwards, the pH of the RD and KRD digestors remained relative stable, while the pH of the KD digestor decreased slowly, probably through accumulation of volatile fatty acids. It can be suspected that the addition of alkaline retentate to food waste may have a positive buffer effect on the pH during anaerobic digestion. However, further research is needed to validate this assumption.

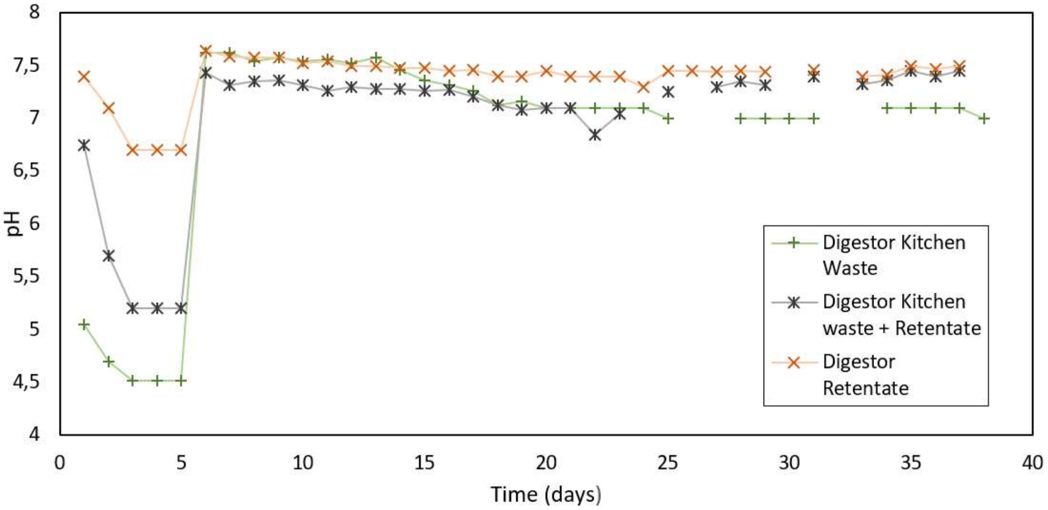

Figure 4.12 *Evolution of pH in the digestors over time*

After 30 days of operation at a sludge retention time of 20 days and at an organic loading rate ranging from 1.7 to 1.8 g VS/L.day, a stable biogas generation was achieved by the KRD digestor at an average production level of 1183 ± 33 mL/d (Figure 4.13) equal to a biogas yield of 436 ± 12 mL/g VS added or 380 mL/g COD added. Thus, the theoretical organic removal rate averaged 71%, which is in line with the study by Tuyet et al. (2016). In this study, Tuyet et al. (2016) ran an laboratory-scale anaerobic reactor on a combination of kitchen waste and concentrated sewage, which recorded an organic removal rate between 70% and 95% at an organic loading rate of 2 g VS/L.d. Figure 4.15 shows that the biogas production of the other 2 digestors (RD and KD), with an average organic loading rate of 0.31 and 1.5 g VS/L.day, increased steadily and reached maximum values of 70 mL and 185 mL respectively after 40 days.

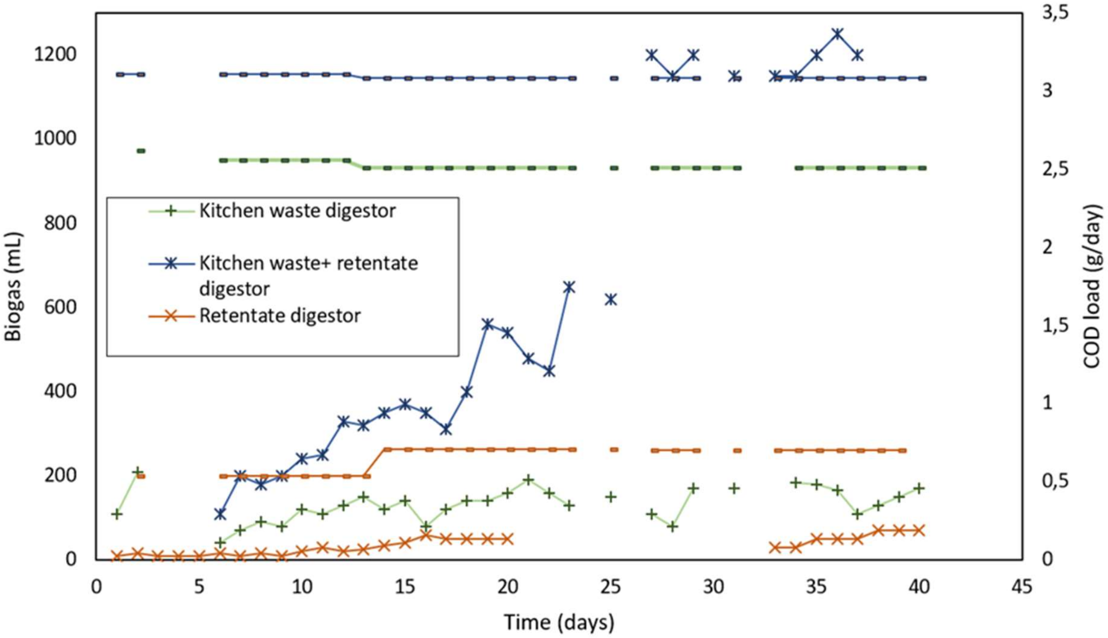

Figure 4.13 *Biogas production and COD load over time per digestor*

5. Discussion

5.1 Optimization of Andicos^{TM} technology

The main goal of this thesis project was to find the optimal settings for membrane filtration of the primary effluent of the Jajmau STP. These settings are important to the start-up of the future Andicos^{TM} pilot plant. Reducing the negative effect of concentration polarization/fouling will be essential to achieve the desired continuity in the filtration process, while a high permeate flux can reduce the overall costs of the Andicos^{TM} treatment plant. Moreover, an adequate balance between effluent quality and carbon up-concentration in the membrane tank has to be looked for to satisfy both ecological and economic incentives. With regard to these criteria, the different ultrafiltration settings are evaluated in this section.

5.1.1 Filtration settings

A first important point to stress out with regards to the membrane filtration is that all membranes have the same removal efficiency, whereas differences were observed in terms of fouling capacity. For membrane A and B, a stable filtration flux of 25 $L.h^{-1}.m^{-2}$ was found in the long-term filtration experiments, whereas for membrane C there was an exponential increase in transmembrane pressure for this flux after approximately 70 hours of filtration. A possible explanation can be found in the experimental set-up that led to a different transmembrane air flux for membrane C. Process lines A and B were equipped with air flux regulators resulting in the possibility to fix the air flux at a value of 0.7 $N.m^3.h^{-1}$ but in reality, the air flux fluctuated between 0.55 $N.m^3.h^{-1}$ and 0.7 $N.m^3.h^{-1}$ because of non-continuous air compression. However, the possibility of air flux regulation was non-existing for line C resulting in lower transmembrane air fluxes. Due to this lower transmembrane air flux, membrane C was more sensitive for concentration polarization/fouling. Therefore, caution is needed when analyzing the results of the different membranes and when a new IPC-membrane filtration system is built. An excessive transmembrane airflow could lead to the degradation of organic matter, which negatively impacts the carbon recycling and thus methane production (Diels L., 2020; Heylen C.,2018). The optimal air flux should prevent fouling without causing much organic matter decay. To find the optimal transmembrane air flux to increase the overall efficiency of the Andicos^{TM} treatment technology, additional research is recommended.

As the optimal backwash strength varies between 1.5 and 2.5 according to Chang H. (2017) and Heylen C. (2018), the impact of backwash strength 1.5 and 2 on fouling capacity was tested. The results stated that an increased backwash strength played a significant role in fouling reduction. Although the effect was found to be statistically relevant, the recorded difference only averaged a value of 0.007 bar. Therefore, this parameter setting was of minor relevance among others. Nevertheless, a stronger backwash flux consumes an elevated proportion of the produced permeate resulting in a lower treatment capacity. It was found that the membrane filtration unit with a backwash strength of 2 treated on average almost 5% less water than the filtration system with a backwash strength of 1.5. Previous experiments with the UF membranes showed that the backwash period is irrelevant to the transmembrane pressure when the minimum backwash duration is reached. The minimum backwash period is defined as “the time when the pressure on the permeate side of the membrane at the end of a backwash cycle reached the atmospheric pressure maintained on the feed side” (Akhondi E., 2014;

Heylen C., 2018). This constraint was fulfilled by using the standard settings (backwash duration of 40 seconds) and therefore this parameter was not further investigated.

Total suspended solids concentration is an important contributor to the fouling activity (Diels L., 2020). Therefore, the response of transmembrane pressure for a high suspended solids concentration was compared to a low suspended solids concentration. It was found that an increasing suspended solid concentration negatively affected transmembrane pressure. However, the measured difference in TMP was not as high as expected. A possible explanation could be the fact that a large fraction of suspended solids was settled to the bottom of the membrane tank and thus not affecting the filtration process. The membrane tank was partly unstirred (volume under membranes), which favored settling. Another explanation could be that soluble particles clumped together through flocculation in the membrane tank, resulting in an increased percentage share of particulate solids in the retentate which could reduce the membrane fouling tendency (Tuyet et al., 2016). Although the increased suspended solid concentration had only a minor effect on TMP, caution is required when extrapolating the critical fluxes to higher TSS concentrations. Nevertheless, COD and TSS concentration were strongly correlated in the tank and further up-concentration is not recommended to achieve effluent quality in agreement with the Indian wastewater discharge regulation.

Also, the origin of the wastewater played a crucial role on fouling. As influent to ultrafiltration, the IIT wastewater caused the steepest transmembrane pressure increase comparing with the Jajmau sewage. This is quite remarkable considering that the Jajmau wastewater contained a higher load of organic matter and suspended solids. This finding implies that compared to wastewater maturity, fresh wastewater rich in readily degradable organic matter has the most significant impact on filterability of the wastewater (Zheng et al. 2009). During ultrafiltration of wastewater, the most pronounced fouling resistance contribution is caused by the soluble organic fraction (Zheng et al. 2009). As the soluble organic fraction contributed up to 70.3% of the total organic matter in the IIT wastewater, the filterability of the IIT wastewater is expected to be low. The soluble fraction of fresh wastewater, rich in oligo -and polysaccharides-like and protein-like compounds, may strongly contribute to the irreversible fouling by accumulating in the membrane pores (Wu et al. 2019; Zheng et al.2009). Internal pore absorption of this organic compounds to the hydrophilic PVDF-membrane cannot be removed by backwashing and relaxing, which may have resulted in the increased membrane resistance (Deseau I., 2019; Wu et al. 2019; Zheng et al., 2009).

Due to the higher level of maturity, the Jajmau wastewater probably contained larger-sized particles. This assumption is forced by the smaller percentage share of the soluble organic matter in the Jajmau wastewater (29%). Large-sized particles with a greater diameter compared to the pore size accumulate onto the membrane resulting in cake layer deposition and an increased flow resistance (Deseau I., 2019). Due to the strong backwashability of the IPC membranes, the cake layer formation (e.g. reversible fouling) can be strongly suppressed. It can be concluded that IPC membranes with their strong backwashability are well suited to treat water containing high loads of particles with greater diameter compared to the pore size of the membrane, which is illustrated by the low TMPs recorded during the Jajmau filtration experiment. Whereas the IPC membranes are prone to fouling accumulation by filtration of small-sized particles (e.g. < 80nm), because of irreversible internal pore absorption. More research is recommended to allow the identification and quantification of the major fouling mechanisms during ultrafiltration (Zheng et al. 2009).

As backwash strengths higher than 1.5 have a minor effect on TMP, the critical flux for wastewater originating from the Jajmau treatment plant was assessed for the lowest backwash strength as possible (1.5). With the flux stepping protocol, a critical flux of 28.15 L.h^{-1} .m^{-2} was found for the Jajmau wastewater. Compared to previous experiments with the IPC membranes on Kanpur wastewater (Heylen C., 2018), a critical flux of 28.15 L.h^{-1} .m^{-2} is rather high. For surface water filtration with IPC membranes, the flux can typically be set from 20 up to 50 L.h^{-1} .m^{-2} (Heylen C., 2018; VITO, 2015). However, the water quality of Jajmau wastewater is far worse, which increases the sensitivity to fouling. Due to an outstanding backwashability of IPC membranes, higher fluxes can be reached with these membranes than with other UF membranes on the market (Heylen C., 2018).

Since each flux-step is sustained only for an interval of 1 hour, the flux stepping protocol is unusable to forecast fouling rates for long-term filtration processes (Le Clech et al. 2003). To overcome this drawback, long-term experiments have been executed for the Jajmau wastewater. During this long-term filtration test, the fluxes 15, 20, 25 and 30 L.h^{-1} .m^{-2} were evaluated. The permeate flux could reach a value of 25 L.h^{-1} .m-^{2} without a strong increase in TMP. An exponential increase in TMP was found for fluxes above this value and therefore reached the maximum TMP of 0.5 too fast (within 42 hours). In the low-flux region, there also exits some fouling processes and thus the transmembrane pressure built-up is measured over time for the 25 L.h^{-1} .m^{-2} (Choi K.Y.J., 2005). For the Jajmau wastewater, the average increase of TMP is 1.8.10^{-3} bar/hour for a flux of 25 L.h^{-1}.m^{-2}. To keep the TMPs low, membrane cleaning is recommended once in a while. One cleaning each month should keep the TMP under 0.1 bar. As for cleaning, the oxidizing reagent (NaClO) can be used because of its proven ability to restore membrane permeability by vanishing the accumulated organic matter (Heylen C. 2018). Besides, the membranes can be treated with an acid to reduce scaling (Heylen C., 2018; Kimura, 2004).

5.1.2 Effluent quality

During the filtration tests of Jajmau wastewater, the permeate quality was assessed after membrane filtration with regards to the influent and retentate characteristics. It was found that IPC membrane filtration significantly reduced TSS, COD, sCOD, TKN and total chromium concentrations in the permeate, while its effect on the reduction of NH_4^+ and SO_4^{2-} concentration in the permeate was not significant. The pore size of the IPC membranes (80nm) could explain these differences in removal efficiencies. The pores will act as a barrier for suspended solids (>0.45 um) and its associated compounds, while small molecules/particles can go through (Heylen C., 2018). A particle size greater than the pore size however does not guarantee complete removal, therefore a non-zero concentration of suspended solids was observed in the permeate. The permeate suspended solids concentration averaged 4.3 mg TSS/L equal to a removal efficiency of 99.5%.

Chromium is a heavy metal of high relevance in the industrial setting of Kanpur, therefore chromium-containing industrial effluents are discharged in the domestic wastewaters. The release of chromium in the Ganges river can be catastrophic for human health and environment (Troch M., 2018). A strong removal efficiency is thus of high importance for the Ganges ecosystem. In aquatic environments, chromium exists primarily in two different oxidation states: trivalent chromium (Cr(III)) and hexavalent chromium (Cr(VI)), which have opposing mobilities and toxicities (Dai et al. 2012; Fendorf, S. 1995). Chromium (VI) is toxic and tends to be highly mobile in aquatic environments because of two important aspects: (1) Almost no immobilization of the anionic contaminant by mechanisms of absorption; and, (2) no solubility constraints (Guertin et al, 2004). Whereas, chromium (III) is rather benign and immobile due to adsorption and precipitation at a pH above 4 (Fendorf, S. 1995; Nriagu, J.O. & Nieboer, E. 1988). As no Cr(VI) is present in the fresh tannery effluent of the Jajmau array (Apte et al., 2006) and anoxic conditions prevail in wastewater, it can be expected that the Jajmau wastewater exclusively contains the reduced chromium (III) species. At pH 7, 90% of chromium (III) is bound to the suspended solids while the remainder of the chromium is precipitated in sewage (Stasinakis et al., 2005). In line with the high removal efficiency of suspended solids (99.5%) through the IPC membranes, it was found that all permeate samples had a total chromium concentration under the detection limit (<0.1 ppm). Under conditions prevailing in the natural environment, Cr(III) can be oxidized to Cr(VI) by oxygen or manganese dioxide, which can result in major environmental and agronomic issues (Apte et al., 2006). This major drawback can be prevented by removing the benign and immobile Cr(III) from the wastewater, before its release in the environment.

As organic matter exists in different particle sizes, only a part is retained by the ultrafiltration membrane (>0.08um) whereas the small organic matter (<0.08um) easily passes the membrane barrier into the permeate (Heylen C., 2018; Vlaeminck S., 2020). As expected, the permeate COD concentration was correlated with the membrane tank COD concentrations. The correlation line undergoes almost a perfect positive linear translation when the flux increases. For an increment of 5 $L.h^{-1}.m^{-2}$ in filtration flux, the permeate contains 1.7 mg COD/L more. The permeate COD concentration increased drastically for flux 30 $L.h^{-1}.m^{-2}$, although only two measurements were obtained because of system failure for this filtration flux. The slopes of the correlation lines were almost equal, the highest fluxes were however characterized with the strongest slopes (e.g. 5 mg permeate $COD.L^{-1}$/1000mg membrane tank $COD.L^{-1}$). It was observed that an increased flux, required a higher transmembrane pressure. Masciola D. (1999) states that permeate organic carbon concentration inflates for an increased transmembrane pressure as a result of a thickened and more dense boundary layer. In line with this, the exponentially increased TMP for filtration flux 30 $L.h^{-1}.m^{-2}$ could have caused the excessive permeate COD concentrations for this flux. These observations underline the importance of regular membrane cleaning to reduce the TMP and thus permeate COD concentrations. It was found that 95% of the single permeate COD measurements will not exceed the Indian municipal discharge standards (<120 mg/L) as the tank COD concentration equals 9096 mg/L for a flux of 25 $L.h^{-1}.m^{-2}$ (maximum stable flux), while the maximum average permeate COD concentration is scheduled to not exceed 116 mg/L for these operational settings with a confidence of 95%. Therefore, it is recommended to reach this membrane tank COD concentration to achieve optimal carbon recycling, while being in accordance with the Indian discharge standards.

The removal efficiency of nitrogen was evaluated by monitoring two different fractions: Total-Kjeldahl-Nitrogen and ammonium (NH_4^+). A significant reduction in N-TKN was observed, whereas the reduction in NH_4^+ was not significant. The reduced permeate N-TKN concentration can be explained by the fact that the UF membranes retain a large part of the organic matter fraction and thus also the incorporated organic-bound N, which made up for 66.5 ± 2.6 % of the influent N-TKN (Vlaeminck S., 2020). As ammonium ions are small enough to pass the membrane barrier, no sieving effect for the ions was expected (Diels L., 2017). Nevertheless, a small reduction of the ion in the effluent was observed. This difference is possibly due to the fact that a large fraction of NH_4^+ ions are bound to suspended solids and therefore can be retained by the UF membranes (Heylen C., 2018). The same could be concluded for the reduced amount of sulphate in the effluent. The notable amount of ammonia in the effluent (14,8 ± 1.1 mg.L^{-1}) should not be a major issue, because a large part of the effluent of the Andicos^{TM} pilot plant is planned to be used as irrigation water for the farmers. (Pavitra Ganga, 2020)

Table 5.1 gives the effluent quality based on the average influent contaminant concentration and the removal efficiencies recorded during the test period. Due to ultrafiltration, the effluent quality of the Andicos^{TM} technology is far superior as compared to the current Jajmau ASP facility (TSS <5mg.L^{-1}, COD <120mg.L^{-1} and total chromium <0.1mg.L^{-1}) (Olivares et al., 2019). According to Dotaniya et al (2014), chromium containing effluents used as irrigation water will have a considerable impact on seed germination, shoot development and root growth in oat, wheat and sorghum plants (Dotaniya et al. 2014). In addition, chromium translocation from root to shoot was found in sorghum and wheat (Lopez-Luna et al., 2009). As the Indian-Gangetic Plain is the production center for wheat and oat of India, the use of unfiltered tannery effluents in this area can lead to food scarcity and harmful effects to human health (Dotaniya, et al. 2014). Due to the use of the treated effluent as irrigation water, a strong removal of chromium out of the wastewater is crucial to secure high food quality and production in the surroundings of Kanpur. Moreover, the ultrafiltration membrane will retain all bacteria because of its smaller pore size in comparison to the diameter of bacteria (Vlaeminckx, 2020; Diels L.,2017). As infections can enter a crop production system with irrigation water, the removal of pathogenic bacteria out of the wastewater is crucial to sustain high crop yields. The neglectable chromium and bacteria content in the MBR effluent in combination with the low sieving effect for ammonium ions makes the permeate of ultrafiltration well suited for irrigation, while having a small impact on the surface water (TSS <5mg.L^{-1}, COD <120mg.L^{-1}) and human health (no waterborne bacterial diseases).

Table 5.1 *Effluent quality of the different treatment technologies for Jajmau wastewater.*

	Primary effluent Jajmau	**MBR technology (Overall)**	**Membrane technology (Optimized)**	**ASP technology**
TSS (mg/L)	979.4	4.9	4.9	183.1
COD (mg/L)	1138.8	107.0	113.7	485.1
sCOD (mg/L)	433.6	107.0	113.7	165.6
N-TKN (mg/L)	55.1	21.0	21.0	42.3
N-NH4 (mg/L)	17.6	14.8	14.8	10.1
Total chromium (mg/L)	6.7	<0.1	<0.1	2.2

The removal efficiencies for total and soluble COD recorded during the filtration experiment with IIT wastewater were far below the ones observed during the Jajmau experiment. The difference in removal efficiencies between IIT and Jajmau wastewater is attributed to the maturity of the wastewater. The freshly produced IIT wastewater may still contain a large fraction of readily biodegradable COD including simple sugars, alcohols, amino acids, fatty acids, etc. These molecules can easily pass the UF membrane pores due to their small diameter. As the major part of the organic matter is soluble and a considerable fraction of the soluble organic matter may have a smaller diameter compared the pore size, the membrane barrier could only retain a reduced amount of (s)COD for IIT wastewater. It was expected that the mature Jajmau sewage primarily consists of organic matter with a larger diameter compared to the pore size, because of the absence of readily biodegradable COD and bio-flocculation.

5.1.3 Carbon up-concentration

During the Jajmau experiment, the UF membranes retained between 87.8% and 96.7% of the influent COD depending on the membrane tank COD concentration. Therefore, the organic matter accumulated in the membrane tank. However, the theoretical concentration factor based on treated volume was never reached, indicating that biodegradation occurred in the membrane reservoir (Tuyet et al., 2016). The importance of biodegradation was examined by the estimation of cumulative COD in the concentrate and effluent and compared to the COD in the wastewater feed. During the three weeks of experiment, it was found that the COD loss averaged 29.5 ± 8.8% of the total influent COD, which is rather low compared to the IPC membranes experiment executed at the treatment plant of Ho Chi Minh, where COD losses were recorded up to 50% after only 3 days (Tuyet et al, 2016). These differences in COD loss between both experiments can be explained by the fact that the “Ho Chi Minh” experiment made use of freshly produced wastewater directly obtained from the sewerage of a residence building, while this experiment operated with more maturated sewage obtained after primary treatment in the Jajmau treatment plant. The fresh wastewater probably contains a larger fraction of readily biodegradable COD prone to degradation in the membrane tank in comparison to the mature wastewater of the Jajmau treatment plant (Tuyet, et al, 2016).

According to Tuyet et al. (2016) the biodegradation can be reduced by maintaining a short SRT and HRT for the IPC filtration system. However, the differences in SRT and HRT did not impact the COD loss in the membrane tank during the Jajmau experiment. Because of rapid changes in parameter setting, the equilibrium status was possibly not reached and therefore no valid conclusion could be made about the impact of SRT and HRT on the COD loss. Nevertheless, the SRT affected the partitioning of COD between the particulate and soluble fraction. The percentage share of soluble COD ranged between 17% and 38%. For an SRT of 3 and 5.2 days, we recorded an average soluble COD percentage of 28.5% and 22.5%, respectively. It can be concluded that the dissolved organic matter clustered together in the membrane reservoir, which could be due to bio-flocculation (Tuyet et al., 2016). As dissolved organic matter is characterized by higher digestion rates in comparison with particulate organic matter and hence the requirement of a lower retention time during anaerobic digestion, a high soluble COD concentration in the retentate is preferred (Hernández et al., 2010; Tuyet et al. ,2016). Thus, the retention time should be short enough to reduce the impact of bio-flocculation and long enough to maximize concentration (Tuyet, T. et al. 2016).

As mentioned before, the optimal COD concentration in the membrane tank should be around 9 g/L to achieve an effluent quality below the Indian discharge limits and to have a membrane tank COD concentration as high as possible. During the last week of testing, a stable filtration process with a membrane tank COD concentration of 8.8 g/L was achieved. A representative mass balance could be derived from these results. It was found that the COD of the influent was divided into three fractions: 57% into the retentate, 11% into the effluent and 34% loss. In contrast, the effluent volume made up 94% of the influent volume while the retentate volume only comprised 6% of the original volume. For these conditions, a 9.5-fold concentration of

COD was achieved, whereas the concentration factor based on volume equaled 16.6. These results are rather satisfactory compared to the experiment of Tuyet et al., 2016, where only a 3.8-fold up-concentration could be reached for volume concentration factor of 12.3.

During the concentration process, not only COD is retained in the membrane tank. It is expected that the Jajmau wastewater exclusively contains the reduced chromium (III) species. As the major part of chromium(III) is bound to suspended solids (90%) or precipitated 10 (%) in wastewater, it was found that the UF membrane acted as an absolute barrier for chromium (Stasinakis et al., 2005). Therefore, the chromium concentration increased in the membrane tank according to the volume concentration factor. The accumulated chromium in the retentate equaled 90% of the cumulative influent chromium. Unequal distribution in the influent wastewater or retentate during sampling could have caused this small error. For the membrane tank COD concentration of 8.8 g/L, a chromium concentration of 109.7 ppm could be expected (16.6-fold influent concentration). As the immobile chromium(III) can be oxidized to the mobile and toxic chromium (VI) in aerobic conditions, caution is recommended when using this concentrated retentate. For example, the chromium-rich sludge can be used for anaerobic digestion, while aerobic composting is not recommended (Diels L., 2020).

The results indicated that the carbon recovery by the Andicos^{TM} was more efficient for Jajmau wastewater than for IIT wastewater. The higher recovery rate for Jajmau wastewater was the result of higher COD retention and less biodegradation than in the IIT test. The difference in COD loss between both experiments can be attributed to the different maturity of the wastewaters. As mentioned, the IIT experiment was carried out with freshly produced wastewater, while the Jajmau experiment operated with more maturated wastewater. The IIT wastewater probably contained a larger fraction of readily biodegradable COD fraction prone to degradation in the membrane tank in comparison to the mature wastewater of the Jajmau treatment plant.

By comparing different wastewaters, it was found that the results of the membrane filtration experiments with Jajmau wastewater cannot be extrapolated to wastewater with another origin without additional tests. Experiments on IIT wastewater showed different results for critical flux, removal efficiency and COD loss. The worse effluent quality, the unstable filtration process and high COD loss during the IIT wastewater tests could be due to the fact that the IIT wastewater was more fresh and unstable. (Diels L.,2020) It can be concluded that the Andicos^{TM} treatment concept is better adapted for the treatment of mature wastewater than for fresh wastewater.

5.1.4 Anaerobic digestion

Normally, the creation of carbon-rich retentate is considered as a major drawback for filtration techniques, although the Andicos^{TM} treatment technology turns the production of this 'waste' stream into an advantage (Heylen, C. 2018).

The "Kitchen waste + retentate"-digestor worked with an average load of 1.7 g VS/L.d and 2 g COD/L.d at a retention time of 20 days. After 30 days of operation, the digestor had a stable biogas production of 436 ± 12 mL/g VS added or 380 ± 11 mL/g COD added. The theoretical organic matter removal averaged 71%, which is in line with the study by Tuyet et al (2016). In this experiment, the organic matter removal ranged from 70 to 95% for a digestor fed with a mixture of kitchen waste and retentate (2 g VS/L.d) at a retention time of 50 days (Tuyet et al.

2016). It can be expected that the biogas yield can be enhanced by increasing the sludge retention time, although a larger digestor will be required. Besides, a higher loading rate can result in a more economically favorable process by increasing the biogas yield per volume digestor (Tuyet et al. 2016). In our experiment, we opted for a rather low organic loading rate due to the fact that the digestors were just started-up and the digestion processes were still fragile. This assumption finds its origin in the fact that the digestors strongly acidified during the first days of operation due to a high share of volatile fatty acids in food waste (Bose P., 2020). Nevertheless, it is expected that the addition of retentate to kitchen waste may have a positive effect on pH and thus on the total digestion process. The alkaline pH of the retentate could compensate a part of the acidity of the formed volatile fatty acids during the acidogenesis (Bose P., 2020; Tuyet et al. 2016). However, further research is needed to validate this assumption. The other 2 digestors reached only low biogas yields (e.g. 141 ml/g VS (retentate only) and 77 ml/g VS (kitchen waste only). A possible explanation could be that the digestors required more time to reach optimal biogas production, because of the low loading rates (retentate) and the unstable pH (kitchen waste) (Bose P., 2020).

5.2 Full-scale Andicos^{TM} treatment facility

5.2.1 Mass balance of the system

Finally, the Andicos^{TM} treatment technology was dimensioned for the domestic wastewater treated by the current ASP (130 MLD). To enable this calculation, the following assumptions were made: (i) The sewage load per day is 130 million liters; (ii) the average COD concentration of the sewage is 1.139 kg/m^3; (iii) filtration flux is fixed at 25 l/m^2.h; (iv) COD concentration in the tank is 9 g/L; (v) The permeate COD concentration is 0.1137kg/m^3 based on figure 4.6 (vi) The COD loss is set to be 36% of the retained fraction; (vii) the volume of the IPC membrane tank is based on an SRT of 5.2 days; (viii) the OLR is 2.0kg VS/m^3 with an SRT of 20 days; (ix) organic waste contains 187 g COD/ kg; (x) the biogas production is 0.38 L/g COD added with the ratio of methane to carbon dioxide in the biogas of 65:35 (Tuyet et al, 2016).

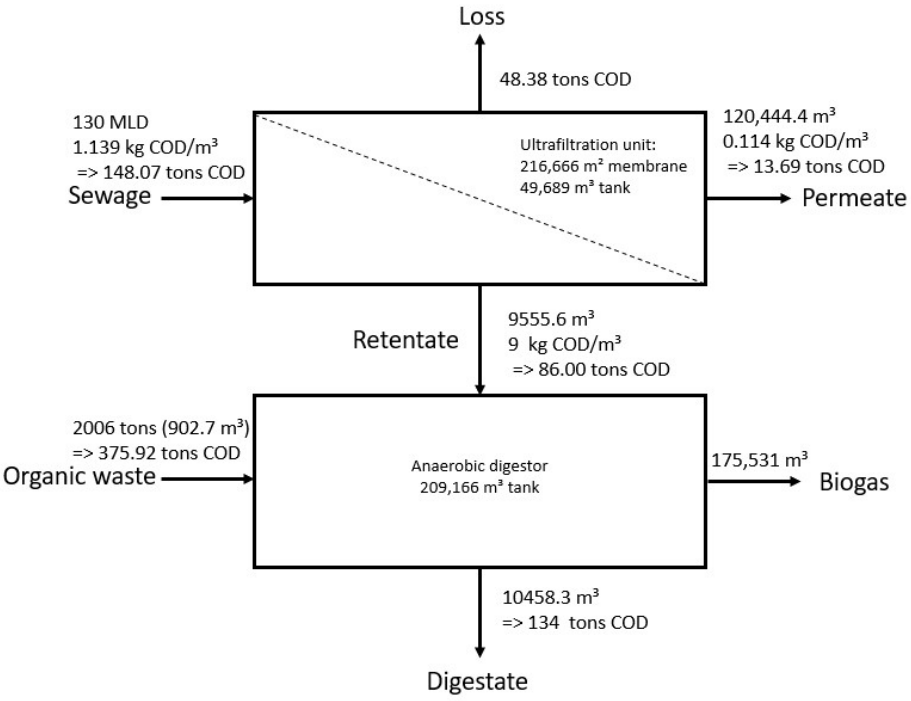

Figure 5.1 *COD balance of 130 MLD Andicos^{TM} treatment facility*

Figure 5.1 shows the results. By means of concentration in the membrane tank, COD recovery of the domestic wastewater can reach up to 68 tons per day, which accounts for 58% of the total COD amount of the original sewage. The percentage share COD loss by degradation and of the effluent fraction is estimated to be 32.7% and 9.2%, respectively, while the produced biogas and digestate represent respectively 41.3% and 16.7% of the total COD amount in the system. The digestate fraction is expected to be suitable for further composting, due to its high lignocellulose content. Everyday an amount of 9555.6 m^{3}retentate is produced by the membrane tank, which should be enriched with 2005.7 tons of municipal organic waste. All organic fractions should be considered, not only kitchen waste. Transporting the municipal organic waste to the Jajmau STP site will be a huge logistic challenge, therefore a gradual implementation of the Andicos^{TM} treatment technology is recommended (Tare V., March 23, 2020).

For this treatment facility, 1 kg COD is retrieved from 1512L of sewage and then combined with 4.37-kilogram organic waste COD. Together, they produce 1.33 m^3 methane, which has an electrical capacity of 5.54 kWh at an electrical conversion efficiency of 40% (Tuyet et al. 2016). Therefore, it is expected that 1 kg of COD in sewage produces 1.03 kWh in the Andicos^{TM} system. This result is lower than the finding of Van Lier (2008), who found that 1kg COD of wastewater can create an electrical power of 1.5 kWh via anaerobic digestion (Tuyet et al., 2016). However, it can be expected that the COD originating from sewage has a higher anaerobic biodegradability compared to the COD of kitchen waste. Only a small volume of wastewater has to be treated to recover 1kg of COD compared with the results of Tuyet et al (2016). According to Tuyet et al. (2016), 140 m^3 of settled sewage is required to retain 1kg of COD. The difference in the recovered amount of COD per treated volume can be explained by the high COD concentration of the Jajmau wastewater. As the energy consumption for ultrafiltration is estimated to be fixed at 0.4kWh/m^3 for permeate and influent pumping, cleaning and coarse bubble aeration, the high COD concentration of the Jajmau wastewater is a major advantage in the energy recovery process (Tuyet et al., 2016). When the energy consumption of ultrafiltration is subtracted, the Andicos^{TM} treatment facility (130 MLD) could produce approximately 1.136 GWh per day. Thus, it can be concluded that the Andicos^{TM} treatment technology is a sustainable concept in comparison to conventional sewage treatment plants (Tuyet et al., 2016). To get the full picture, a traditional activated sludge plant for wastewater purification consumes 0.3-1.9 kWh/m^3 sewage, whereas a composting plant for organic waste disposal requires 20-35 kWh/ton organic solid waste (Tuyet et al., 2016; Mizuta & Shimada, 2010).

To achieve a treatment capacity of 130-MLD, a 49689-m^3 ultrafiltration membrane tank equipped with a membrane surface of 216,667 m^2 and a 209,165-m^3 anaerobic digestor have to be constructed. Although, a reduction of the volume of the membrane tank is recommended to increase economic feasibility, while diminishing HRT and SRT of the membrane tank. (Tuyet et al, 2016) The anaerobic digestion capacity is dependable on the organic waste availability. In case of low municipal organic waste availability, the retentate can be enriched with other organics (as agricultural waste, offal, etc.).

5.2.2 Comparison to actual wastewater treatment technologies

A. *Environmental sustainability assessment*

Ultrafiltration improves the effluent quality by retaining a considerable amount of the influent COD, sCOD, TSS, TKN, NH_4^+, SO_4^{2-} and chromium. However, there already exist other technologies to reduce these contaminants in order to resilience the Ganges river, therefore it is of importance to compare the sustainability of the different technologies (Heylen C.,2018). To evaluate the sustainability of the treatment technologies with regards to their capacity to restore the Ganges river quality, the technology evaluation should assess the treatment efficiency, energy demand and greenhouse gas emissions of the different technologies. Currently, the Activated Sludge Process and Upflow Anaerobic Sludge Blanket are used in Kanpur (Heylen C., 2018).

It was found in our experiments that ultrafiltration has higher removal efficiencies for COD (87.8 vs 57.4), sCOD (67.9 vs 61.8), TSS (99.5 vs 81.3), TKN (61.9 vs 23.2) and chromium (100.0 vs 77.1) than the ASP technology. However, the current ASP facility was more efficient in the removal of NH_4^+ (42.9 vs 16.3). Although, the observed removal efficiencies for COD and TSS of the Jajmau ASP facility were lower than the official reported removal efficiencies by the STP staff. Their results indicated that the removal efficiencies averaged 88.3% for COD and 93.7% for TSS (Heylen C., 2018). The differences in efficiency could be due to the fact that other measurement techniques were used or that the treatment facility operated in different conditions (influent, temperature,..) (Heylen C., 2018).

In a previous experiment, the effluent quality of the UASB reactor was assessed. According to Heylen, C. (2018) the removal efficiencies for COD and TSS of this treatment facility averaged 44% and 50.9%, respectively. These values are far below the obtained result for ultrafiltration. Due to the time lag of 2 years, one should be careful with making a comparison between these results.

The Central Pollution Control Board reported other removal efficiencies as the ones that were observed. In India, the ASP technology removes between 51% and 94% of the COD and between 48% and 99% of the TSS (Heylen C., 2018). However, Heylen C. (2018) stated that the actual removal efficiencies are lower. The removal efficiencies for COD and TSS of the UASB technology are 46.2 and 58.7, respectively, according to the Central Pollution Control Board (Heylen C. 2018). Because of the low removal efficiencies of the UASB reactor, an additional technology should be connected to reach the effluent limits (Heylen C., 2018).

Although the removal efficiencies of the current treatment facilities variated strongly according to source. Our results clearly showed that the ultrafiltration technology has a better performance in terms of EQI for the Jajmau wastewater than the current treatment facilities, indicating on a lower contaminant discharge for ultrafiltration of Jajmau wastewater (128.3 tons/day) than for the activated sludge process (303.4 tons/day). As mentioned, the better effluent quality of IPC membranes filtration is primarily due to more removal of organic matter and suspended solids.

Table 5.2 shows the expected pollutant load of 130 MLD wastewater of Kanpur city into the Ganges River without treatment and with treatment through the optimized Andicos^{TM} technology or the current ASP facility. When the wastewater is discharged without treatment into the Ganges river, the high contaminant load of the wastewater will contribute to the bad water quality of the Ganges (Heylen C., 2018). To reduce the impact of the high-volume untreated wastewater on the Ganges, new treatment facilities has to be built in Kanpur (Heylen C., 2018). Table 5.2 shows that both the Andicos^{TM} technology and the ASP technology could cut down the impact of wastewater discharge on the water quality of the Ganges river. However, the Andicos^{TM} technology is more suitable to reduce TSS, (s)COD and N-TKN loads in comparison to the current ASP technology.

Table 5.2 *Expected pollutant load of 130 MLD wastewater of Kanpur city into the Ganges River without treatment and with treatment through the optimized Andicos^{TM} technology or the current ASP facility.*

	Loads of untreated wastewater	**Loads of treated wastewater by Andicos^{TM} technology**	**Loads of treated wastewater by ASP technology**
TSS (tons/day)	127.32	0.64	23.81
COD (tons/day)	148.04	14.78	63.07
sCOD (tons/day)	56.37	14.78	21.53
N-TKN (tons/day)	7.16	2.73	5.50
N-NH4^{+} (tons/day)	2.30	1.92	1.31
SO4^{2-} (tons/day)	15.08	14.81	*
BOD$_5$ (tons/day)	84.39	15.86	13.92

As mentioned, the discharge of the Ganges river variates strongly over the year. The average discharge of the Ganges falls to 173 m³/s during dry season, while its average discharge equals 2,918 m³/s during monsoon (Heylen C., 2018). The impact of the contaminant load on the Ganges strongly depends on this flow variability (Heylen C., 2018; Troch, M. 2018). Therefore, it is recommended to assess the effect of Kanpur's wastewater discharge into the Ganges for each season separately. As the flow is very high during monsoon season (e.g. 2,918 m³/s), the discharge of untreated wastewater has the smallest effect on the water quality of the Ganges river during this period due to dilution (Heylen C. 2018; Troch M. 2018). It was estimated that the discharge of 130 MLD untreated wastewater results in an increment of 0.59 mg COD/L, 0.51mg TSS/L and 0.03 mg N-TKN/L in the Ganges river during monsoon. The implementation of the Andicos^{TM} technology could reduce the impact and improve the water quality of the Ganges river through a reduction of -0.53 mg COD/L, -0.51mg TSS/L and -0.02 mg N-TKN/L, while the ASP technology only reduces the effect with -0.34 mg COD/L, 0.41 mg TSS/L and 0.01 N-TKN/L.

During summer season, the Ganges has the lowest flow and thus the discharges of untreated wastewater into the Ganges have the highest impact on the river quality (Heylen C. 2018; Troch M. 2018). The discharge of 130 MLD untreated wastewater will drastically increase the COD, TSS and N-TKN concentrations of the Ganges during summer; 8.45 mg COD/L, 9.82 mg TSS/L and 0.47 mg N-TKN/L, respectively. Therefore, the treatment of wastewater will be the most advantageous for the river quality during this low flow period. According to our estimations, the treatment by Andicos^{TM} could result in a huge water quality improvement of the Ganges river (-8.84 mg COD/L, -8.41 mg TSS/L and -0.29 N-TKN/L) in summer. The ASP technology results in a smaller benefit: -5.64 mg COD/L, -6.87 mg TSS/L and -0.36 mg N-TKN/L.

The treatment of 130 MLD by the Andicos^{TM} system could drastically decrease the contaminant concentration in the Ganges river. According to Troch M. (2018), the most problematic pollutions in the Ganges river are COD and BOD$_5$ among other contaminant. Both COD and BOD$_5$ concentrations near Kanpur are classified as Organization for Economic Co-operation and Development (OECD) water quality class 5, the most deteriorated water qualification possible. More information about the OECD classification can be found in Troch M. (2018).The implementation of a new 130-MLD Andicos^{TM} facility to manage untreated wastewater could promote the Ganges quality for COD to OECD water quality class 4 around Kanpur during the summer season. As the decay of organic material leads to the consumption of a substantial amount of the dissolved oxygen in the river water, the high removal efficiency of Andicos^{TM} is critical to prevent life threatening situation for many aquatic species (Norah et al. 2015). Due to the reduced COD load, the dissolved oxygen in the Ganges will increase, which can give potential for diatoms to grow (Diels L., 2017). In deteriorated rivers, diatomic growth is inhibited by elevated ammonia concentrations and hypoxia (Cox et al., 2009). To recover the hyper-eutrophied Ganges river towards more resilient state, the COD and ammonia loads have to be reduced below certain thresholds to stop potential diatomic growth inhibition (Cox et al., 2009). As mentioned, the implementation of the Andicos^{TM} can result in a drastic reduction of COD concentration in the Ganges river. The reduction of COD concentration in the Ganges will lead to a higher dissolved oxygen concentration, which can enhance the natural nitrification processes. When a sufficient low ammonia concentration is reached, the river may reach a turning point from where the oxygen concentration increases in the river without implementing additional treatment facilities (Cox et al., 2009). The Ganges river regime will shift from net oxygen consumption to net oxygen production (Van damme S., 2020). In addition, the increased diatomic growth will transform the river to a net carbon sink instead of a large carbon dioxide emitter (Cox et al., 2009). To achieve this resilient state, it may be required to attach additional nutrient recovery technologies to the Andicos^{TM} technology.

The ultrafiltration technology recorded poorer results for ammonium removal while this nutrient is potentially very harmful to the environment (Fazeli S., 2012; Heylen C., 2018). Although, the major part of the effluents of the Jajmau STPs are used to irrigate agricultural fields, therefore a higher amount of ammonium can be beneficial to the farmers because of its nutritional value to crops (Pavitra ganga, 2020). The EQI was a valuable tool to compare the effluent qualities of the different treatment methods, but one should asses each contaminant separately according to the purpose of the effluent to apprehend the real impact of the treatment system on the environment. (Heylen C., 2018)

The quality of the Ganges river is not only threatened by the high sewage discharges, also the increased solid waste dumping endangers the Ganges river quality. By attaching value to organic solid waste, the Andicos^{TM} could improve the waste collection and thereby reduce the impact of solid waste dumping on the surface water. As other sewage treatment technologies do not manage to include solid waste in their treatment processes, the current solid waste management system of Kanpur is likely to be sustained, which only includes primary and secondary collection, transportation and open dumping (Zia & Devadas, 2008). The open dumping sites however contaminate the soils and surface water of Kanpur (Zia & Devadas, 2008).

Besides positively impacting the Ganges river quality, a sustainable water treatment technology has to minimize its constitution to the energy consumption and the emission of greenhouse gasses. The Andicos^{TM} technology is found to be a net-energy producer up to 3.2 kWh/m³ sewage, while the traditional activated sludge plants consume 0.3-1.9 kWh/m³ sewage for wastewater purification. The transformation of treatment operations into energy producers instead of energy consumers will translate to a decrease in energy consumption and carbon dioxide emissions. Thereby, the implementation of the Andicos^{TM} technology could reduce the impact of water treatment processes on the greenhouse effect and energy scarcity in development countries.

Moreover, the wastewater treatment sector is the sixth largest emitter of N_2O gasses (Sobańtka A., 2014; Heylen C., 2018). It is expected that the Andicos^{TM} treatment technology can reduce the contribution to the N_2O emissions compared to the conventional activated sludge process as there is no to little aeration of the wastewater (Heylen C., 2018).

Another major advantage of membrane technology is its capacity to manage higher organic-loading rates in comparison to the ASP (Heylen C., 2018; Verliefde, 2017). Besides creating a good effluent quality, all studied treatment technologies have however different focusses. The ultrafiltration technology ought to accumulate as much organic matter as possible, while the organic matter is degraded in the UASB technology to generate biogas and the ASP technology degrades organic matter in such a way that the sludge production is minimalized (Heylen C., 2018). For activated sludge process-based systems, sludge management can contribute to more than 25% of the total investment costs (Heylen C., 2018; Rabeay, 2016).The validation of the organic matter in the Andicos^{TM} treatment system is therefore a considerable economic advantage.

B. Economic assessment

Besides contributing to a sustainable natural environment, the treatment technologies have to be economically feasible. Therefore, the capital and operational costs of the Andicos^{TM} technology is assessed in the next section and compared to the current treatment technologies. To achieve their respective effluent quality, all technologies demand a different type of infrastructure and a different amount of energy (Heylen C., 2018). For the Andicos^{TM} treatment technology, we focused on the possibility to recover funds from the energy provided by anaerobic digestion to compensate for the costs of the membrane filtration unit (Heylen C., 2018).

For the capital costs of the Andicos^{TM} treatment technology, the land occupation, civil engineering, the membranes and work management were considered (Heylen C. 2018). To reach a treatment capacity of 130 MLD with a filtration flux of $25 L.m^{-2}.h^{-1}$, the Andicos^{TM} treatment facility needs a total membrane surface of 216,667 m².

The operational costs include the cleaning agents, the energy and the manpower. The power demand is mainly dependable on the energy required for pumping and membrane aeration (Heylen C., 2018). Therefore, the power costs can be calculated from the flux of filtration and the flux of aeration (Judd S., 2011). Based on the optimized settings described above, the energy cost equals 0.105 \$/m³ permeate (7.96 Rs/m³ permeate) for flat sheet filtration (Judd S., 2011).The energy consumption calculation does not include retentate nor gas management.

However, the anaerobic digestion produces biogas and thus energy, resulting in a reduction of the operational costs (Diels L., 2017; Heylen C., 2018). For 130 MLD of wastewater with an average concentration of 1.14g COD, each day 86,000 kg COD can be recovered for anaerobic digestion. As the UF membranes can retain organic matter in the membrane tank up to a concentration of 9 g/L, 9556 m³ of retentate have to be removed from the membrane tank to fill the digestors. To increase the productivity of the digestors, 2006-ton kitchen waste must be added to the retentate stream to reach the recommended volatile solids load of 2 VS/L.d (Tuyet et al., 2016). According to World bank (2012), the average food waste generation in India is 0.7kg solid waste per capita, whereof 58% is organic waste (Silpa et al. 2018). Therefore, the total organic waste production of Kanpur is estimated to be 2044 tons, which is in the same range as the required organic waste for the Andicos™ treatment facility (2006 tons). Thus, it can be concluded that the Andicos™ treatment concept is a good solution to tackle both the wastewater discharge and the municipal solid waste dumping. The increasing population in combination with an increasing waste generation per capita will result in an even higher solid waste production in Kanpur in the near future. Therefore, the call for an integrated waste solution will become even more pronounced.

Combining the retentate and the solid municipal waste , generates an organic matter input of approximately 462-ton COD per day for the anaerobic digestion part of the Andicos™ technology. Considering a methane gas production of 0.247m³/kg COD with an electrical conversion efficiency of 40% (Tuyet et al. 2017; Van Lier, 2018), the anaerobic digestion could generate up to 475,398 kWh or 4,278,582 Rupees/day (figure 5.2). To implement the anaerobic digestion process, a digestor of 209,165 m³ has to be constructed. This construction requires additional investments (land requirement, civil engineering, etc.) (Heylen C., 2018; Tuyet et al. 2016). Besides, the collection of municipal organic waste costs on average 16 USD/ton in Indian metropolitans (Parthan A., 2009). However, a futureproof city requires an adequate waste collection management (Heylen C., 2018).

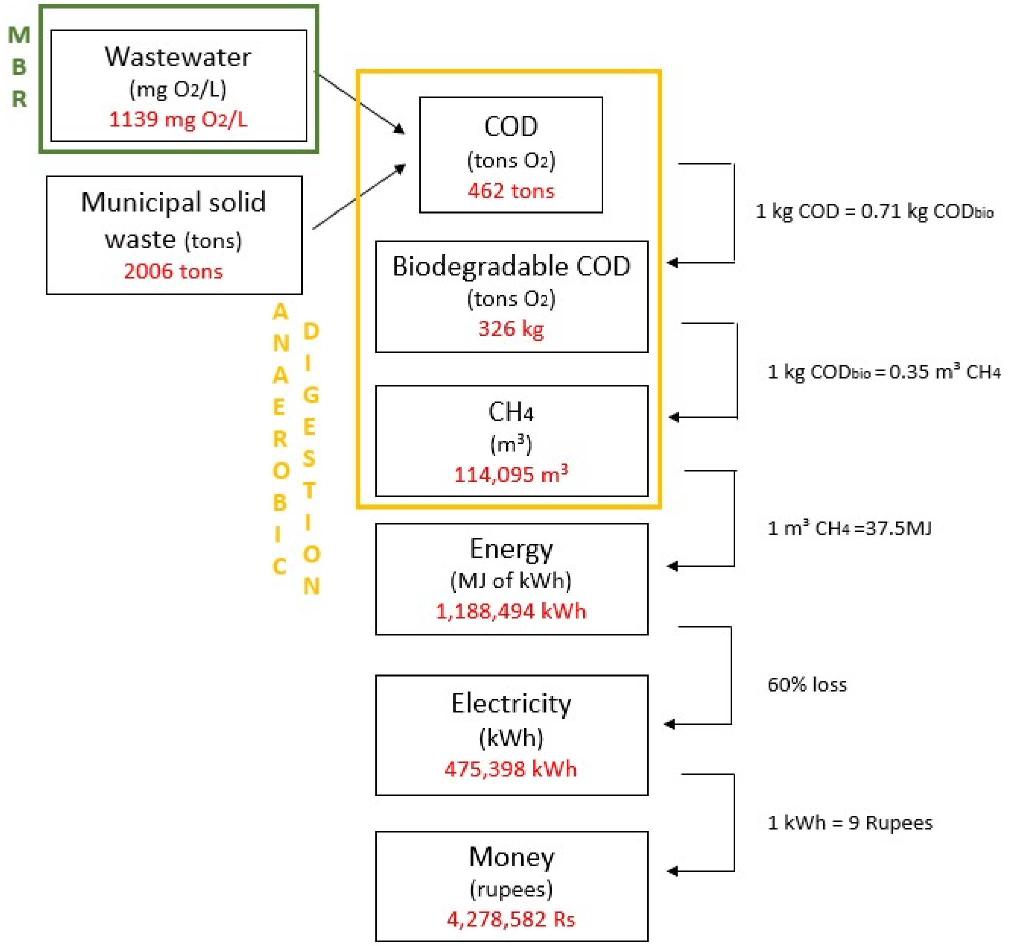

***Figure 5.2** Schematic representation of the different steps of anaerobic digestion from wastewater and municipal solid waste to money per day.*

The total cost calculation for the MBR technology, the Andicos^{TM} technology, the ASP technology and the UASB technology can be found in Appendix E. It was found that the implementation of membrane filtration without anaerobic digestion (318.2 million Rs/year) would be more expensive in comparison to the traditional ASP (215.5 million Rs/year) and UASB (212.9 million Rs/year) technologies. Combining the membrane filtration with anaerobic digestion would result in a profitable investment. The energy production via anaerobic digestion compensates the high investment costs of the membranes and in addition creates a yearly profit of 262 million rupees. The estimated profit could be exaggerated due to simplifications in the cost estimations.

C. *Overall assessment*

As both effluent quality and costs are important criteria for the implementation of new technologies, an assessment in terms of costs and effluent quality of the different technologies is made in this section. This comparison includes the current treatment technologies in Kanpur with the MBR and Andicos^{TM} treatment technologies (Heylen C., 2018).

In the previous section, the costs of the technologies were estimated by considering the capital and operational costs, which were calculated according values found in the literature (Heylen C., 2018; Indian Institute of Technology, 2010; Judd S., 2011; Pathan S., 2009). The capital costs included land requirement, civil engineering, membranes and management costs, while the operational costs included labor, power, reparations chemical agents and municipal waste collection (Heylen C., 2018). However, costs related with sludge, retentate, digestate and gas management were not considered (Heylen C., 2018).

The EQI was estimated by applying the observed removal efficiencies on the mean contaminant concentrations of the primary effluent of the Jajmau treatment plant. The EQI estimation for the UASB plant was based on the treatment efficiencies observed during the research project of Heylen C. in 2018.

The MBR/Andicos^{TM} treatment technology would clearly discharge an increased effluent quality in comparison to the current technologies (ASP and UASB). However, the high costs involved with the implementation of IPC membranes discourages the Indian government to implement this technology (Bose P., February 25, 2020). Therefore, the Andicos^{TM} treatment technology, integrating anaerobic digestion into the ultrafiltration process, could be the right solution (Heylen C., 2018). Through anaerobic digestion of the carbon-rich stream, Andicos^{TM} generates energy and thus monetary value, which repays the debt of the MBR-units. Figure 5.3 shows that Andicos^{TM} could be a profitable investment, although some simplifications in the cost calculation could have led to an overestimation of the net profit. In addition to the other technologies, the Andicos^{TM} technology also tackles the increasing municipal solid waste problem and energy shortages in India.

It can be concluded that Andicos^{TM} could be an appropriate technology to tackle the increasing pressure on the environment (wastewater + municipal solid waste), while being economically profitable for the authorities.

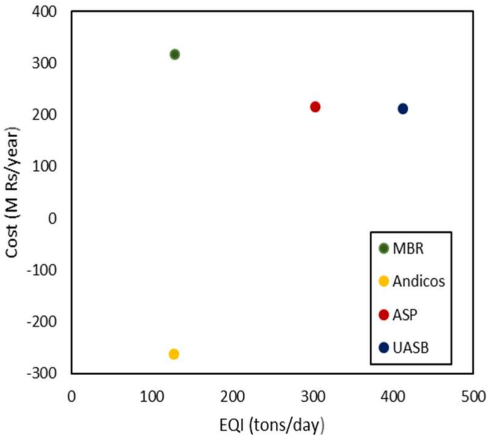

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Figure 5.3 The technologies (MBR, Andicos^{TM}, ASP and UASB) are compared according their capacity to treat Jajmau wastewater with regards to the effluent quality (tons contaminant/day) and the cost (million rupees/year)

6. Perspectives

This manuscript showed that the implementation of the Andicos^{TM} technology could result in more sustainable and economic waste treatment in Kanpur. Compared to the traditional wastewater technologies, Andicos^{TM} generates a better effluent quality with lower operational costs, while being a net-energy producer instead of a net-energy consumer which reduces its pressure on the weak electrical grid and emerging climate change. The improved effluent quality of ultrafiltration in comparison to the traditional ASP and UASB could help to increase the resilience of the Ganges river (Heylen C. 2018). As the Andicos^{TM} treatment technology combines the interests of the economic development and those of the natural environment, this clean technology could give incentives to the government and enterprises to invest in sustainable water treatment (Heylen C., 2018). While there are clear benefits associated with the implementation of the Andicos^{TM} technology, there are some hurdles to overcome.

For the water treatment sector in Kanpur, the Andicos^{TM} pilot-scale treatment plant will be the first experience with membrane filtration. Knowledge and experience are missing and therefore the implementation of the Andicos^{TM} technology will first face an exploratory phase wherein the system still has some teething problems (Heylen C., 2018). Also, laborers and technicians will need appropriate instruction and training to guarantee the efficient functioning of the system. The huge learning step in combination with the high investment cost may discourage the government of potential investments in the Andicos^{TM} technology (Heylen C., 2018). However, it was found that electricity production via anaerobic digestion could compensate for these investment costs. Although, the capital recovery via anaerobic digestion, which is of critical importance for the economic viability of the Andicos^{TM}, could be a major problem in Kanpur. The water treatment sector in Kanpur has already the possibility to recover funds through the implementation of an anaerobic digestion process in the UASB facilities, but this is not the case (Heylen C., 2018). No explanation was found that could clarify this missed opportunity. Maybe this manuscript can show the feasibility and the advantages of anaerobic digestion to the authorities of Kanpur.

As a sufficient amount of organic waste is required to enforce the anaerobic digestion process in the Andicos^{TM} technology, the development of a comprehensive municipal organic waste collection system in Kanpur will be crucial. Kanpur Nagar Nigam reports an average waste collection of 90% in the city center (1,266 tons/day) (Zia & Devadas, 2007). However, the collection rates for the suburbs are expected to be lower. To expand the waste collection system, huge investments in collection cars, sorting machines, storage rooms, etc. have to be made. The high proportion of organic waste in the municipal solid waste of low-income countries is beneficial for the rentability of the waste collection and sorting in Kanpur. The up-coming Indian industrialization can cause a decrease in the proportion of organic waste, which may increase the collection and sorting costs in the future.

As municipal waste primarily consists of kitchen waste, the retentate was enriched with kitchen waste to make a carbon-rich stream and test its biodigestibility in this experiment. It was found that 1kg kitchen waste of the IIT campus contains 187-gram COD, which had a biodegradability of 71% when diluted in the retentate. However, it can be expected that the organic waste fraction in the municipal waste of Kanpur has a lower COD content (e.g. 0.16 kg COD/kg organic waste according to Kumar (2015)) and may be characterized by a lower biodegradability. This is assumed because municipal organic waste also contains municipal green waste and garden waste with a high lignocellulose content. Therefore, it can be expected that the rentability of a full-scale anaerobic digester fed with municipal organic waste will be lower.

The optimal settings for the Andicos^{TM} technology were defined during a short test period (February-March 2020). During this period, the Jajmau wastewater characteristics were quite stable and thus some primary wastewater parameters showed only minor variability. As the major part of the influent originates from open drains with as main contributor the Sisamau drain (60 MLD), it can be expected that the influent quality is prone to intra- and inter-annual changes according to the climate (Heylen C., 2018). Our research was executed during the summer season with an average total monthly rainfall of 17.1mm at Kanpur, therefore the wastewater was not much diluted by rainwater resulting in a stable and strongly concentrated influent for the Jajmau STPs. During the monsoon season, the Jajmau influent will be more diluted and variable as the average total monthly rainfall can reach values up to more than 300mm during this period (Heylen C.,2018). Less concentrated wastewater could be advantageous for membrane filtration, due to less concentration polarization/fouling. Therefore, higher filtration fluxes may be achieved during monsoon season in comparison with the highest stable flux found during this experiment. However, organic matter concentration in the retentate could be worsened due to low organics in sewage mixed with rainwater. An increased sludge retention time could counter this drawback but would also result in an increase of investment costs (Heylen C., 2018). It can be expected that the Andicos^{TM} technology will have alternating optimal settings throughout the different seasons of the year. In addition, climate change can induce an increased inter-annual variability in precipitation and temperature which may force the Andicos^{TM} technology to regularly adjust its settings. Therefore, it is recommended to further investigate the impact of intra- and inter-annual variability of the wastewater on the functioning of the Andicos^{TM} technology. Furthermore, the increasing population of Kanpur could have an impact on the wastewater quality in the future (Heylen C., 2018). However, this effect is considered to be of minor importance because Kanpur will mainly be subjected to horizontal expansion (Heylen C., 2018). Therefore, the wastewater quality will not change much over time as new suburbs will be colonized and new open drains will be formed (Heylen C.,2018).

Another drawback is the land requirement to install a new large-scale treatment plant. Although the land demand for the Andicos^{TM} is low in comparison to conventional treatment technologies, the required surface area for the implementation of a 130MLD-Andicos^{TM} treatment facility is not available at the Jajmau STP site and the dense population of Kanpur does not offer the ability to colonize a new STP ground in the city center (Heylen C., 2018). Therefore, the government decided to move the construction of new wastewater facilities to the peripheral areas of the city (Heylen C., 2018). The transportation of wastewater from the city center to the outlying regions will require huge investment costs in sewerage as the current coverage of the sewerage is insufficient (Heylen C., 2018). Moving the treatment facility to the peripheral areas of the city may imply a change in influent composition. Due to the outlying location of the future STP ground and the insufficient sewerage coverage, the fraction of suburb wastewater may increase at the expense of the wastewater from the city center. As mentioned, the origin of the wastewater can strongly affect the overall performance of the Andicos^{TM} treatment technology with regards to fouling contribution, effluent quality and carbon loss through biodegradation. Freshly produced wastewater should be avoided as the readily degradable organic fraction is suspected to be the major cause of the deteriorated functioning of the Andicos^{TM} system. To make the Andicos^{TM} technology more robust against changing influents, more testing with different influents will be required.

When Kanpur considers implementing a large-scale Andicos^{TM} treatment plant, they should pay attention to the elements mentioned above. As the construction of a new Andicos^{TM} facility deals with these hurdles, this technology may be the most suitable technology for waste and wastewater treatment at Kanpur with regards to environmental sustainability and economic profitability.

7. Conclusion

A combination of rapid population growth, urbanization and economic development in the developing countries has spurred an overwhelming increase in production of wastewater and municipal solid waste (Avraamidou et al. 2018). The development of treatment facilities and disposal sites has not caught up with the fast-growing waste and wastewater production, causing high loads of untreated sewage and municipal solid waste in the rivers and its banks with serious consequences for the urban river quality (Xu et al. 2019). The new conceptual waste treatment approach Andicos^{TM}, combining wastewater filtration by IPC membranes with anaerobic digestion of the concentrated retentate to produce energy, could be an adequate solution to the dualistic waste problem of low-income countries. This technology consists of two main steps: treating wastewater through membrane filtration and retentate processing via anaerobic digestion with biogas and organic fertilizer production. As the organic carbon concentration of the membrane concentrate is not sufficient high to allow efficient anaerobic digestion, the retentate is combined with processed organic municipal solid waste.

This MSc thesis investigated the implementation of the Andicos^{TM} technology to solve the devastating waste problem in Kanpur, India, and thereby provided an illustrative case to other cities in developing countries. As currently huge loads of untreated domestic wastewater are directly drained into the Ganges river near the city of Kanpur which contributes to the deteriorated state of the Ganges river basin, this study aimed attention at the treatment of domestic wastewater and looked for the optimal system settings to allow efficient functioning of the Andicos^{TM} technology at the Jajmau STP ground of Kanpur to facilitate the future implementation of a pilot-scale Andicos^{TM} plant.

To achieve the desired continuity in the membrane filtration process, the negative effect of concentration polarization/fouling had to be minimized while a sufficient high permeate flux had to be sustained to reduce the overall costs of the Andicos^{TM} treatment plant. Moreover, an adequate balance between effluent quality and carbon concentration in the membrane tank had to be looked for to satisfy both ecological and economic incentives. With regard to these criteria, our experiments found out that a filtration phase with a flux of 25 $L.h^{-1}.m^{-2}$ sustained for 9 minutes followed by a backwash phase for 40 seconds with a strength of 37.5 $L.h^{-1}.m^{-2}$ and a 20-seconds during relaxation period were the optimal membrane filtration configurations to generate as much as possible permeate with minimal fouling for the filtration of primary effluent of the Jajmau ASP. The primary effluent contained a high load of organic matter (1138.8 ± 164 mg COD/L and 433.6 ± 61.5 mg sCOD/L) and suspended solids (979.4 mg TSS/L ± 134.5). During the Jajmau wastewater filtration experiments, the IPC membranes efficiently retained organic carbon (91.4 ± 2.3 %) whereof a considerable amount (32.3 ± 9.6 %) was lost, probably through biodegradation. As the retention capacity of the membranes was strongly correlated with the membrane tank COD concentration, the membrane tank COD concentration should not exceed 9096 $mg.L^{-1}$ to meet the Indian regulation standards (<120 mg $COD.L^{-1}$). However, the critical flux, removal efficiency and COD loss depend a lot on the origin of the wastewater. Mature wastewater with a high particulate COD:total COD ratio allowed high filtration fluxes, COD levels in the retentate and good effluent quality to be achieved, whereas fresh wastewater with a high readily biodegradable fraction recorded significantly poorer results for fouling sensitivity, organic matter removal and carbon recycling.

To validate the assumption of reducing operational costs through biogas production via anaerobic digestion of the retentate, its biodegradability was tested in a digestor test. Anaerobic digestion of the retentate combined with processed organic kitchen waste showed a biodegradability of 71% for a sludge retention time of 20 days resulting in the production of 436 ± 12 mL/g VS_{added} or 380 ± 11 mL/g COD_{added}. The addition of alkaline retentate to food waste may have had a positive buffer effect on the pH-drop through volatile fatty acid formation during digestion. As an increased sludge retention time in the membrane tank negatively affected the percentage share of soluble organic matter in the retentate, the biodegradability of the retentate could be increased by reducing the membrane tank SRT. To reach a volatile solid load of 2 g $VS.L^{-1}.d^{-1}$, 210-gram kitchen waste (containing 187 $g_{COD}/kg_{kitchen\ waste}$) should be added to 1L of retentate ($9g_{COD}/L$). Via anaerobic digestion, the carbon-rich stream will produce 0.88 $m^3{}_{methane}/m^3{}_{sewage\ treated}$ or 3.66 $kWh/m^3{}_{sewage\ treated}$ at an electrical conversion of 40%, which is by far more than the expected power requirement for membrane filtration (e.g. $0.4kWh/m^3{}_{sewage}$ according to Tuyet et al., 2016). Thus, the Andicos^{TM} technology can shift the water treatment processes from a net-energy consumer to a net-energy supplier making it a profitable investment.

After optimization of the membrane filtration set-up, the IPC membrane ultrafiltration recorded high removal efficiencies for the major contaminants (95.5 ± 0.3% for TSS, 87.8 ± 0.3% for COD, 67.9 ± .5 for sCOD, 61.9 ± 1.1 N-TKN, 16.3 ± 5.1 N-NH_4 and 100.0 ± 0.0 for total chromium). As the ultrafiltration heavily reduced the contaminant load, the implementation of a full-scale Andicos^{TM} (130-MLD) could decrease the EQI of the Jajmau primary effluent from 786.2 ton/day to 128.3 ton/day after treatment. This is considerably better than the current ASP, which has an EQI of 303.4 ton/day. The results imply that the implementation of a large-scale Andicos^{TM} facility (130 MLD) could improve drastically the Ganges river water quality during the low flow regime in summer season (-8.84 mg COD/L, -8.41 mg TSS/L and -0.29 N-TKN/L) and thereby could contribute to the resilience of the Ganges river.

It can be concluded that Andicos^{TM} is economic and environmentally sustainable waste and wastewater treatment technology as it delivers an excellent effluent quality to resilience river systems while being a net-energy producer and reducing greenhouse gas emissions.

Hopefully, this manuscript opens the way for future implementations of Andicos^{TM} technology-bases treatment facilities to resolve the overwhelming waste problematic in Kanpur and other fast-growing cities of developing countries

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Appendix A: Description of the analysis

The Chemical Oxygen Demand (COD) “is the amount of oxygen required to oxidize by chemical means organic carbon completely to CO2 (mgO2/L)” (Heylen C., 2018). To determine the COD, the closed Reflux Method was used. Different proceedings are executed during The Closed Reflux Method to oxidize the organic matter in the sample by $K_2Cr_2O_7$ under stringent conditions (concentrated sulphuric acid medium, 150°C) (Heylen C., 2018). The amount of $K_2Cr_2O_7$ reacted is expressed in terms of its oxygen equivalent (Heylen C., 2018).

A water sample of 2.5 mL is placed in a tube with 1.5 mL of 0.01667 M standard potassium dichromate digestion solution. To prepare this digestion solution, 4.963 g $K_2Cr_2O_7$ is dissolved into 500mL distilled water with 167mL concentrated H_2SO_4 and 33 g $HgSO_4$. Then, the solution is made-up to 1L. Afterwards, COD acid (3.5ml) is added to the water sample. The COD acid is a mixture of Ag_2SO_4reagent and concentrated H_2SO_4 at the rate of 5.5 Ag_2SO_4/kg H_2SO_4. Before use, the solution should stand for 1-2 days to dissolve the Ag_2SO_4.. After mixing the tubes, the tubes were heated for 2 hours at 150°C. Then, the samples are cooled to room temperature and titrated with 0.10M Ferro-Ammonium-Sulfate solution and 1 to 2 drops of ferroin indicator. To prepare the 0.10M Ferro-Ammonium-Sulfate, 39.2 g $Fe(NH_4)_2(SO_4)_2*6H_2O$ is dissolved in 980L of distilled water and 20mL of concentrated H_2SO_4.The same protocol is repeated for the four blankets with 2.5ml of deionized water. Two blankets are heated (“hot blankets’), whereas the other two are not heated (“cold blankets”). (Heylen C, 2018)

Then, the COD is defined by

$$COD = \frac{(v_1 - v_2) * M_{FAS} * 8000}{V_s}$$

With

$$M_{FAS} = \frac{v_s}{v_3} * 0.1$$

Where COD is expressed in mgO_2/L, V_1 represents the volume of consumed FAS by the hot blank (mL), V_2 is the volume FAS consumed by the sample (mL), V_s is the volume of the sample (mL), M_{FAS} is the molarity of the FAS solution,V_3 is the volume of FAS consumed by the cold blank (mL).

To increase to representability of the analysis, two duplicates have to be analyzed for each sample. As the Closed reflux method is only valid for COD concentrations between 40 and 400 mg/L, concentrated samples were diluted.

For soluble Chemical Oxygen Demand, the same protocol was followed after filtration of the sample through a 0.45um filter.

The total suspended solids “is the concentration solids removed by (0.45 um).” (Heylen C., 2018) The total suspended solids were gravimetrically analyzed by weighing the suspended solids yielded from a known volume of sample by filtration through a 0.45um paper. Before filtration, the paper was dried overnight in an oven at 105°C and weighted on an analytical balance. Then, the sample of 5ml water was filtered through a 0.45um filter. After filtration, this filter was again placed in an oven at 105°C.. Finally, the dried sample was weighted. The difference between the two measurements reveals the total suspend solid concentration.

The TSS is defined as by

$$TSS = (w_2 - w_1) * 200$$

Where w_2 is the weight of the filter after filtration and w_1 is the weight of the filter before filtration.

Total Kjeldahl nitrogen (TKN) is defined as the sum of N-NH4 and organically bound nitrogen in mg/L NH_4-N. The method consists of a pretreatment of the sample and the actual NH_4 determination. During the pretreatment, the sample is boiled in presence of K_2SO_4, H_2SO_4 and $CuSO_4$ to convert the organic matter in the sample into CO_2 and H_2O. Hereby, the organically bound nitrogen will convert to ammonia nitrogen. To measure the ammonia concentration, ammonia combines with the Nessler's reagents to form a yellowish complex. The formed complex absorbs light at a spectrum of 410-440nm. The amount of light absorbance defines the concentration of ammonia. (Indian Institute of technology Kanpur, 2020)

The sample is prepared by adding 50 mL water sample and 10mL of digestion solution in a Kjeldahl flask. To prepare the digestion solution, 13.4 g K_2SO_4 is diluted in 65mL of water and 20mL of concentrated H_2SO_4. Then, 2.5 ml of mercuric sulfate solution (8g of red mercuric oxide in 100mL of 6N H_2SO_4) is added while stirring to the digestion solution and diluted to 100mL. The mixture of sample with digestion solution is boiled until the solution becomes transparent and then the solution is cooled to room temperature. The boiling time is approximately 45 minutes. Then, the sample transferred to a measuring flask. The content is rinsed in the same flask until the volume becomes 50 mL and the pH is adjusted to nearly 7. Finally, the sample is diluted in such a way that the expected concentration lies within the calibration range. (Indian Institute of technology Kanpur, 2020)

After preparation phase, the procedure to determine the ammonium nitrogen starts. First, an EDTA reagent is prepared by dissolving 50g disodium EDTA dihydride in 60 ml of water containing 10g NaOH. If necessary to complete dissolution, gentle heat can be applied. Then, the mixture is cooled to room temperature and diluted to 100ml. Afterwards, 10 g HgI_2 and 7 g KI is diluted in a small amount of water to prepare the Nessler reagents This mixture is slowly added to a solution of 16g NaOH dissolved in 50mL of water while stirring. Then, the solution is further diluted to 100ml and have to be stored in the dark. In addition, a stock ammonium solution is prepared by diluting NH_4Cl in distilled water, so that 1ml equals 10ug of NH_4-N. With this stock ammonium solution, standards can be prepared for the calibration curve. Standards should be prepared by diluting the stock solution in distilled water in such a way that the calibration range will be 1mg/L to 4mg/L NH_4-N. (Indian Institute of technology Kanpur, 2020)

To define the ammonium content, 1 drop of EDTA solution is mixed into the prepared TKN-N sample and the standard solutions. Then, 2 mL of Nessler's reagent is added to the sample and standards. After mixing, one should let the color development proceed for 10 minutes. Finally, the absorbance of the sample and standards is measured at 410nm. With the readings of the standards the absorbance versus concentration curve can be drawn. The calibration curve is then used to determine the N-TKN (mg/L NH_4-N) concentration in the water sample. (Indian Institute of technology Kanpur, 2020)

To define only **the ammonium content** of a water sample, the same procedure has to be followed without the sample preparation. As organically bound nitrogen should not be converted to ammonia nitrogen, the EDTA solution and Nessler's reagent are directly added to the water sample. (Indian Institute of technology Kanpur, 2020)

Total Chromium content in the water sample was measured following the acid digestion method EPA 3050 proposed by USEPA. The method provides a digestion procedure to prepare a wastewater sample for analysis by flame atomic absorption. The acid digestion will dissolve almost all elements chromium that could become available to the environment. This includes almost all dissolved and absorbed chromium, while chromium bound in silica structure is normally not dissolved by this procedure. However, the in silica bound chromium is considered as not "environmentally available". To digest the sample, 1g (wet weight) sample is heated with several additions of nitric acid and hydrogen peroxide. (Abbruzzini et al. 2014)

First, a representative sample (1g) is sieved and homogenized. For the digestion of the sample, 10mL of 1:1 HNO_3 is added and mixed with the slurry. Then, the mixture is heated till 95°C and refluxed without boiling for 15 minutes. After cooling, another 5 ml of 1:1 HNO_3 is added to the sample and then the sample is again refluxed at 95°C for 2 more hours. Afterwards, the samples are cooled and 3ml of 30% H_2O_2 and 2ml of distilled water were added. Again, this mixture is boiled at 95°C till effervescence subsidized. Afterwards, the mixture can be cooled and diluted with 5mL of HCL and 10mL of distilled water. The solution is than reheated a final time for 5 minutes at 95°C. Finally, the samples can be cooled and diluted till 50mL. With the help of Atomic Absorption Spectrometry, the concentration of total chromium can be determined. (Abbruzzini et al.2014)

The sulfate content of the samples was determined by a gravimetric method using barium sulphate precipitation. To determine the sulphate content of a water sample, the sulphate is precipitated as barium sulphate in dilute HCL with barium chloride. The precipitated barium sulphate is separated from the solution by means of filtration and dried. Then the precipitate can be weighted. (Opoku,.E. 2014)

First, 3ml of 1:1 HCL is added to 250ml of the water sample. Then the solution is heated to approximately 90°C and 80ml of 0.05M $BaCl_2$ is added. After stirring, the solution is digested for 30 minutes. To validate the completeness of the test, several drops of $BaCl_2$ have to be added to the mixture. When precipitation clouds are formed, an additional 40ml of 0.05M $BaCl_2$ should be added. This step has to be repeated until no cloudiness is formed. Before filtration, the weight of a dried filter paper is measured. Then, the precipitated $BaSO_4$ is filtered through the weighed filter paper. Finally, the filter paper is dried and weighed again. (Opoku, E. 2014)

$$SO_4(\frac{mg}{l}) = (w_2 - w_1) * 0.4116 * 4$$

Where w_1 is the weight of the dried filter paper, w_2 is the weight of the filter paper after filtration of $BaSO_4$, 0.4116 equals the gravimetric factor and the factor 4 represents the sample volume.

Appendix B Results of filtration test

Origin	Date of sampling	Date of testing	Volume membrane tank (L)	Volume retentate removed (L)	Membrane tank COD (mg/L)	Influent volume (L)	Influent COD (mg/L)	Permeate 1 volume (L)	Permeate 1 COD (mg/L)	Permeate 2 volume (L)	Permeate 2 COD (mg/L)	Permeate 3 volume (L)	Permeate 3 COD (mg/L)
IIT	10/02/2020	10/02/2020	42.7	-	1120	686	134.4	33.7	120	31.8	128	23.1	136
	11/02/2020	11/02/2020	42.7	-	1350	480	86.8	32.2	83	30.7	90	22.5	98
	12/02/2020	12/02/2020	42.7	-	1575	304	84.3	31.7	75	30.4	90	22.2	92
	13/02/2020	13/02/2020	42.7	-	1745	300	85.4	32.1	58	30.6	65	22.7	61
Jajmau	18/02/2020	19/02/2020	42.7	-	2450 (711)	114	1230 (472)	27.3	65.0	26.4	68	17.6	60
		20/02/2020	42.7	-	3675 (845)	83	1175 (451)	31.5	68	30.4	68	21.1	75
		21/02/2020	42.7	-	4950 (941)	86.1	1190 (473)	32.1	75	31.9	82	22.1	82
		22/02/2020	42.7	9.2	6050 (1029)	78.5	1140 (412)	29.3	90	28.6	92	20.6	98
		23/02/2020	42.7	9.2	6580 (1349)	84.5	1150 (478)	27.9	93	27.3	96	20.1	96
		24/02/2020	42.7	9.2	7120 (1566)	92.7	1180 (449)	30.7	96	30.4	98	22.4	105
		25/02/2020	42.7	-	6710 (1543)	59.8	1120 (432)	19.4	98	18.9	98	12.3	106
Jajmau	27/02/2020	27/02/2020	42.7	-	6680 (1703)	-	-	-	-	-	-	-	-
		28/02/2020	42.7	14.1	8930 (1290)	124.3	1280 (493)	30.4	108	42.5	111	51.4	113
		29/02/2020	42.7	14.1	8850 (2434)	137.2	1360 (484)	30.7	106	41.6	112	50.8	112
		1/03/2020	42.7	14.1	8480 (2374)	140.3	1290 (497)	31.3	104	42.3	108	52.6	111
		2/03/2020	42.7	14.1	8230 (2346)	142.6	1310 (482)	32.2	104	42.9	107	53.4	107
		3/03/2020	42.7	6.7	7910 (2294)	140.8	1370 (501)	31.6	105	42.4	107	52.7	108
		4/03/2020	42.7	6.7	9120 (2280)	131.5	1340 (512)	30.9	112	41.8	112	52.1	116
		5/03/2020	42.7	-	9490 (1993)	72.4	1280 (466)	16.9	117	21.6	118	27.2	117
Jajmau	7/03/2020	8/03/2020	32.3	-	7030 (1195)	-	-	-	-	-	-	-	-
		9/03/2020	32.3	6.2	9020 (1450)	115.8	940.0 (382)	62.7	115	53.1	113	-	-
		10/03/2020	32.3	6.2	9110 (1867)	107.5	970.0 (364)	48.9	117	52.4	116	-	-
		11/03/2020	32.3	6.2	8830 (1943)	102.1	910.0 (362)	43.1	114	52.8	115	-	-
		12/03/2020	32.3	6.2	8710 (2047)	100	910.0 (362)	42.2	110	51.6	112	--	-
		13/03/2020	32.3	6.2	8650 (1946)	104.1	930.0 (331)	43.6	112	54.3	114	-	-
		14/03/2020	32.3	6.2	8720 (2006)	102.5	930.0 (331)	42.9	109	53.4	113	-	-
		15/03/2020	32.3	-	8760 (2059)	101.3	910.0 (356)	42.3	107	52.8	110	-	-

Origin	Sampling date	Test date	TSS (mg/L)					N-TKN (N-NH$_4$) (mg/L)					SO$_4^{2-}$ (mg/L)					Total chromium (mg/L)				
			INF	P1	P2	P3	RET	INF	P1	P2	P3	RET	INF	P1	P2	P3	RET	INF	P1	P2	P3	RET
IIT	10/02/2020	10/02/2020	145	4.3	-	-	-	-	-	-	-	-	-	-		-	-	-	-	-	-	-
	11/02/2020	11/02/2020	202	6.8	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	12/02/2020	12/02/2020	165	2.3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	13/02/2020	13/02/2020	212	7.3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Jajmau	18/02/2020	19/02/2020	1012	-	-	-	1012	-	-	-	-	-	-	-	-	-	-	7.1	<0.1	<0.1	<0.1	15.1
		20/02/2020	1032	2.5	2.6	2.6	2454	-	-	-	-	-	-	-	-	-	-	6.5	<0.1	<0.1	<0.1	25.9
		21/02/2020	986	9.9	7.3	8.0	3972	-	-	-	-	-	-	-	-	-	-	6.2	<0.1	<0.1	<0.1	36.7
		22/02/2020	1046	0.6	2.2	2.6	5620	-	-	-	-	-	-	-	-	-	-	6.4	<0.1	<0.1	<0.1	46.6
		23/02/2020	1002	1.8	7.3	5.3	7104	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		24/02/2020	1061	17.9	7.1	###	7122	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		25/02/2020	1024	3.4	8.6	9.6	7334	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Jajmau	27/02/2020	27/02/2020					6792	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		28/02/2020	1093	4.0	4.1	4.4	8557	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		29/02/2020	1119	3.4	4.6	1.6	7949	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		1/03/2020	1107	0.9	0.7	2.0	7501	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		2/03/2020	1142	3.0	2.0	2.2	7302	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		3/03/2020	1136	3.1	3.0	3.0	7074	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		4/03/2020	1128	2.8	3.6	4.0	8010	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		5/03/2020	1087	2.8	2.7	2.8	7867	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Jajmau	7/03/2020	8/03/2020	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		9/03/2020	812	5.9	7.1	-	9672	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		10/03/2020	807	5.4	1.4	-	9482	52.3 (15.4)	19.0 (12.7)	19.3 (12.8)	-	356.3 (15.6)	114	110	113	-	136	-	-	-	-	-
		11/03/2020	792	2.5	2.6	-	9264	55.8 (19.5)	20.4 (16.1)	22.2 (16.5)	-	372.2 (18.9)	129	126	125	-	149	-	-	-	-	-
		12/03/2020	798	3.1	6.1	-	9137	49.7 (17.2	19.7 (15.1)	19.8 (15.6)	-	379.1 (17.6)	106	105	103	-	112	-	-	-	-	-
		13/03/2020	816	7.4	6.8	-	9136	53.6 (18.6)	19.8 (14.8)	23.2 (17.7)	-	384.8 (18.8)	-	-	-	-	-	-	-	-	-	-
		14/03/2020	786	1.2	1.2	-	8964	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		15/03/2020	781	4.0	4.6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

$Appendix C Results of Jajmau ASP

Origin	Sampling Date	TSS (mg/L)		TKN (mg/L)		COD (mg/L)		sCOD (mg/L)		Cr (mg/L)	
		INF	E	INF	E	INF	E	INF	E	INF	E
Jajmau	18/02/2020	1012	124	57.9 (18.7)	46.4 (10.8)	1230	665	472	145	8.8	2
	27/02/2020	1093	222	61.4(16.4)	43.7 (9.5)	1280	515	493	223	5.3	1.4
	7/03/2020	812	192	52.3 (15.4)	41.3 (8.6)	940	314	382	148	7.1	1.4

Appendix D Results of anaerobic digestion tests

		pH			Volume feed (mL) added		VS load (g/L.d)			COD load (g/L.d)			Biogas (ml)		
Date	D	FW	FW/R	R	In	Out	FW	FW/R	R	FW	FW+ R	R	FW	FW +R	r R
28/02/2020	1	5.05	6.75	7.4	80	80	1.5	1.8	4.4	1.6	1.95	0.34	110	-	10
29/02/2020	2	4.7	5.7	7.1	80	80	1.5	1.79	-	1.6	1.95	0.34	210	-	15
1/03/2020	3	4.5	5.2	6.7	-	-	-	-	0.3	-	-	-	-	-	10
2/03/2020	4	4.5	5.2	6.7	-	-	-	-	0.3	-	-	-	-	-	10
3/03/2020	5	4.5	5.2	6.7	-	-	-	-	0.3	-	-	-	-	-	10
4/03/2020	6	7.6	7.4	7.6	80	80	1.5	1.8	0.3	1.6	1.95	0.34	40	110	15
5/03/2020	7	7.6	7.3	7.6	80	80	1.5	1.8	0.3	1.6	1.95	0.34	70	200	10
6/03/2020	8	7.5	7.4	7.6	80	80	1.5	1.8	0.3	1.6	1.95	0.34	90	180	15
7/03/2020	9	7.6	7.4	7.6	80	80	1.5	1.8	0.3	1.6	1.95	0.34	80	200	10
8/03/2020	10	7.5	7.3	7.5	80	80	1.5	1.8	0.3	1.6	1.95	0.34	120	240	20
9/03/2020	11	7.6	7.3	7.5	80	80	1.5	1.8	0.3	1.6	1.95	0.34	110	250	30
10/03/2020	12	7.5	7.3	7.5	80	80	1.5	1.8	0.3	1.6	1.95	0.34	130	330	20
11/03/2020	13	7.6	7.3	7.5	80	80	1.5	1.7	0.3	1.6	1.93	0.34	150	320	25
12/03/2020	14	7.5	7.3	7.5	80	80	1.5	1.7	0.3	1.6	1.93	0.44	120	350	35
13/03/2020	15	7.4	7.3	7.5	80	80	1.5	1.7	0.3	1.6	1.93	0.44	140	370	40
14/03/2020	16	7.3	7.3	7.5	80	80	1.5	1.7	0.3	1.6	1.93	0.44	80	350	60
15/03/2020	17	7.3	7.2	7.5	80	80	1.5	1.7	0.3	1.6	1.93	0.44	120	310	50
16/03/2020	18	7.1	7.1	7.4	80	80	1.5	1.7	0.3	1.6	1.93	0.44	140	400	50
17/03/2020	19	7.2	7.1	7.4	80	80	1.5	1.7	0.3	1.6	1.93	0.44	140	560	50
18/03/2020	20	7.1	7.1	7.5	80	80	1.5	1.7	0.3	1.6	1.93	0.44	160	540	50
19/03/2020	21	7.1	7.1	7.4	80	80	1.5	1.7	0.3	1.6	1.93	0.44	190	480	-
20/03/2020	22	7.1	6.9	7.4	80	80	1.5	1.7	0.3	1.6	1.93	0.44	160	450	-
21/03/2020	23	7.1	7.1	7.4	80	80	1.5	1.7	0.3	1.6	1.93	0.44	130	650	-
22/03/2020	24	7.1		7.3	-	-	-	-	-	-	-	-	-	-	-
23/03/2020	25	7.0	7.3	7.5	80	80	1.5	1.7	0.3	1.6	1.93	0.44	150	620	
24/03/2020	26	-	-	-	-	-	-	-	-	-	-	-	-	-	-
25/03/2020	27		7.3	7.4	80	80	1.5	1.7	0.3	1.6	1.93	0.44	110	1200	-
26/03/2020	28	7.0	7.4	7.5	80	80	1.5	1.7	0.3	1.6	1.93	0.44	80	1150	-
27/03/2020	29	7.0	7.3	7.4	80	80	1.5	1.7	0.3	1.6	1.93	0.44	170	1200	-
28/03/2020	30	7.0	-	-	80	80	1.5	1.7	0.3	1.6	1.93	0.44	-	-	-
29/03/2020	31	7.0	7.4	7.5	80	80	1.5	1.7	0.3	1.6	1.93	0.44	170	1150	-
30/03/2020	32	-	-	-	-	-	-	-	-	-	-	-	-	1150	-
31/03/2020	33	-	7.3	7.4	-	-	-	-	-	-	-	-	185	1150	30
1/04/2020	34	7.1	7.4	7.4	80	80	1.5	1.7	0.3	1.6	1.93	0.44	180	1150	30
2/04/2020	35	7.1	7.5	7.5	80	80	1.5	1.7	0.3	1.6	1.93	0.44	165	1200	50
3/04/2020	36	7.1	7.4	7.5	80	80	1.5	1.7	0.3	1.6	1.93	0.44	110	1250	50
4/04/2020	37	7.1	7.5	7.5	80	80	1.5	1.7	0.3	1.6	1.93	0.44	125	1200	45
5/04/2020	38	7.0	-	-	80	80	1.5	1.7	0.3	1.6	1.93	0.44	140	-	70
6/04/2020	39	-	-	-	80	80	1.5	1.7	0.3	1.6	1.93	0.44	150	-	60
7/04/2020	40	-	-	-	-	-	-	-	-	-	-	-	160	-	60

Appendix E cost estimation of the different technologies

	Unit	MBR	Andicos™	ASP	UASB	Source
Capital cost						
Land cost						
Total area	m^2	27330	53475.6	117000	130000	Indian Institute of technology, 2010
Area requirement	$m^2.MLD^{-1}$	0.00021023	0.000411351	0.0009	0.001	Indian Institute of technology, 2010
Land cost per m^2	Rs/m^2	40	40	40	40	Heylen C., 2018
Land cost per liter	$Rs.L^{-1}$	0.00840923	0.016454031	0.036	0.04	Heylen C., 2018
Civil engineering cost		6	10.42	4.08	4.42	
Module of membrane						
Required surface	m^2	216667	216667	0	0	
Membrane cost per m^2	$m^2.L^{-1}$	5250	5250	0	0	Heylen C., 2018
Membrane cost per L	$Rs.L^{-1}$	8.75	8.75	0.00	0.00	Heylen C., 2018
Evaluation & management cost	$Rs.L^{-1}$	24	24	2.72	2.38	Heylen C., 2018
Total	$Rs.L^{-1}$	32.80	43.19	6.84	6.84	
	$Rs.L^{-1}.year^{-1}$	2.19	2.88	0.46	0.46	
Operation & maintanance cost						
Power cost	$Rs.L^{-1}$	0.008	0.008	0.410	0.280	Indian Institute of technology, 2010; Judd S., 2011
Repair costs	$Rs.L^{-1}.year^{-1}$	0	0	0.24	0.25	Indian Institute of technology, 2010
Manpower	$Rs.L^{-1}$	0.013	0.022	0.022	0.022	Indian Institute of technology, 2010
Chemical Cost	$Rs.L^{-1}.year^{-1}$	0.24	0.24	0.53	0.63	Indian Institute of technology, 2010
Total	$Rs.L^{-1}.year^{-1}$	0.26	0.27	1.20	1.18	
Anaerobic digestion gain						
Waste collection						
Amount per liter	$Kg.L^{-1}$		0.015			
Waste collection cost	$Rs.Kg^{-1}$		0.019			Pathan S., 2009
Organic matter	$kg_{COD}/ kg_{food\ waste}$	-	0.19	-	-	
Wastewater		-	0.0007	-	-	
Organic matter						
Production biogas	$m^3{}_{biogas}/L_{wastewater}$	-	0.0013	-	-	
Production methane	$m^3{}_{methane}/L_{wastewater}$	-	0.0009	-	-	
Production electricity	$kWh/L_{wastewater}$	-	0.004	-	-	
	$Rs/L_{wastewater}$	-	0.033	-	-	
Cost	$Million\ Rs.year^{-1}$	318.23	409.33	215.45	212.89	
Gain	$Million\ Rs.year^{-1}$	0.00	671.40	0.00	0.00	
Total	$Million\ Rs.year^{-1}$	318.23	-262.07	215.45	212.89	