ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

PERFORMANCE TESTS OF HYBRID MEMBRANE BIOREACTOR (IFAS MBR) SYSTEM IN DIFFERENT SLUDGE AND HYDRAULIC RETENTION TIME

M.Sc. THESIS

Elif Ceren ESEN

Department of Environmental Engineering

Environmental Science Engineering and Management Programme

JULY 2024

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ISTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

HİBRİT MEMBRAN BİYOREAKTÖR (IFAS MBR) SİSTEMİNİN FARKLI ÇAMUR YAŞI (SRT) VE HİDROLİK BEKLETME (HRT) SÜRELERİNDE PERFORMANS TESTLERİNİN YAPILMASI

YÜKSEK LİSANS TEZİ

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Çevre Bilimleri Mühendisliği ve Yönetimi Programı

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TEMMUZ 2024

Elif Ceren Esen, a M.Sc. student of İTU Graduate School student ID 501211709 successfully defended the thesis/dissertation entitled "PERFORMANCE TESTS OF HYBRID MEMBRANE BIOREACTOR (IFAS MBR) SYSTEM IN DIFFERENT SLUDGE AND HYDRAULIC RETENTION TIME", which she prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

Thesis Advisor : **Assist. Prof. Türker TÜRKEN** ....
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Yıldız Technical University

Date of Submission : 24 May 2024
Date of Defense : 08 July 2024

To my family,

FOREWORD

I am deeply grateful to my advisor, Dr. Türker TÜRKEN, and my esteemed professor, Prof. Dr. İsmail KOYUNCU, for their guidance and for giving me the opportunity to work at MEMTEK. Through their dedication and discipline, I have learned a great deal from them.

I would like to extend my sincere thanks to my valuable mentors and colleagues at MEMTEK who have always been by my side and have never hesitated to offer their support and assistance in every matter.

I am deeply thankful to my dear friend Ahsen UÇAR, who was always there for me, providing morale, motivation, and support during my toughest times.

My thesis work was carried out within the scope of the TÜBİTAK project number 121G037. I would like to thank TÜBİTAK for their financial support.

I am immensely grateful to dear Berk ESENLİ for his unwavering moral and academic support, and for always being by my side.

Lastly, I would like to thank my mother, Cevriye ESEN, my father, Eyüp ESEN, and my brother, Doğukan Ozan ESEN, for their patience and support throughout my life. Without you, none of my achievements would have been possible.

July 2024

Elif Ceren ESEN
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ABBREVIATIONS

APHA : American Public Health Association
BEPR : Biologically Enhanced Phosphorus Removal
BOD : Biochemical Oxygen Demand
COD : Chemical Oxygen Demand
IFAS : Integrated Fixed Activated Sludge
MBBR : Moving Bed Biofilm Reactor
MBR : Membrane Bioreactor
MLSS : Mixed Liquor Suspended Solids
MLVSS : Mixed Liquor Volatile Suspended Solids
NTU : Nephelometric Turbidity Units
UF : Ultrafiltration
PVDF : Polyvinylidene Difluoride
RAS : Return Activated Sludge
SVI : Sludge Volume Index
TMP : Trans Membrane Pressure
TN : Total Nitrogen
TP : Total Phosphorous
TSS : Total Suspended Solids
TVSS : Total Volatile Suspended Solids

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PERFORMANCE TESTS OF HYBRID MEMBRANE BIOREACTOR (IFAS MBR) SYSTEM IN DIFFERENT SLUDGE AND HYDRAULIC RETENTION TIME

SUMMARY

In recent years, research has intensified on new treatment processes that occupy less space, are cost-effective, and provide highly efficient treated effluent quality due to the increasing volumes of water requiring treatment. Membrane technologies are at the forefront of these technologies. Particularly, Membrane Bioreactor (MBR) systems, which can be used as alternatives to conventional treatment systems in domestic wastewater treatment plants, have created a wide range of research opportunities due to their economic and easy operability.

Membrane Bioreactor (MBR) systems are widely used in the treatment of domestic and industrial wastewaters. They are combined treatment systems where biological treatment using activated sludge is integrated with membrane filtration for solid-liquid separation. The MBR process primarily relies on the physical separation of treated water and activated sludge by membranes. Due to its high separation efficiencies, it involves the incorporation of a membrane module providing physical separation instead of the final sedimentation tank found in conventional domestic wastewater treatment plants, either submerged or externally integrated into the process.

According to research, wastewater discharge from the Marmara Basin is approximately 5 million m3. According to data from the Ministry of Environment and Forestry, approximately 1.5 million m3 of this wastewater is discharged directly after preliminary treatment. With rapid population growth and industrialization, it is anticipated that this wastewater discharge will increase further in the coming years. In Istanbul specifically, due to spatial constraints, wastewater is only subjected to preliminary treatment before being discharged into the Sea of Marmara through deep-sea outfalls. Additionally, industries such as textiles, which generate a significant amount of wastewater, contribute to point source pollution in the Sea of Marmara. While the recent emergence of mucilage is believed to be nitrogen and phosphorus-related, efforts are needed to reduce the nutrient load entering the Marmara Sea. Action is required to address both water scarcity issues and promote resource recovery, as well as to upgrade existing systems to advanced biological treatment. In this context, the thesis in question has implications for reducing wastewater discharge and preventing marine pollution.

At the current stage, it is imperative to upgrade conventional wastewater treatment plants to ensure the removal of nitrogen and phosphorus and to achieve treatment efficiencies sufficient for wastewater recovery in water intensive industries. In this regard, new technologies should be employed, and whenever possible, facility designs and equipment selections should leverage local resources. This approach aims to eliminate dependence on foreign sources in the environmental sector. Integrated Fixed-film Activated Sludge (IFAS) is a relatively new wastewater treatment

technology that offers various advantages over traditional activated sludge technologies. It involves the addition of a growth media to the activated sludge tank to facilitate biomass growth and enhance the treatment process. The added media can be fixed or free-floating. The technology is relatively new and can be installed as an upgrade to an existing facility or built anew. The IFAS treatment process combines traditional activated sludge and biofilm technologies in a single reactor. It offers a performance increase of up to about 40% without the need to add new aeration tanks to existing systems. IFAS adds a high surface area to the activated sludge tank, providing additional biomass and increasing the rate of microbial growth.This not only increases the sludge age but also ensures high-performance wastewater treatment. Within the scope of the thesis, the combination of MBR (Membrane Bioreactor) and IFAS (Integrated Fixed-film Activated Sludge) systems within a single system is planned to enhance the efficiency of the membrane system. In this regard, utilizing the film attachment feature offered by IFAS, low F/M (Food to Microorganism) ratio filtration is conducted in the membrane tank, thereby increasing flux rates and reducing transmembrane pressure. Additionally, due to the high microbial attachment, high-efficiency wastewater treatment can be achieved in small footprint areas hydraulically. This situation will provide numerous advantages, especially in areas with spatial constraints, during the revision of conventional wastewater treatment plants to advanced biological wastewater treatment plants and in capacity expansions, enabling much more wastewater treatment in the same volume.

Within the scope of the thesis, a 500 L/day capacity IFAS MBR system was designed and constructed. The designs of the systems were created using a 3D drawing program. Wastewater feed to the IFAS MBR system was introduced from beneath the fixation materials placed within the biological pool, ensuring homogeneous distribution. The system was fed with real wastewater, with hydraulic feed gradually increased. In this way, organic and hydraulic loading rates were determined for each system, identifying the maximum wastewater quantities that could be treated. Additionally, within the thesis scope, the IFAS MBR system was operated at different sludge ages. It was observed that even at low sludge ages, as low as 5 days, the nitrification rate was high in the IFAS MBR system operated at different sludge ages. Another promising feature of the IFAS MBR system is its ability to achieve high nitrification rates and total nitrogen removal even at low sludge ages.

Since the majority of discharges into the Sea of Marmara consist of domestic wastewater, the IFAS MBR system will be utilized for domestic wastewater treatment within the ITU Ayazaga Campus. Subsequently, this system can be adapted for the treatment of various types of industrial wastewater as well. Within the project scope, the efficiency of the membrane system was enhanced by combining the MBR system with the IFAS system within a single system. In this regard, low F/M ratio filtration was achieved in the membrane tank using the film attachment feature offered by IFAS, thereby increasing flux rates. The integrated use of the IFAS system with the MBR system is not widely documented in the literature, thus contributing valuable information to the field. Operating the hybrid IFAS MBR system within the project will reduce the footprint of wastewater treatment facilities, facilitating the revision of existing systems. This means that advanced biological treatment can be achieved at much higher capacities using existing conventional systems.

HİBRİT MEMBRAN BİYOREAKTOR (IFAS MBR) SİSTEMİNİN FARKLI ÇAMUR YAŞI (SRT) VE HİDROLİK BEKLETME (HRT) SÜRELERİNDE PERFORMANS TESTLERİNİN YAPILMASI

ÖZET

Su arıtımı ihtiyacının artmasıyla birlikte, son dönemlerde, daha az yer kaplayan, ekonomik ve yüksek kalitede temiz su sağlayan inovatif arıtma yöntemleri üzerine yapılan araştırmalar yoğunlaşmıştır. Bu alandaki lider teknolojilerden biri olan membran teknolojileri, özellikle evsel atıksu arıtma tesislerindeki konvansiyonel arıtma sistemlerinin yerine tercih edilmeye başladı. Membran Biyoreaktör (MBR) sistemleri, ekonomik ve işletmesi kolay olduğundan dolayı geniş bir araştırma alanına olanak sağlamıştır.

Membran biyoreaktör sistemleri (MBR), evsel ve endüstriyel atıksuların arıtımında yaygın olarak kullanılan, aktif çamur sistemi ile biyolojik arıtmanın, membran filtrasyonu ile katı-sıvı ayrımının gerçekleştirildiği kombine arıtma sistemleridir. MBR prosesi, temelde arıtılmış su ile aktif çamurun fiziksel olarak membran ile ayrılmasına dayanır. Yüksek ayrım verimleri sağladığı için, MBR sistemi, geleneksel evsel atıksu arıtma tesislerinde bulunan son çökeltim havuzunun yerine fiziksel ayrım sağlayan bir membran modülünün prosese dâhil edilmesiyle oluşturulan bir işlemdir. Araştırmacılar, Marmara Havzasından günde yaklaşık 5 milyon m^3 kanalizasyonun salındığını tespit etti. Bu atık suyun yaklaşık 1,5 milyon m^3'ü Çevre ve Orman Bakanlığı verilerine göre ön arıtmadan hemen sonra deşarj edilmektedir. Hızlı nüfus artışı ve sanayileşmeyle birlikte kaçak atıksu deşarjlarının önümüzdeki yıllarda daha da artması bekleniyor. İstanbul'da, yerleşim sorunları nedeniyle atık sular sadece ön arıtma işlemine tabi tutularak Marmara Denizi'ne derin deniz deşarjı yapılmaktadır. Diğer yandan, tekstil gibi endüstrilerdeki yoğun atık su oluşumu, Marmara Denizi'nde noktasal kirlilik kaynağı oluşturmaktadır. Son dönemde ortaya çıkan müsilaj sorununun azot ve fosfor kaynaklı olduğu düşünülse de Marmara'ya giden besin yükünün azaltılması gerekiyor. Su sorunlarını çözmek ve geri dönüşümü sağlamak için, mevcut sistemlerin ileri biyolojik arıtma sistemlerine dönüştürülmesi gerekiyor. Bu bağlamda, tez atık deşarjını azaltarak ve deniz kirliliğini önleyerek olumlu etkilere sahip olabilir.

Günümüzde, mevcut durumda klasik atıksu arıtma tesislerinin nitrat, fosfat giderimini sağlayacak şekilde yenilenmesi ve su tüketimini azaltan endüstrilerde atıksu geri kazanımının yapılacak seviyeye yükseltilmesi gerekmektedir. Bu amaçla, yeni teknolojilerin kullanılması ve yerli kaynaklardan mümkün olduğunca faydalanılarak tesis tasarımlarının ve ekipman seçimlerinin yapılması önemlidir. Bu sayede, çevre sektöründe dışa bağımlılığın azaltılması gerekmektedir.

Entegre sabit film aktif çamur (IFAS), geleneksel aktif çamur teknolojilerine göre çeşitli avantajlar sunan nispeten yeni bir atıksu arıtma teknolojisidir. Biyokütle büyümesini kolaylaştırmak ve arıtma sürecini güçlendirmek için aktif çamur tankına bağlı bir büyüme ortamı eklenir. Eklenen ortam sabit veya serbest yüzer olabilir. Teknoloji nispeten yenidir ve mevcut bir tesise yükseltme olarak kurulabilir veya yeni

inşa edilebilir. IFAS arıtma işlemi, geleneksel aktif çamur ve biyofilm teknolojilerini tek bir reaktörde birleştirir. Mevcut sistemlere yeni havalandırma tankı eklemeye gerek kalmadan yaklaşık %40'a dayanan bir performans artışı sunar. IFAS, aktif çamur havuzuna yüksek yüzey alanı ekler. Bu ortam/yüzey alanı, ek biyokütle sağlar ve büyüyen mikroorganizma oranını arttırır. Bu, çamur yaşını arttırdığı gibi, arıtma veriminin de yüksek performanslı olmasını sağlar. Tez kapsamında MBR sistemi ile IFAS sistemi tek bir sistem içerisinde birleştirilerek membran sisteminin veriminin arttırılması planlanmıştır. Mikroorganizmaların IFAS'ın sunduğu film sabitleme özelliği kullanılarak membran tankında düşük AKM ile filtrasyon yapılarak akıların artırılması ve transmembran basıncının düşürülmesi sağlanmıştır. IFAS taşıyıcı medyaya yüksek oranda tutunmasından dolayı az alanda bile verimi yüksek ve fazla miktarda atıksu arıtımı yapılabilmektedir. Yer problemi bulunan yerlerde konvansiyonel arıtma sistemlerinin ileri biyolojik arıtma tesislerine revizyonunda, kapasite arttırılmasında, aynı hacimde daha yüksek hacimde ve miktarda atık su arıtımı yapmak için birçok avantajı bulunur.

Tez kapsamında membran sistemlerle entegre yenilikçi sistemlerin kullanılarak özellikle yer problemi olan bölgelerde küçük hacimde fazla miktarda atıksu arıtımı gerçekleştirmek (azot fosfor giderimi dahil) amaçlanmıştır. Yerli membran teknolojileri kullanılarak su geri kazanımı yapacak şekilde klasik arıtma sistemlerinin revizyon olanaklarının belirlenmesi hedeflenmiştir. Entegre Sabit Aktif Çamur Sistemi (IFAS) sisteminin membran sistemlerle entegre edilerek hibrit IFAS MBR sistemi oluşturulması ve arıtma veriminin artırılması amaçlanmıştır. IFAS-MBR sisteminde, hem askıda hem de sabit yatak üzerinde büyüyen mikroorganizmaların konsantrasyonu artırılarak, MBR sistemlerinin gerektirdiği hacimden daha düşük hacimlerde arıtma sağlanmıştır. Klasik bir aktif çamur sisteminde biyolojik havuz içindeki mikroorganizma konsantrasyonu 4000 mg/L seviyesinde tutulabilirken, MBR sistemlerinde bu değer 10.000 mg/L'ye kadar çıkabilir. IFAS-MBR arıtma konseptinde ise sabit yatak üzerinde 10.000-15.000 mg/L, askıda ise 10.000 mg/L mikroorganizma konsantrasyonu sağlanabilir. Bu durum, arıtma sisteminin ihtiyaç duyduğu alanı MBR sistemlerine kıyasla yarıya kadar azaltabilir.

Tez kapsamında 500 L/gün kapasiteli IFAS MBR sistemi tasarlanmıştır. Sistemlerin tasarımı 3 boyutlu çizim programında yararlanılarak tasarlanmıştır. Atık su beslemesi IFAS MBR sisteminde biyolojik havuz içerisine yerleştirilecek sabitleme materyallerinin altından beslenmiştir ve homojen dağılım sağlanmıştır. Sistemde sabit tip IFAS taşıyıcı medyalardan yararlanılmıştır. Hareketli medyaların su içerisindeki hareketi, aerobik reaktörlerde difüzörler, anaerobik ve anoksik reaktörlerde ise karıştırıcılar kullanılarak sağlanır. Bu sayede suyun sirkülasyonu ile reaktör içinde hareket eden taşıyıcılar, mekanik veya hidrodinamik olarak karıştırılmış olur. Sirkülasyonla oluşan yüksek kayma gerilmesi ve taşıyıcıların çarpışması, biyofilm gelişiminin kontrolüne yardımcı olarak reaktör sisteminin stabilizasyonunu sağlar. Sistem gerçek atıksu ile beslenmiş; hidrolik olarak besleme kademeli olarak arttırılmıştır. Bu şekilde her bir sistem için organik ve hidrolik yükleme oranları belirlenerek maksimum arıtılabilecek atıksu miktarları belirlenmiştir.

Ayrıca, farklı çamur yaşlarında yapılan çalışmalarda, IFAS MBR prosesinde nitrifikasyon oranının daha yüksek olduğu gözlemlenmiştir. Bu fark, özellikle düşük çamur yaşlarında IFAS MBR hibrit prosesinin daha verimli çalıştığını göstermiştir. Yüksek mikroorganizma tutunması sayesinde, küçük alanlarda yüksek verimle daha fazla miktarda atık suyun hidrolik olarak arıtılması sağlanmıştır. Tez kapsamında IFAS MBR sistemi farklı çamur yaşlarında işletilmiştir. Farklı çamur yaşlarında işletilen IFAS MBR sisteminde SRT 5 gün kadar düşük çamur yaşı değerlerinde de nitrifikasyon oranının yüksek olduğu gözlemlenmiştir. IFAS MBR sisteminin vaat ettiği bir diğer özellik ise düşük çamur yaşında bile yüksek nitrifikasyon oranları ve yüksek toplam azot giderimi gerçekleştirebilmesidir.

Marmara denizine en fazla deşarj evsel nitelikle atıksu olduğundan dolayı IFAS MBR sistemi İTÜ Ayazağa Kampüsü içerisinde evsel nitelikli atıksu arıtımında kullanılacaktır. Bu sistem daha sonra spesifik olarak her türlü endüstriyel atıksu arıtımı içinde kullanılabilecektir. Tez doğrultusunda, MBR sistemi ile IFAS sistemi tek bir sistem içerisinde birleştirilerek membran sisteminin verimi artırılmıştır. IFAS biyofilm sabitlenmesi sağlar. Bu sebeple membran tankında daha düşük membran basıncı elde edilirken; elde edilen temiz su akısı artar. IFAS sistemi ile MBR sisteminin entegre olarak kullanımı literatürde yaygın değildir. Bu yönüyle literatüre yararlı bilgilerle katkıda bulunacaktır. Proje kapsamında işletilen hibrit IFAS MBR sistemi ile atıksu arıtma tesisleri alan ihtiyacını azaltmakla mevcut sistemlerin revizyonları kolaylaşacaktır. Yani mevcut klasik sistemler kullanılarak çok daha yüksek kapasitede ileri biyolojik arıtma gerçekleştirilebilecektir.

IFAS ve MBR sistemlerinin entegre kullanımı literatürde yaygın değildir ve bu çalışma bu alanda önemli bilgiler sağlayarak literatüre katkıda bulunacaktır. Alan ihtiyacının %10 oranında azaltılması bile, arazi fiyatlarının yüksek olduğu bu dönemde atık su arıtma tesislerinin yapım maliyetlerini önemli ölçüde düşürecektir. Bu durum, birçok yerde kapasite artırılamamasının ve sistemlerin ileri biyolojik arıtma sistemlerine dönüştürülememesinin başlıca nedenlerinden biridir. Sistemin yerli imkanlarla üretilmesi, membran filtre ve diğer kritik ekipmanlar açısından yurtdışına bağımlılığı ortadan kaldırarak tam ekonomik güvenlik sağlamaktadır.

1. INTRODUCTION

1.1. Membrane BioReactors

Growing population has resulted in a significant increase in the number of sectors. This leads to either extreme environmental problems or a massive demand on water resources. Given the state of water resources today, it is critical to apply cutting edge techniques to enhance water cycle management in commercial and public spaces. To fully appreciate the importance of water, innovative sustainable techniques for the water cycle must be implemented. In light of this, wastewater recovery can be viewed as a very important resource that can be achieved with the use of cutting edge technologies (Al-Asheh et al., 2021).

Using a membrane biological reactor is one of the different options for treating wastewater. Membrane Bioreactor (MBR) is the term used to describe a device that combines membrane filtration with biological processes. In this case, the treated wastewater is separated from microorganisms in a membrane module, while biomass degradation takes place inside the bioreactor tank. MBR has drawn a lot of attention over the past 20 years since it can create high quality effluent and has since been recognized as an established wastewater treatment technology (Marrot et al., 2004).

During the Dorr-Oliver research program, Smith et al. unveiled the MBR technology for the first time in 1969. The goal was to use high equality effluent to treat sewage from a manufacturing plant located in Sandy Hook, Connecticut, for six months. To separate treated water and activated sludge, an ultrafiltration membrane was put outside the bioreactor tank in place of a sedimentation tank. Despite producing an extremely high-quality effluent, this configuration's broad use was limited at the time by its high energy cost and associated membrane fouling (Al-Asheh et al., 2021).

Yamamoto et al., (1989) developed an innovative arrangement in 1989 by putting the hollow fiber membrane in the activated sludge aeration tank in order to get around the limitations of the previous arrangement. Rather than use an externally installed pressurized pump to move the mixed liquor across the membrane, suction pressure was introduced into the bioreactor, allowing the membrane to submerge directly into the aeration tank.

After the development of the immersed configuration, numerous studies have been conducted to expand the use of MBR technology by offering large scale, high quality permeate at a lower investment price since the mid 1990s.

The membrane's pore size distribution, shape, and operating conditions are among the parameters that have been studied in order to reduce the occurrence of membrane fouling while developing novel methods of cleaning fouled membranes (Al-Asheh et al., 2021).

1.2. CAS and MBR

The two basic phases of conventional activated sludge (CAS) are as follows. The first one uses an aeration tank to treat wastewater using activated sludge, which is made possible by active microorganisms. The secondary clarifier, also known as the sedimentation tank, is where the activated sludge and treated water are separated. The treated effluent is typically used for lighter fraction since activated sludge cannot be entirely separated in the sedimentation tank. On the other hand, most of the activated sludge can be separated when employing MBR due to the presence of membranes with varying pore sizes (Al-Asheh et al., 2021). Table 1.1. gives a summary of MBR's advantages and limitations in comparison to CAS.

Table 1.1 : Advantages and disadvantages of MBR compared to CAS (Judd, 2008).

Advantages	Disadvantages
• By omitting the sedimentation tank, a smaller bioreactor size is achieved, resulting in a reduced footprint.	• Fouling is a frequent issue in MBR systems, requiring various operational strategies to mitigate the membrane's fouling tendency, irrespective of the process and operational complexities involved in membrane installation.

Table 1.1 continuous : Advantages and disadvantages of MBR compared to CAS (Judd, 2008).

Advantages	Disadvantages
• There are no restrictions on the concentration of Mixed Liquor Suspended Solids (MLSS) in MBR systems, which reduces the production of Waste Activated Sludge (WAS). For example, the maximum MLSS concentration in CAS is limited to around 5000 mg/L due to secondary clarifier constraints, whereas the optimal MLSS level in MBR ranges from 8000 to 12000 mg/L.	• The MBR process involves higher capital and operational expenditures, primarily due to the costs associated with membrane procurement and the implementation of antifouling strategies.
• The quality of treated water and bioreactor MLSS is determined by the Solid Retention Time (SRT). In MBR systems, precise control of SRT is possible because secondary sedimentation tanks are not required.	• The complexity of the process is largely due to the methods used for membrane maintenance and cleanliness.
• Generally, longer SRT enhances wastewater treatment efficiency. In MBR systems, applying longer SRT (over 20 days) compared to CAS (typically 5-15 days) results in higher effluent quality during the treatment process.	• High foaming tendency is another issue, partly due to the increased aeration requirements of MBR systems.

Table 1.1 continuous : Advantages and disadvantages of MBR compared to CAS (Judd, 2008).

Advantages	Disadvantages
• The presence of membranes with pore sizes smaller than suspended solids ensures the production of high-quality treated effluent. However, for effective secondary clarifiers, the typical suspended solids concentration is around 5 mg/L. Therefore, MBR systems generally eliminate the need for additional tertiary treatments like filters.	• Higher power consumption during operation can be a concern, with energy use sometimes being twice as much as that in Conventional Activated Sludge (CAS) systems.

1.3. Membrane Fouling

The primary issue that occurs while membrane separation operations function is fouling. Therefore, the management of the MBR process has a major impact on its effectiveness. Numerous variables, including membrane cleaning techniques, influent wastewater parameters, membrane properties, and operating circumstances, influence the fouling phenomenon. The outline of the membrane fouling phenomenon and related cleaning techniques is shown in Figure 1.1.

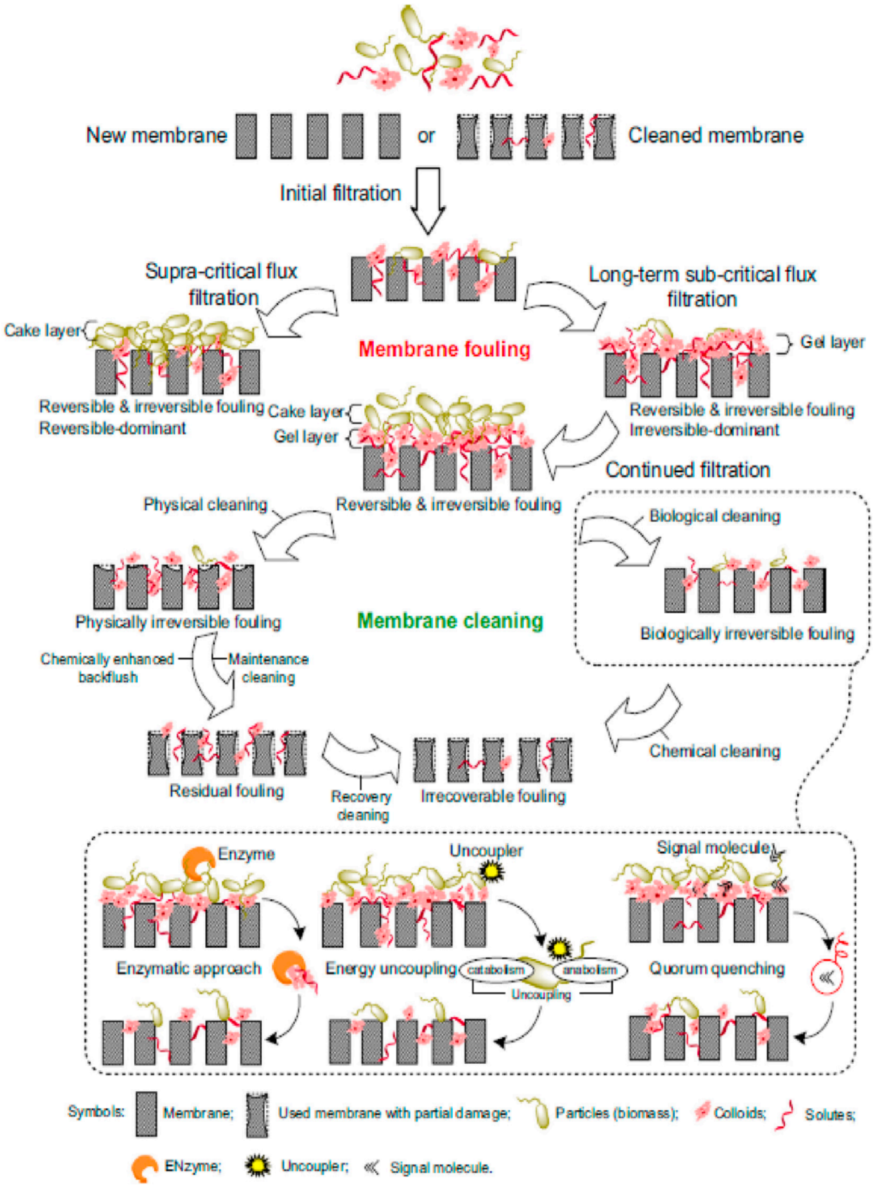


Figure 1.1 : Membrane fouling and cleaning outline (Wang et al., 2014).

1.4. Types of Novel MBR Applications

1.4.1. Aerobic and anaerobic membrane bioreactor (AnMBR)

Aerobic treatment method has been used for over a century to clean domestic and industrial wastewater. The main disadvantages of this technology are its massive footprint, high maintenance costs, high energy requirement for the aeration process, high sludge generation, and emission of greenhouse gasses like nitrous oxide (N2O). Reducing the amount of energy needed is essential for wider adoption of aerobic MBR, and aeration management techniques in aeration tanks are a key factor in lowering the process's overall energy consumption. Recent research on full-scale MBRs demonstrated that using an ammonia N based aeration management technique reduced aeration and energy consumption rates by 20% and 4%, respectively (Sun et al., 2016).

It is important to note that, because of incomplete nitrification, reducing airflow rate to save energy usage may have a direct impact on greenhouse gas emissions. Therefore, one of the most essential keys to reducing the environmental footprint is knowing the relationship between operational conditions and direct and indirect GHG emissions. According to a report, influent dynamics with close loop aeration applied while maintaining a constant dissolved oxygen concentration inside the aerobic reactor,as opposed to open loop aeration,are necessary for a successful decrease in the operating costs of MBRs plants by 13–17% (Maere et al., 2011).

In general, an aerobic process is employed to treat effluents with a biodegradable COD concentration of less than 1000 mg/L, whereas a highly and strongly polluting method is used for effluents with a biodegradable COD amount greater than 4000 mg/L. Anaerobic processes are frequently employed. Anaerobic treatment is an adaptable technique that can decompose organic matter in wastewater to generate biogas, treat wastewater, recover water, and, finally, recover nutrients to produce fertilizers for agricultural use (Chan et al., 2009).

A different MBR design has been created to treat waste water and over some MBR process challenges by combining membrane filtering and anaerobic digestion treatment. In this case, the decomposition of organic matter into methane rich biogas lowers the energy needed for wastewater treatment. Furthermore, because precipitation transforms nutrients into chemically accessible forms, recovery of nutrients is feasible after precipitation. However, some of the major obstacles preventing its development are salt accumulation, reduced resources, membrane fouling, and membrane stability (Maaz et al., 2019).

The two components of the AnMBR plant were the membrane models and the anaerobic bioreactor. The most popular bioreactor configurations (Figure 1.2.) for AnMBR are up flow anaerobic sludge blanket (UASB), completely stirred tank reactor (CSTR), and anaerobic fluidized bed bioreactor (AFBR). The CSTR is the most widely used structure because of its simple construction and operation (C. Chen et al., 2016).

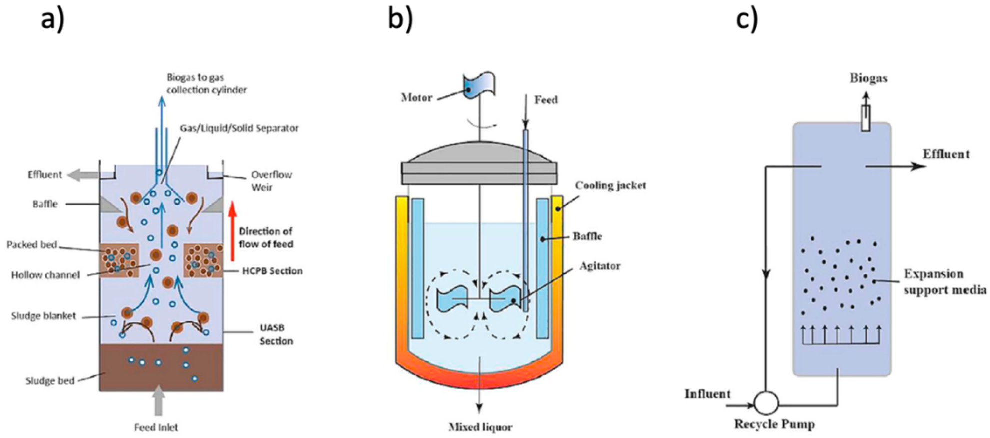


Figure 1.2 : Typical anaerobic bioreactors a) up flow anaerobic sludge reactor; b) continuous stirred tank reactor; c) anaerobic fluidized bed reactor (C. Chen et al., 2016)

Anaerobic bioreactors and membrane models can be combined in three ways, as seen in Figure 1.3.; AnMBR can be configured in three distinct ways: (a) side-stream, in which the membrane module is outside the bioreactor tank; (b) internal submerged, in which the membrane is submerged inside the bioreactor tank; and (c) external submerged, in which the membrane unit is submerged in a chamber apart from the bioreactor that is actually in use (Zhen et al., 2019).

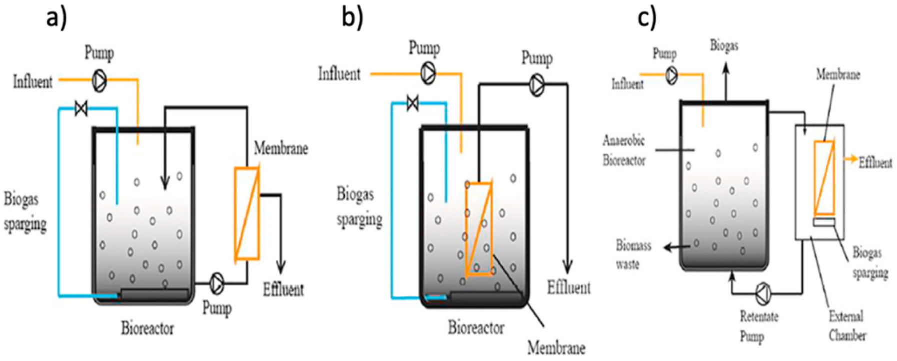


Figure 1.3 : Basic configurations of anaerobic membrane bioreactor (AnMBR): (a) external AnMBR, (b) internal/submerged AnMBR, and (c) external submerged AnMBR (Zhen et al., 2019)

Recently, external submerged configurations have been employed extensively in pilot scale applications and have shown a high degree of potential for large scale implementation in the treatment of domestic wastewater. In comparison to lab scale AnMBR and aerobic MBRs, C. Shin & Bae, (2018) observed reduced energy demand for pilot scale external submerged AnMBR configuration (usually hollow fiber membrane were employed) (ranged from 0.04 to 135 kWh).

1.4.2. Anaerobic fluidized membrane bioreactor (AFMBR)

Although AnMBRs have shown promising results in the removal of antibiotics and other associated advantages, membrane fouling of these instruments prevents their widespread use. AFMB has been created recently to increase the removal of antibiotics from wastewater while concurrently reducing the development rate of cake layer. It combines membrane technology with particle sprinkling and liquid circulation. The key advantages of this approach over traditional AnMBR are a decrease in the concentration of EPSs and SMPs, an increase in the growth rate of bacteria that can breakdown antibiotics (i.e., enhancing antibiotic removal), and a more stable sludge with larger size. However, more research is need to fully comprehend how well such a unique approach performs. According to reports, the energy required for the AFMBR's operation is significantly less than the ordinary AnMBR; for the AFMBR, it was between 0.039 and 0.13 kWh, whereas for the regular AnMBR, it was between 0.25 and 7.3 kWh/m^3 (W. Guo et al., 2020).

1.4.3. Membrane photobioreactor (MPBR)

Hollow fibers or flat sheets combined with PBRs are examples of submerged micro or ultrafiltration membranes that composed MPBRs. MPBR has several benefits, including efficient microalgae separation, system stability, and enhanced effluent quality. However, the inability of this design to treat primary raw domestic wastewater with high organic matter concentration is a significant barrier to its development. This is due to the fact that it mostly consists of a low concentration of organic materials, which microalgae can consume as food and grow to treat wastewater. Studies have been conducted on the impact of many parameters, including organic loading rate (OLR) and HRT, on MPBR performance. Research indicates that the optimal condition for MPBR performance to maintain 0.016 m3/day as a fouling frequency during the treatment of domestic wastewater is an OLR of up to 0.014 kg with two days of HRT.

The system is capable of efficiently producing microalgal biomass while simultaneously eliminating organics and nutrients, and the scientists claim that it does not require an external source of aeration (Ashadullah et al., 2021).

1.4.4. Membrane bioreactor integrated with microbial fuel cell (MFC-MBR)

One of the main issues limiting MBR from being used widely is the fouling phenomenon. It has been demonstrated that applying an electric field in MBR can lower the amount of foulant that accumulates on the membrane surface, thus decreasing the fouling phenomena. Therefore, researchers' attention has been drawn to a unique arrangement in recent years where MFCs and MBRs are merged. The electricity generated by MFC's wastewater treatment process can be utilized in MBRs to reduce their tendency to foul. This new arrangement uses less energy for the process than the MBR because it does not apply direct electricity, and the powerful electric fields do not impair the bacteria's performance too (Yin et al., 2020). The fouling properties of sludge in MFC-MBR have been studied by H. Li et al., (2021).

The hollow fiber membrane was used to submerge the anodic and cathodic chambers of the MFC in the aerobic MBR. To examine the fouling process, the extended Derjaguin-Landau-Verwey-Overbeek (XDLVO) model was applied. The results demonstrated that in MFC-MBR compared to control systems (C-MBR), there is a decrease in the free energy of adhesion between the SMPs and clean membrane or SPM-fouled membrane. The scientists also came to the conclusion that the SMPS in MFC-MBR have greater energy barriers to absorption on the membrane surface, which inhibits adsorption and, in turn, lessens the fouling process. Another benefit of this design is that sludge flocs in MFC-MBR have less negative surface charge and are less hydrophobic (Li et al., 2021). Numerous studies have examined how well various MBR configurations work to treat different kinds of wastewater as their feedstock, including synthetic wastewater and actual industrial wastewater. Research has been done at several levels to assess the suggested configuration's viability at the industrial level. As a result, the effectiveness of MBRs under various operating conditions was determined on both a lab and pilot scale.

1.4.5. Integrated fixed film activated sludge membrane bioreactor systems

Integrated fixed film activated sludge membran bioreactor systems are another novel example of a innovative hybrid MBR technologies. Detailed explanations about IFAS MBR systems will be given in next chapters.

1.5. Integrated Fixed Film Activated Sludge Systems (IFAS)

Global warming and clean water are the two main challenges of the day. To address those issues, a great deal of research on water treatment, reuse, and recycling has been done (Di Trapani et al., 2011). To achieve the regulations, several physical, chemical, and biological wastewater treatment techniques have been put into place. Each of them has advantages and disadvantages of their own. However, additional advancements are still need to raise the effluent quality and satisfy stricter regulations (Waqas et al., 2020). It is therefore necessary to update the current procedures because stricter regulations are being placed on the discharge requirements. As a result, an advanced procedure that ensures sufficient effectiveness for treatment has been developed continuously (Di Trapani et al., 2010; Leyva-Díaz et al., 2017).

Microorganisms are used in the biological process of secondary wastewater treatment to convert biodegradable organic materials into simpler, more stable compounds and biomass (Lee et al., 2001). Both attached and suspended growths are a part of the classical processes. In the former, as in rotating biological contactors (RBCs) and trickling filters, microorganisms attach to a rigid surface to create a biofilm; in the latter, as in membrane bioreactors and conventional activated sludge (CAS) processes, the bacteria are suspended (Abu Bakar et al., 2018). Wastewater is treated by them all around the world (Waqas et al., 2020). In the integrated fixed-film activated sludge (IFAS) process, the attached and suspended growth systems are combined (Jabari et al., 2014; Mannina, Capodici, Cosenza, Di Trapani, et al., 2017). A notable level of nitrification and denitrification is provided by IFAS, which is also effective in eliminating dissolved organic carbon (Arias et al., 2018). IFAS has become an advanced wastewater treatment solution. The moving bed biofilm reactor (MBBR), which grows biofilm on suspended media, is developed further by IFAS (Di Biase et al., 2019; Di Trapani et al., 2010). Through the start of floating bio-carriers, which biofilm can grow on, IFAS integrates the biofilm and CAS in this way (Rosso et al., 2011). The media is kept either as a fixed surface or moveable surface inside the bioreactor. With a little adjustment, the CASs can be adapted into IFAS to increase the treatment capacity (Mannina & Viviani, 2009; Ødegaard, 2017; Rosso et al., 2011). The nitrifiers attached to the carrier media enable IFAS to achieve better biological nitrogen removal (BNR) while also improving its robustness and compactness (Bai et al., 2016). Both autotrophic and heterotrophic bacteria can be accommodated by the coexistence of biofilm and floc, which improves phosphate removal and BNR (Boltz et al., 2009). Because of the biofilm's durability and ability to function under very long sludge retention times, IFAS is able to accomplish year-round nitrification and high treatment efficiency (SRT) (Kim et al., 2011). In contrast to other attached growing methods like RBC, which only use part of the bioreactor's volume, IFAS maximizes the usage of the bioreactor's volume (Waqas & Bilad, 2019). Therefore, the IFAS incorporates the beneficial characteristics of both attached and suspended growth systems (Leyva-Díaz et al., 2014).

Any kind of treatment method that combines elements from multiple different technologies might be referred to as hybrid. The integrated fixed film activated sludge (IFAS) method, which combines fixed film and traditional suspended growth activated sludge treatment procedures, is the key focus of the term "hybrid processes." As shown in the primary objective (Figure 1.4.) of an IFAS process is to provide more biomass inside the reactor volume of an activated sludge process in order to increase the system's capacity or performance

In fact, by employing media in an IFAS process, the effective mixed-liquor suspended solids (MLSS) concentration can be almost doubled. An increase in the solids loading rate does not adversely influence the operation of the downstream final clarifiers because the biomass is fixed on a media system, preventing an increase in suspended-growth mixed liquor concentrations. As a matter of fact, fixed-film growth frequently results in a decrease in the sludge volume index (SVI), which enhances clarifier performance.

Consequently, in existing treatment plants that need to include nutrient removal, the IFAS process has generally been viewed as an upgrade option. By enabling the aerobic treatment processes to be finished in a smaller volume thanks to the media and the biomass it supports, some of the current tank capacity can be changed to an anoxic zone or integrated with an anaerobic zone for biologically enhanced phosphorus removal.

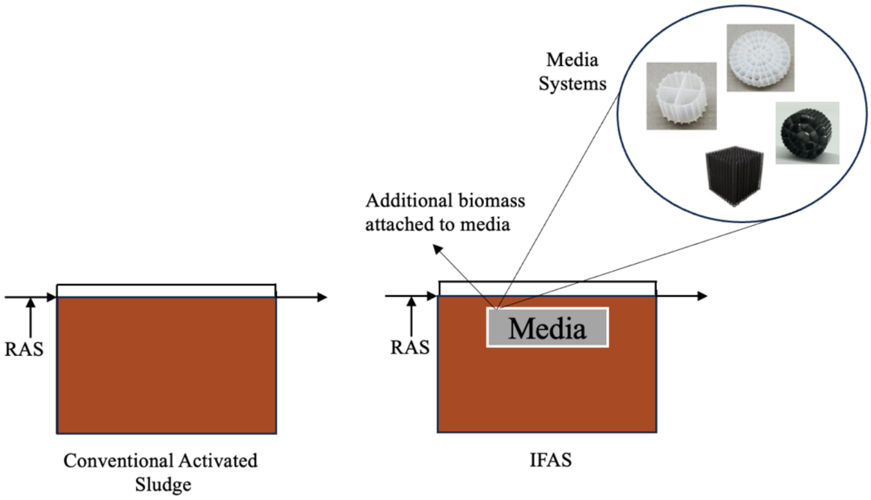


Figure 1.4 : IFAS process and conventional activated sludge process.

Although there would be hydraulic limitations to a capacity increase, it is also feasible because the clarifiers are not exposed to the higher mixed-liquor concentration. Therefore, IFAS provides an efficient and often affordable method for upgrading treatment facilities that have limited space and need to operate at a higher level.

Almost any kind of reactor setup and process flow diagram can be used with the IFAS process. It has mostly been applied to improve nitrification and biochemical oxygen demand (BOD) removal in the aerobic zones of treatment processes. As a result, the modified Ludzack-Ettinger (MLE or improved MLE) type procedure has seen a large number of IFAS applications. IFAS has, however, also been used to improve denitrification in anoxic zones, depending on the type of media. In an anaerobic zone, IFAS has not been used in media for enhanced biological phosphorus removal (EBPR), although EBPR depends on exposing biomass to sequential anaerobic and aerobic conditions. The application of IFAS in an anaerobic zone to enhance the production of volatile fatty acids required for EBPR has, nevertheless, been the subject of some investigation.

As previously indicated, there is flexibility in the reactor configuration types that can be modified for IFAS. Both complete-mix and plug-flow reactors have used the IFAS process; however, as will be discussed later, each form of reactor has unique design issues based on the kind of media used. Batch reactors with sequencing and lagoons have also been used with the IFAS process.

The moving bed biofilm reactor (MBBR) process and the IFAS process are commonly confused due to their shared use of media. But because the MBBR is a pure fixed film process, it does not use return activated sludge (RAS). The IFAS process keeps mixed liquor concentrations typical of the conventional activated sludge process and does have a return sludge.

The following is a summary of some of the main advantages and disadvantages of IFAS systems that have been observed by previous experience. A few of these are depends on the media and will be discussed in more detail later sections.

1.5.1. Advanteges of IFAS systems

IFAS systems have the following advantages:

- The ability to gradually add more capacity or enhance performance by using more media;
- Additional biomass to be treated without increasing the final clarifiers' solids loading;
- Further treatment in a smaller area is made possible by higher rate treatment procedures;
- Enhanced settling properties (Lower SVIs);
- Lowered sludge production;
- Simultaneous nitrification and denitrification;
- Better ability to come back from upsets in the process;
- Reduced footprint; and
- Increased anthropogenic composite removal (Moretti et al., 2015; X. J. Wang et al., 2006)

1.5.2. Disadvantages of IFAS systems

Some the disadvantages of IFAS systems are the following:

- Odor-producing potential (after tank dewatering),
- Extra equipment for operation,
- Moving media is required; and
- Higher headloss related to media retention screens

1.6. Basic Concepts and Configuration of IFAS Systems

IFAS has two common microbial communities with distinctive characteristics: flocs and biofilm. Their involvement in the degradation of contaminants are revealed by their structural and physicochemical features (Albizuri et al., 2009; Mahendran et al., 2012). For example, the floc in the CAS is compact (denser than water) and settles easily to produce nearly sludge free effluent. On the other hand, because of its physicochemical characteristics, the sludge that separates from the biofilm does not settle easily (Liu & Tay, 2002). The settleability of both floc and biofilm is thereby explained by their specific characteristics (Ødegaard, 2017). In both aerobic and anaerobic zones, IFAS allows the use of either fixed or free floating high surface area carrier media. MBBR has a similar process structure to IFAS, except it does not use mixed liquid suspended solids (MLSS) (Hem et al., 1994). Both IFAS and MBBR use fixed media (based on looped cords) or free-floating (neutrally buoyant plastic formed into coated cylinders or chips) as carrier media for the biofilm (Figure 1.5.) formation (Mahendran et al., 2012). The concentration of MLSS is increased by the biofilm on the carrier media (Mannina, Ekama, Ødegaard, et al., 2018). The ability to increase the MLSS has allowed the IFAS to be stable across year-round nitrification and to support capacity development (Kim et al., 2010).

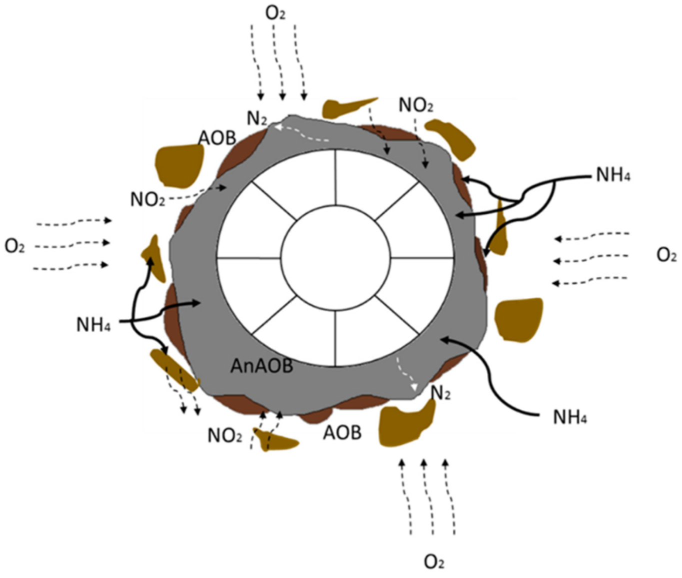


Figure 1.5 : Basic mechanism of IFAS showing the microbial activity.

It then takes into account the advantages given by further techniques of improved phosphorus and nitrogen removal (Di Trapani et al., 2010; Mannina et al., 2011). The MBBR is extended and upgraded by IFAS. Typically, an MBBR has a carrier filling ratio of up to 60–70 v%, which reduces its hydraulic capacity (Sriwiriyarat, Pittayakool, et al., 2008; Sriwiriyarat, Ungkurarate, et al., 2008). Contrarily, IFAS operates at low media loading rates, which helps increase resistance to fluctuations in hydraulic and organic loads (Bassin et al., 2016). There are significant differences between IFAS and MBBR sludge recycling systems. In MBBR, there is no need to recirculate sludge in an (Figure 1.6. (a) and (b)) anoxic/anaerobic bioreactor, and microorganisms grow on a support that is moved by agitation within the bioreactor (Leyva-Díaz et al., 2013). Agitation is important to suspend the carrier media and create shear forces to maintain a uniform and thin biofilm. Conversely, IFAS contains either solid or suspended media, as well as suspended flakes whose settled sludge is partially recycled into the bioreactor (Martín-Pascual et al., 2015). A sedimentation tank or membrane filtration can be used in IFAS for floc (Figure 1.6. (c) and (d)) separation.Adding carrier media does not increase clarifier loading. Clarifier loading rate often limits the treatment capacity of CAS (Di Trapani et al., 2010). Biofilm formation is a common feature of both the MBBR-MBR and IFAS-MBR models, which include the use or incorporation of carrier media for biofilm development (Leyva-Díaz, López-López, et al., 2015; Ødegaard, 2017).

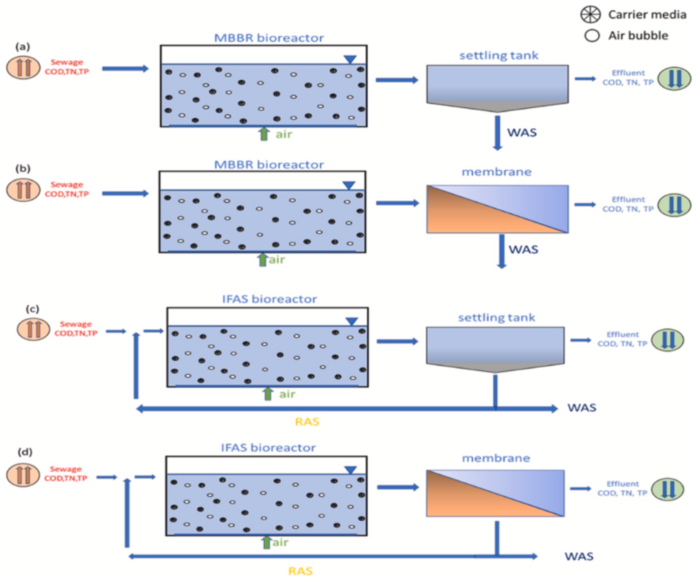


Figure 1.6 : Schematic diagram of (a); MBBR followed by secondary settling tank (b); MBBR followed by membrane separation (c); IFAS followed by secondary settling tank (d); and IFAS followed by membrane separation (Waqas et al., 2020).

1.7. IFAS Operating Parameters

There has been extensive reporting on the pilot and full scale IFAS performances. The roles of variables including carrier media, dissolved oxygen (DO), aeration rate, SRT, hydraulic retention time (HRT), and carrier filling ratio are reported. The IFAS demonstrates highly encouraging biological performances concerning BNR and phosphorus removals (Martín-Pascual et al., 2015). The three most crucial IFAS components are biology, operating conditions, and carrier media/filling ratio (Figure 1.7.). Thus, choosing the right carrier media in terms of type, material, and filling ratio is crucial (Hooshyari et al., 2009; Sriwiriyarat & Randall, 2005).

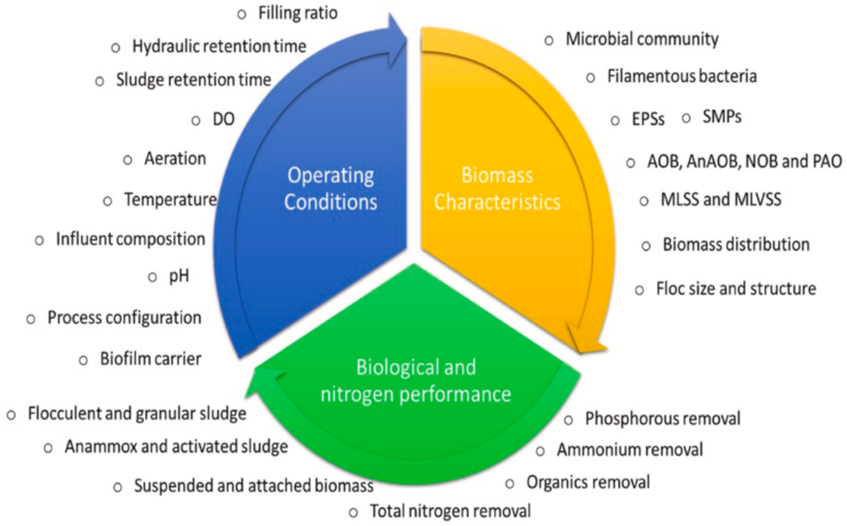


Figure 1.7 : Main parameters of IFAS (Waqas et al., 2020).

According to the feed wastewater parameters and intended effluent quality, the career media filling ratio in IFAS appears to be chosen (Sriwiriyarat & Randall, 2005). Aeration is necessary to maintain the suspension of the carrier media in the process of breaking down organic compounds, and parameters like the DO level are crucial for the survival of microorganisms (Sriwiriyarat & Randall, 2005). The wastewater strength and needs for effluent determine the choice of hydraulic loadings and HRT (L. Li & Visvanathan, 2019; Mannina, Capodici, Cosenza, et al., 2018). Only organics removal is possible with a short SRT, but oxygen transfer is hampered by a longer SRT that would increase MLSS concentration (Krampe & Krauth, 2003). Low pH and temperature have a negative impact on the floc's biological activity (Di Trapani et al., 2013). The microbial community and DO have a significant influence on the biomass properties in IFAS (C. Li et al., 2012). While nitrite-oxidizing bacteria (NOB) and anaerobic ammonium (anammox) bacteria mainly grow in the biofilm under anaerobic or anoxic circumstances, filamentous and ammonia-oxidizing bacteria (AOB) are aerobic and grow in the floc (Liu et al., 2017; L. Zhang et al., 2008). The composition of the feed wastewater and other operational factors affect the competition between AOB, NOB, anaerobic AOB (AnAOB), and phosphate-accumulating organisms (Guerrero et al., 2011; Winkler et al., 2012). The rate of oxygen transport is influenced by floc size and MLSS. Additionally, high MLSS concentrations affect the distribution and supply of DO (Germain et al., 2007; Krampe & Krauth, 2003).

1.7.1. Separation of suspension

Gravity settling is an essential process for the biosolid-liquid separation involved in attached and suspended growth processes. The floc's settling capability and compactness perform a crucial role in assessing the effluent quality. The flocs are collections of microorganisms made up of various microbial groups as well as organic and inorganic particles that have been inserted into a polymeric complex made of extracellular polymeric substances (EPS). The two most frequent issues with biomass separation are (i) poor flocculation (the creation of small, light flocs) and (ii) sludge thickening brought on by the growth of filamentous bacteria. Large, robust, and dense flocs are typically desirable for settling (J. Guo et al., 2014; Mesquita et al., 2011). The process of floc production requires energy. It depends greatly on biological, chemical, and physical elements. Size distribution and morphology are two examples of floc characteristics that vary significantly depending on feed and operational conditions (B. Jin et al., 2003; B. Wilén et al., 2010). Inadequate floc settling increases the concentration of solid waste in the effluent, boosts the cost of treating solid waste, decreases the effectiveness of disinfection, and increases environmental issues. Because there is more MLSS inside the bioreactor with higher SRT, there is also more floc density (Waqas et al., 2020). Full-scale IFAS incorporates reduced effluent solids, which may account for around 33% of the lower floc (McQuarrie et al., 2004). The CAS emphasizes the disadvantage of sludge settling because of its capacity for sludge thickening (Leyva-Díaz et al., 2017). Higher organic loading rates are made possible by both MBBR and IFAS operating at high MLSS (Chan et al., 2009).

1.7.2. Characteristics of floc and biofilms

Numerous factors influence the characteristics of biofilm and floc. The formation and stabilization of floc/biofilm depend significantly on the surface charge. The type, structure, quantity, filling ratio, and placement of the carrier media all have an impact on the floc/biofilm characteristics. EPS and biofilm dissociation are further factors (Aqeel et al., 2019). The biofilm/floc's hydrophobicity and surface charge have an impact on the sorption of colloidal particles and dissolved organics, as well as biomass attachment and flocculation (Sponza, 2003). Compared to biofilm, floc has a higher negative charge and more hydrophobicity. The IFAS floc's surface charge ranges from 0.2 to 0.6 meq/g of volatile suspended solids (VSS) (Mahendran et al., 2012). They are mostly determined by the composition of EPS (B.-M. Wilén et al., 2003). The floc's hydrophobicity and flocculation have a strong correlation. A high biomass population density is a result of strong hydrophobicity, which facilitates floc formation and stabilization (Olofsson et al., 1998). The growth of bacteria is also impacted by floc hydrophobicity. Faster growing bacteria have a higher hydrophobicity and are more likely to floc instead of build biofilm on the carrier media (Cerca et al., 2005; Stricker et al., 2009). In BNR, the biofilm plays a greater role. IFAS supports the decoupling of its Solid Retention Time (SRT), thereby fostering the proliferation of slow-growing nitrifying bacteria within the biofilm (Mannina, Capodici, Cosenza, Laudicina, et al., 2017a). Under shorter SRT operations, the floc populations multiply and remove organic materials. Consequently, the majority of the organic carbon oxidation eliminated in the floc is represented by the chemical oxygen demand (COD) (Onnis-Hayden et al., 2011). It is currently unclear how much biofilm and floc contribute to BNR in relation to one another. With an 85% biofilm contribution, Regmi et al., (2011) were able to achieve complete nitrification. The majority of nitrifiers and nitrification activity (>75%) preferentially reside on the carrier media as opposed to the suspension (Onnis-Hayden et al., 2011). According to Van Den Akker et al., (2010) the biofilm and floc both contributed equally to BNR. In BNR, a different study found that the floc had more nitrification roles than the biofilm (Kim et al., 2011). In order to achieve partial nitrification, Jabari et al., (2014) used more floc than biofilm. The variations in the food and conditions could potentially have an impact on the variance in the results. Further research is still needed to determine the function of nitrifiers in an IFAS. The distinction between the roles of floc and biofilm is further complicated by the seeding process. It is described as a typical IFAS phenomenon when the biofilm separates and becomes suspended (Qiqi et al., 2012). Because unattached biofilm rich in nitrifiers has better access to the dissolved contaminants, seeding improves BNR. In certain situations, as was previously mentioned, this phenomenon could account for the floc's primary function in BNR. However, overseeding causes the slow growing bacteria to be washed away through excessive sludge removal, which lowers nitrification and subsequently complicates biomass separation (Singh & Kazmi, 2016).

1.7.3. Hydraulic retention time (HRT)

The needed reactor volume is determined by HRT and the carrier falling ratio. They control the efficiency of the IFAS and must be improved, especially for ammonium removals (Frederick et al., 2011; Huang et al., 2016; Waqas et al., 2020). Low HRT (3–12 h) is necessary for wastewater with low strength. However, it is still unclear why various reports were assigned different HRT-values. COD removals are made easier by long HRTs, particularly when working persistent compounds. However, the Oil sands process affected water (OSPW) treatment's COD elimination shows a slight improvement with the extension of HRT from 48 to 96 hours. In order to assess the impact of HRT on COD removal, Huang et al., (2016) ran IFAS at HRTs of 48, 72, and 96 hours. For the raw and ozonated OSPW, the HRTs of 48, 72, and 96 hours provided COD elimination of 43.12% and 47.25%, 44.42% and 46.31%, and 44.42% and 46.21%, respectively. It's important to remember, too, that their HRTs were far higher than average amounts. M. Zhang et al., (2016) used lab-scale IFAS to assess how HRT (6–12 h) affected the anaerobic anoxic oxic-biological contact oxidation (AAO-BCO) process's ability to remove COD at influent COD levels of 170–310 mg/l. According to their findings, increasing HRT has a minor impact on COD elimination (80–84%). The elimination of ammonium decreased by 3% as hydraulic loading increased (0.39–1.56 k/ (m^3.d). The stability of the AAO-BCO mechanism was suggested by the authors' conclusion that HRT had a negligible impact on COD elimination. A pilot-scale IFAS was operated by Mannina, Capodici, et al., (2018) to examine the effects of SRT and HRT. They observed that the system performed better with a lower SRT/HRT ratio. Because of the low SRT/HRT ratio, there was more organic loading rate, which enhanced the removal of nitrogen through sludge waste. Higher organic input in conjunction with a low SRT increased heterotrophic activity. Additionally, a lower SRT/HRT ratio encouraged the creation of EPS (Deng et al., 2016). Raising the HRT only slightly improves the COD or nitrogen elimination. It is difficult to reach a more comprehensive conclusion on how HRT affects COD and nitrogen removals due to the different characteristics of the studies. However, IFAS shows its resilience by continuing to function biologically well across a broad range of HRTs, indicating that it can tolerate changing circumstances (Sriwiriyarat & Randall, 2005; Waqas et al., 2020).

1.7.4. Extracellular polymeric substance in biofilm and suspended floc

The components of flocs/biofilm, known as EPS, are either results of metabolism or are produced from the remains of lysing cells. Additionally, wastewater itself has a suspension of both firmly and loosely bound EPS (LB-EPS). The components of flocs/biofilm, known as EPS, are the metabolic products that shape the floc's structural and functional integrity, therefore determining its physicochemical qualities (Waqas et al., 2020). Thus, the floc settling, flocculation, and dewatering properties are significantly influenced by the EPS (X. Chen et al., 2019; B. Jin et al., 2003). The material known as EPS is released by microorganisms and resembles slime. Proteins and carbohydrates make up the majority of EPS's components. Floc or biofilm is mostly composed of humic compounds, which constitute 20% of the EPS content. Nucleic acids, lipids, inorganic components, and uric acid are a few examples of small components. By altering the surface chemistry of the cell walls, EPSs increase the adhesion of the cells to one another or to a solid surface (Waqas et al., 2020). Elevated biofilm could lead to an increased total EPS. Additionally, EPS protects nitrifying bacteria from rapid environmental changes and promotes cell adhesion, which helps the bacteria grow. On the other hand, high EPS encourages viscous bulking, which prevents organics from diffusing and degrades performance (Van Den Akker et al., 2010).

H.-S. Shin et al., (2001) investigates how DO affects IFAS's ability to produce EPS. They discovered that while the protein composition remained unchanged, a higher DO level improved carbohydrates. Proteins and carbohydrates have comparable amounts in EPS at low DOs. Compared to the floc in IFAS, the biofilm generates more EPS. But as the microorganisms get used to their environment, the amount of EPS in the floc increases and eventually equals the productivity of the biofilm. These variations can be linked to the floc's dynamics or the seeding impact (Singh & Kazmi, 2016).

According to Singh et al., (2018), the concentration of bound EPS was originally six to ten times higher than that of soluble microbial products (SMP). Nonetheless, the content of SMP became progressively at modest aeration intervals. A possible cause could be associated with stress circumstances (anoxic zone), whereby LB-EPS separates from the biofilm and SMP is released via cell autolysis (Luna et al., 2014). The carbon/nitrogen (C/N) ratio and EPS are closely related. According to Shao et al., (2017) there is an increase in EPS concentration from 129.3±6.7 to 187.6±8.7 mg/reactor when the C/N ratio decreases from 10:1 to 5:1. In a pilot IFAS-MBR, Mannina et al., (2018f) assessed the impact of the C/N ratio on nitrous oxide (N2O) emission. N2O emissions accounted for about 1% of the nitrogen input. The aerobic reactor produces more N2O when the C/N ratio grows. The C/N ratio has a significant impact on both biological function and N2O generation. According to a recent study, increased N2O emission occurred when denitrification efficiency dropped by 14.7% at the lowest C/N ratio (2 gCOD/gN) (Mannina et al., 2018f). The N2O production for the IFAS-MBR indicates that the aerobic and MBR ponds were the primary N2O sources, with the anoxic reactor producing the greatest N2O emission (1228 µg N2O–N/l) at the lowest C/N ratio (Waqas et al., 2020). The ratio of polysaccharide to protein in the EPS also affects floc's settleability. The phrase "sludge volume index" is used to evaluate sludge's settleability (H.-S. Shin et al., 2001). The EPS's amount of carbohydrates negatively impacts the mixed liquid's floc settleability and decreases its settleability (McSwain et al., 2005). The floc and biofilm have quite different EPS compositions. The biofilm has a higher ratio of polysaccharides to proteins than the floc (Shao et al., 2017). Polysaccharides in the biofilm enhance cell adhesion to a solid surface. Sludge production rate, settleability, and EPS content are all impacted by intermittent aeration (IA) (Waqas et al., 2020). Singh et al., (2018) examined how IA affected the properties of the sludge and the formation of EPS. The floc's EPS concentration increases at a faster non aeration to aeration time ratio. Compared to the MBR, the SMP in the IFAS-MBR is higher. In the MBR, the average SMP is 0.5%, whereas in the IFAS-MBR, it is 8.6%. The membrane fouling tendency was discovered to be caused by this SMP (Mannina et al., 2018e). Both the aerobic and anoxic reactors' EPS concentrations increase with the decrease in the C/N value, measuring 440 and 880 mg/g total suspended solids (TSS), respectively. These findings indicate that reduced C/N encourages the production of EPS since there is less carbon available for microorganisms to consume (Mannina et al., 2018f). Because of EPS's protective effect of preserving the biofilm, IFAS exhibits strong tolerance to low-temperature operation. Additionally, it provides improved sludge settleability (Waqas et al., 2020). Ye et al., (2010) assessed the effectiveness of IFAS in removing ammonium at low temperatures (7–9 °C) and high DO levels (4–6 mg/l). The discharge limit is met by the effluent nitrate, indicating that IFAS is a desirable option in sub-tropical areas with low temperatures. The carrier media provides resistance against low temperatures and helps to complete the nitrification process all year round (Kim et al., 2010). Additionally, Di Trapani et al., (2013) reported that even below 9°C, IFAS may retain effective COD removal. The microbial community is hardly affected at all by the pH shift.

1.7.5. Filling ratio of IFAS carrier media

IFAS involves use of carrier media that biofilm is attached to. The components of carrier media are significant and have an impact on the microbial ecology (Lariyah et al., 2016). As carrier media, a range of materials have been employed. It can be listed as activated charcoal, stones, sand, clinker, ceramic, plastic sheets, metals, and foams (X. Zhang et al., 2016). The filling ratio performs a crucial role in controlling microbiological activity. The filling ratio range is selected based on the mix of feed, ranging from 30% to 70% (Barwal & Chaudhary, 2014; Rodgers & Zhan, 2003). Because of the volume that the media occupies, the filling ratio has an impact on the HRT and SRT (from a few hours to a few days) (Leyva-Díaz et al., 2017). The effective volume is reduced by a high filling ratio and vice versa.

Due to the diversity of the feeds, the filling ratio variation for IFAS treating industrial wastewater (industrial IFAS) is significantly greater than that for domestic wastewater (domestic IFAS), which has generally consistent feed characteristics. The significant variance seen in the industrial IFAS suggests that it is a crucial design parameter that is chosen in accordance with feed characteristics and expected effluent quality (Di Trapani et al., 2008; Leiknes & Ødegaard, 2007). The selection of HRT, SRT, organic loading rate, and hydraulic loading rate further compounds the carrier filling ratio (Bassin et al., 2016; Mannina et al., 2011). A higher carrier filling ratio reduces free volume and floc, which eventually decreases the HRT (Wang et al., 2005). High packing ratios (60–70%) shorten the floc HRT, which raises the biofilm SRT at the same time as lowering the IFAS hydraulic capacity because they leave less volume available to hold the mixed liquid (Sriwiriyarat, Pittayakool, et al., 2008; Sriwiriyarat, Ungkurarate, et al., 2008). Lower filling ratios, on the otherhand, cause the system to turn against quicker hydraulic stresses and increase HRT. Because of its higher SRT and increased biofilm quantity, IFAS can achieve notable nutrient removals at high filling ratios. In order to reduce energy input (for agitation/aeration) and opex, the industrial IFAS operates at a reduced filling ratio (Lariyah et al., 2016; Martín-Pascual et al., 2015; Sriwiriyarat & Randall, 2005). The industrial IFAS has a filling ratio of 15–60%, while domestic IFAS ranges from 8 to 60%. The median values for industrial and domestic IFAS are 30% and 40%, respectively. The filling ratio is chosen according to the desired performance; an increased ratio is required for a higher nitrification demand since it results in a higher relative volume of biofilm. According to Martín-Pascual et al., (2015), a high organic removal efficiency can be attained with only 20% carrier media.

Only a limited amount of research systematically examines the effect of filling ratio. According to L. Zhang et al., (2015) the BNR increased from 80 to 85% with a slight increase in filling ratio from 15 to 20%. Kim et al., (2010) found that floc settleability was improved by a higher filling ratio. According to Wang et al., (2018) there was no noticeable difference between the biological performance of two IFAS systems with filling ratios of 50% and 40%. De La Torre et al., (2013) used polyethylene carrier media in a two-hybrid IFAS-MBR with a 50% filling ratio. To achieve greater than ninety eight percent removals, the systems were operated at HRT of 11.6–14.45 h and SRT of 10–20 d.

Biofilm, commonly known as biofouling, on the membrane surface of the IFAS-MBR enhanced the biological activity as well (Bilad et al., 2010). The free-floating carrier in IFAS-MBR contributes in controlling membrane fouling (Leiknes & Ødegaard, 2007). They remove foulant by scouring it off, enabling an extended filtration process. Chen et al., (2016) examined the effects of carrier media for fouling management by operating two moving bed membrane bioreactors (MBMBRs). The effectiveness of the carrier media for controlling membrane fouling was demonstrated by the MBMBR, which increased the filtration with and without scouring by 1.5 and 8 times of the referenced MBR, respectively (L. Jin et al., 2013). The biofilm's SRT can be changed by adjusting the degree of media filling (Kim et al., 2011; C. Li et al., 2012). With the introduction of bio-carrier, MLSS can be increased by up to two times without requiring a larger tank. The carrier media offers nitrifying/denitrifying and anammox bacteria an additional secure to make a growing environment. As a result, the biofilm has been found to contain far greater AOB and NOB than the floc.

Numerous media have been employed to the systems, and a few of them have established themselves as industry standards. Generally, the diverse media kinds can be classified as either fixed or movable. Media that has been weaved into a rope or a hexagonal pattern is referred to as fixed media. The fixed media in the activated sludge basin is secured on frames and stays in place. Free-floating media can be made up of tiny plastic carrier parts that look like wagon wheels or cylinders made of a sponge material.

In an IFAS system, almost any kind of fixed-film media can be utilized. Plastic sheets and trickling filter medium were utilized in experiments early in the development of IFAS. Some characteristics that influence a given medium's potential use are its specific surface area (SSA), clogging susceptibility, growth control capacity, durability, installation needs, and operator needs (Water Environment Federation, 2011). To enable free floating, a carrier with a high internal specific surface area (SSA) and a density similar to the liquor is preferred (Leiknes & Ødegaard, 2007).

1.7.6. Selection of carrier media for IFAS

Choosing the right carrier material is essential when building an IFAS for wastewater treatment. The surface area available for biofilm formation, biomass retention, and overall treatment effectiveness are directly impacted by the carrier media selection. The right carrier media should be chosen after taking a number of things into account (Shreve & Brennan, 2019).

To encourage the formation of biofilms and make it easier for microorganisms to attach, the carrier media should have plenty of surface area. The IFAS's capacity for treatment is improved and microbial activity is allowed to rise due to its larger surface area. Increased surface area-to-volume ratio media can hold more biomass and enhance treatment effectiveness. The porosity and void area of the carrier media must be adequate to allow for the correct flow of air and wastewater inside the system. Hydraulic performance, nutrition transport, and oxygen transfer are all enhanced by adequate void space. High porosity media encourage even wastewater dispersion and protect against blockages or channeling problems (Onnis-Hayden et al., 2011).

The carrier media must to be durable, resistant to biological and chemical degradation, and strong. This ensures that the media won't break down or lose its effectiveness despite harsh operating conditions, mechanical stress, and cleaning operations. Durable carrier media ensure consistent treatment performance and minimize maintenance needs. The cost of the carrier media, including its acquisition, installation, and replacement, needs to be assessed in accordance with the project's overall budget as well as the intended treatment goals. It is crucial to find a balance between the price and the expected lifetime and performance of the media (Regmi et al., 2011). Carrier media are used in the attached growth process to help treat wastewater by giving the biofilm a surface on which to grow. In IFAS, a variety of common carrier media types are employed, each with special qualities and benefits. The characteristics of the various carrier media types employed in IFAS are compared in Table 1.2. One of the most popular carrier media in IFAS is Kaldnes K1. It features a large surface area per unit volume and is constructed of polyethylene (Waqas et al., 2023). There are lots of places to attach in the media for the growth of biofilms. Kaldnes K1 is appropriate for a range of wastewater treatment applications due to its great endurance and low clogging potential. In terms of organic matter and nutrient removal, it offers outstanding treatment efficacy and creates an optimal habitat for microbial growth. Another well-liked carrier media in IFAS is biocarrier. It has a large surface area that is ideal for biofilm attachment and is likewise composed of polyethylene. Because of the media's porous nature, excellent biomass retention and effective oxygen transfer are made possible (Onnis-Hayden et al., 2007; Waqas et al., 2023).

Matala Media is a carrier media composed of polyester. Its structure is porous and it provides a moderate-to-high surface area per unit volume. The media helps treat wastewater by creating an environment that is conducive to the growth of biofilm. Because of its strong resilience and minimal clogging potential, Matala Media can be used for long periods of time. A fibrous transport medium is coconut fiber, often known as coir pith. It holds a fibrous biofilm attachment structure and an extensive surface area. Cermedia is a carrier media made of ceramic that has a porous structure which allows for a large surface area per unit volume. Cermedia ensures an effective treatment performance and offers a great substrate for the growth of biofilms. A polyethylene-based carrier medium with a large surface area per volume is called Aqua Kaldness K3. It creates ideal circumstances for microbial growth and provides places of attachment for the formation of biofilms. Polypropylene carrier media known as "Bioflo" has a large surface area that facilitates biofilm attachment and gives places of attachment for microorganism development. Bioflo guarantees long-term durability, limited clogging possibility, and effective treatment efficacy (Waqas et al., 2023).

Table 1.2 : Comparing the characteristics of several carrier media types used in IFAS (Waqas et al., 2023).

Carrier Media	Surface Area (m^2/m^3)	Durability	Clogging Potential	Cost
Kaldnes K1	500-700	High	Low	Moderate
Biocarrier MBBR	400-600	High	Low	Moderate
AnoxKaldnes MBBR	500-800	High	Low	Moderate
Matala Media	150-200	Moderate	Low	Low
Coir Pith	100-150	Low	Moderate	Low
Cermedia	800-1000	High	Low	High
Aqua Kaldnes K3	800-1000	High	Low	Moderate
Bioflo	600-800	High	Low	Moderate

A number of considerations, including surface area, attachment mechanism, durability, clogging potential, and specific treatment aims, influence the choice of carrier media in IFAS. The carrier media included in this part, have a variety of qualities and benefits that make them appropriate for use in various wastewater treatment applications. The best carrier media for the IFAS system must be chosen with careful evaluation of these variables and thorough pilot investigations in order to guarantee the best treatment outcomes and long-term operational stability (Waqas et al., 2023).

1.7.7. Temperature

Seasonal changes and temperature can have a big impact on how effectively IFAS performs. Temperature has a significant impact on microbial activity and biological processes, which in turn affects treatment effectiveness and system stability as a whole (Germain et al., 2007). Temperature enhances organic matter and nutrient clearance because it boosts microbial activity and metabolic rates. The growth of thermophilic bacteria, which break down some chemicals more effectively, is encouraged by higher temperatures. Extreme heat or cold, however, adversely affects microbial activity and lowers treatment efficiency (Koc-Jurczyk & Jurczyk, 2017; Zungu et al., 2022). The biological reactions that take place during wastewater treatment are influenced by temperature. Temperature has a significant impact on the rate of biological processes like nitrification and denitrification. Higher temperatures are preferred for nitrification, which is the conversion of ammonia to nitrate, and lower temperatures are preferred for denitrification, which is the reduction of nitrate to nitrogen gas (Dohdoh et al., 2021; Pedrouso et al., 2019). Oxygen restrictions are caused by a decrease in oxygen solubility at warmer temperatures. Oxidation and nitrification of organic matter are two aerobic processes that are prevented by insufficient oxygen availability. In order to compensate up for the decreased oxygen transfer at higher temperatures, more aeration and dissolved oxygen control techniques could be needed. The adhesion and growth of biomasses on the carrier media in the IFAS are influenced by temperature (Trojanowicz et al., 2021). Lower temperatures affect the capacity to retain biomass by reducing biofilm development and adhesion. In order to sustain biomass retention throughout the colder seasons, operational modifications like longer hydraulic retention times or higher recirculation may be required (Rong et al., 2022). IFAS is primarily used in colder nations where removal of nitrogen is restricted by low temperatures. The goal of year-round nitrification can be achieved by having carrier media inside the bioreactor. Important problems preventing ASPs from operating as efficiently as possible are addressed by adding carrier media to the bioreactor (Stricker et al., 2009). The configuration's main goal is to finish nitrification and increase the wastewater treatment plant's treatment capacity (Kim et al., 2010; Waqas et al., 2023).

Comprehensive nitrogen removal by nitrification/denitrification and hybrid processes has been achieved through an extensive examination of the IFAS, resulting in acceptable levels of biological nitrogen and phosphorus removal (Di Trapani et al., 2010; Waqas et al., 2023).

Variations in temperature influence the resilience and stability of the microorganisms found in IFAS. Sudden temperature fluctuations, like those that occur during seasonal changes, disturb the microbial community and decrease the stability of the system. As a result, longer recovery times and worse treatment outcomes could be experienced by the system. The effects of seasonal changes are lessened and steady IFAS functioning is maintained through proper monitoring and management of operational parameters, including temperature. Depending on the wastewater properties, area climate, and system design, different temperatures and seasonal changes have different effects on IFAS performance. To maintain constant treatment efficiency and maximize IFAS performance throughout the year, extensive monitoring, data analysis, and operational modifications are required (Waqas et al., 2023).

1.7.8. Dissolved oxygen

The activity of aerobic microorganisms responsible for nitrification, organic matter oxidation, and other biological activities requires the availability of oxygen (Singh et al., 2016). Aerobic microorganisms require dissolved oxygen to continue their metabolic activities. Sufficient oxygen concentrations facilitate the effective oxidation of organic contaminants and the conversion of ammonia to nitrate during the nitrification process. Increased microbial activity and metabolic rates result from higher dissolved oxygen concentrations, which enhance treatment efficiency (Sriwiriyarat, Ungkurarate, et al., 2008).

Reduced removal effectiveness is the result of limited organic matter oxidation caused by low dissolved oxygen levels. Low DO levels cause organic contaminants to decay in part, which lowers treatment efficacy and generates remaining organic compounds. Sustaining ideal DO levels facilitates efficient elimination of organic materials and prevents the accumulation of resistant substances (Singh et al., 2018).

To support the growth and activity of nitrifying bacteria, nitrification requires a sufficient amount of dissolved oxygen. Low DO levels can prevent nitrification, which can reduce ammonia elimination and could cause ammonia toxicity further. On the other hand, low dissolved oxygen levels are necessary for denitrification, which is the reduction of nitrate to nitrogen gas. Balance between nitrification and denitrification processes in IFAS systems depends on controlling DO levels. A low oxygen level might cause an excessive accumulation of nitrates and inhibit the process of denitrification. Achieving optimal dissolved oxygen levels in different process areas facilitates the effective removal of nitrogen (Cao et al., 2017; Waqas, Harun, Bilad, et al., 2022).

Biofilm growth on the carrier media is influenced by DO levels. Higher DO concentrations stimulate the development of biofilms that are both thicker and more active. Strong biofilms increase the effectiveness of treatment by giving microorganisms a lot of surface area to attach to and better enabling pollutant decomposition (Waqas, Harun, Sambudi, et al., 2022; Yerrell et al., 2001).

Optimum biomass activity and biofilm formation are supported by appropriate dissolved oxygen concentrations. Anaerobic zones within the IFAS system are less likely to form when sufficient dissolved oxygen levels are maintained. Anaerobic environments can promote the growth of anaerobic microorganisms which can cause odor problems, process instability, and the generation of undesirable byproducts. By maintaining appropriate DO levels, avoiding anaerobic zones, and ensuring steady system operation, aerobic conditions are maintained (Ma et al., 2018).

A partial nitritation/anammox (PN/A) is applied by the plug flow IFAS to effectively remove nitrogen compounds from real wastewater. The influent is rich in nitrogen and ammonium (NH_4^+-N 45.0±5.2 and TN 54.7±6.4), with a C/N ratio of 1.3. It also achieved an 82% removal of TN at a nitrogen removal rate of 0.097±0.019 kgN/(m^3d). The performance of PN/A decreased as the ammonium content dropped below 1 mg/L. Conversely, long term stability of the PN/A was attained when the residual ammonium concentration exceeded 3 mg/L (X. Zhang et al., 2016). In order to treat high ammonium wastewater, a pilot plant ASP to IFAS was modified by filling an immobile carrier. The rate at which ammonium was loaded gradually increased in order to maximize removal efficiency. The pilot plant demonstrated excellent results in terms of removing COD, $NH4^+$-N, and $PO4^{3-}$-P; total removal efficiencies of 96.6%, 99.9%, and 98.8% were attained (L. Zhang, Liu, et al., 2015).

Phosphorous removal and denitrification have been compared between the fixed bed bioreactor (FBBR) and the MBBR. Results showed that the FBBR is more effective at removing all nutrients than the MBBR. Total chemical oxygen demand (tCOD) was reduced by 19.8% with MBBR, filtered COD by 35.5%, BOD_5 by 27.6%, acetate by 62.2%, $PO4^{3-}$-P by 78.5%, and $NO3^{-}$-N by 54.2%. Conversely, the FBBR eliminated tCOD by 49.7%, filtered COD by 54.0%, BOD_5 by 63.2%, acetate by 99.6%, $PO4^{3-}$-P 98.6%, and $NO3^{-}$-N by 575.9% (H. J. Choi et al., 2012).

The ideal levels of dissolved oxygen can change based on the particular features of the wastewater; the design of the process, and the IFAS system's conditions of operation. In order to avoid oxygen limitations and excessive energy consumption, optimal dissolved oxygen concentrations must be sustained through regular monitoring of DO levels and adjustments to aeration rates or oxygen transfer mechanisms (Waqas et al., 2023)

1.8. Performance of Integrated Fixed Film Activated Sludge Systems

1.8.1. Removal of organic compounds

The COD removal performance summary for industrial and domestic IFAS is displayed in Figure 1.8.(a) and (b). The boxplot of the removal efficiencies is shown in the insets of Figure 1.8. Domestic IFAS achieves 64.8–100% COD removal, as seen in Figure 1.8(a) with an average value of 95%; half of the data decrease within the 90–96.8% range (refer to the boxplot). The range of the influent COD levels is 60–607 mg/l. In every study, IFAS efficiently eliminates COD with effluent values of less than 100 mg/l (Waqas et al., 2020).

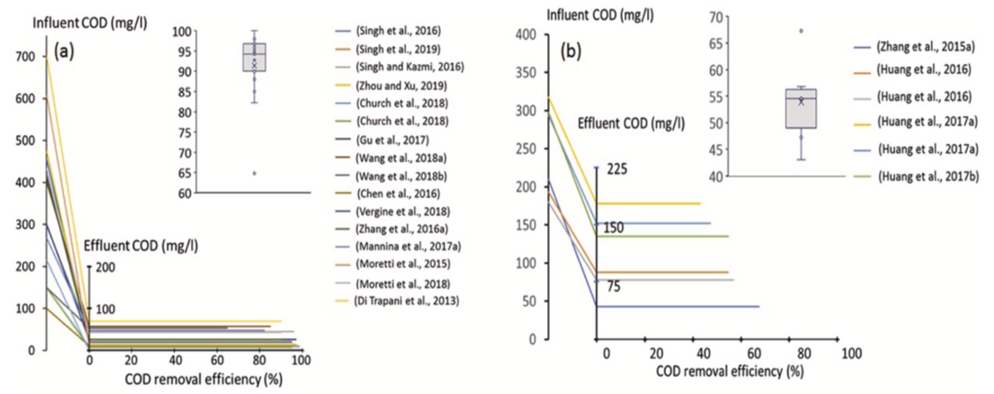


Figure 1.8 : COD removal efficiency (%) and influent and effluent values for (a) domestic wastewater and (b) industrial wastewater (Waqas et al., 2020).

Significantly low COD removals of 55% were attained for the industrial IFAS. Since the feeds are mostly rich in ammonium, the process objective, which places a strong emphasis on BNR, is primarily responsible for the poor removals (Waqas et al., 2020). A low feed COD value for domestic and industrial wastewater is shown in Figure 1.8.(b). Only 43–67.3% of COD removal efficiencies are achieved overall. (Leyva-Díaz, López-López, et al., 2015) operated a pilot IFAS at low SRT of 11 day and achieved 87% COD removal. An IFAS-MBR removed 98% of the COD, according to (Mannina, Ekama, Capodici, Cosenza, Di Trapani, & Ødegaard, 2018) study. The outcomes are consistent with the MBR and IFAS-MBR configurations reported by (Leyva-Díaz, López-López, et al., 2015). Both systems removed more than 98% of the organic matter and had similar medium filling ratios and HRT (Leyva-Díaz, López-López, et al., 2015). Di Trapani et al. (2010) found that when IFAS and CAS were evaluated at the pilot scale, IFAS showed greater reductions of organic matter and ammonium. IFAS has a slightly greater organics removal rate than MBBR-MBR hybrids, although it was run using a different carrier media. The MBBR-MBR was run with varying membrane characteristics (pore size), a reduced HRT, and a low C/N ratio of 3-5 (Leyva-Díaz et al., 2016; Leyva-Díaz & Poyatos, 2015). In IFAS-MBR, the coexistence of aerobic, anoxic, and anaerobic conditions improves the removal of trace organics. Organic removal in the presence of medicinal substances was compared by De La Torre et al., (2013) using three different configurations: MBR, IFAS-MBR, and MBMBR. The IFAS-MBR has the highest COD removal rate (98.95%) and removal rate for trace pharmaceutical chemicals (72.0%). Reduced trace pharmaceutical component removal effectiveness in the MBMBR is caused by lower MLSS and lowest HRT (6 h). However, it was discovered that the membrane fouling problem was crucial when handling anaerobic sludge and would be correctly managed (De Vrieze et al., 2014). It has been demonstrated that IFAS is more resilient to antimicrobial particle exposure. AgNPs, or silver nanoparticles, have excellent antibacterial properties (Hou et al., 2012). Their presence in feed may put microorganisms at risk, particularly those involved in biological treatment processes (Z. Zhang et al., 2016). Biofilm is thought to contribute to good antimicrobial resistance (O. Choi et al., 2008). As a result, IFAS is able to endure a certain amount of feed toxicity. To increase their resistance to AgNPs and activate their self defense mechanisms, microorganisms often produce more EPS (Qiu et al., 2016). AgNP effects on EPS composition, microbial community structure and function, and IFAS-sequencing batch reactor (IFAS-SBR) performance were investigated by Zhou & Xu, (2019). Despite the presence of AgNPs in the feed at levels between 0.1 and 10 mg/l, the system was still able to remove 96% of the COD. The different wastewater COD values were 15.3±3.2, 16.3±3.6, 15.6±3.2, and 17.8±5.0 mg/l, which correspond to concentrations of AgNPs of 0, 0.1, 1.0, and 10 mg/l, in that order. With an effluent concentration of less than 0.10 mg/l, >99% of $NH4^{+}$-N was removed. $PO4^{3-}$-P effluent concentrations never went over 0.07 mg/l. Even at low DO levels (0.7–1.5 mg/l), IFAS can maintain stable effluent COD. Even at low DO (≤0.4 mg/l), IFAS and MBBR provide efficient COD elimination (>90%) (Waqas et al., 2020). Tao & Hamouda, (2019) investigated the elimination of COD in MBBR and IFAS at various aeration rates. Both contained the effluent COD at less than 50 mg/l and removed more than 90% of the COD. Using the PN/A method, Malovanyy et al., (2015) reported similar results for domestic IFAS. Under IA, IFAS is also successful in removing nutrients and organic matter. In order to remove organics and nitrogen from a full-scale residential IFAS, Singh et al., (2019) used IA. The results of the research demonstrate that it is possible to operate IFAS at low DO and still carry out the strict effluent standards.Good removal of resistant organics is also demonstrated by IFAS. The biomass from IFAS, MBBR, and MBR treating resistant organics is compared by Huang et al., (2017). With ammonium removal of >99% for all, the IFAS exceeded the MBBR (influent 412.26±13.4 mg/l; effluent 172.3±8.12 mg/l) and the MBR (influent 519.87±5.13 mg/l; effluent 240.93±4.13 mg/l) in COD removal (feed 297.86±5.67 mg/l; effluent 135.22±8.45 mg/l). The higher density of biofilm in IFAS is thought to provide it a benefit over other types. IFAS-MBR has demonstrated a solid balance between organics and nutrition removal. In a pilot-scale hybrid domestic

(Mannina, Capodici, Cosenza, Laudicina, et al., 2017b) report the organic removal and bacterial community structure; COD of 607 mg/l, total nitrogen (TN) of 65 mg/l, total phosphorous (TP) of 11 mg/l, and COD/TN/TP ratio of 100/10.7/1.8. AnoxKaldnes K1 carrier media (filling ratio: 15 and 40%) with a DO level of 5.33 mg/l and a 20-hour HRT were used in the plant's operation. Despite differences in feed composition, the results indicate a maximum COD removal of 98%, nitrification of 98%, and TP of 40.4%. The biofilm was responsible for nearly all of the ammonium conversion and 98% of the nitrification. Nonetheless, membrane fouling was noted (Lau et al., 2019; Rahmawati et al., 2019). Membrane pore blockage increased as a result of biofilm separation that produced an EPS fraction. The increase in ammonium loading rates may have contributed to the poor TP removals by lowering the C/N ratio and encouraging the synthesis of nitrate. While maintaining a high level of organic removal, IFAS performs a critical role in the elimination of oil and grease as well as linear alkylbenzene sulfonate (LAS) (Waqas et al., 2020). COD, LAS, and oil and grease removal maximized at an organic loading rate of 0.44 g COD/(l.d.), according to Eslami et al. (2017). Efficiency was reduced by a subsequent increase in the organic loading rate. At an organic loading rate of 0.44 g COD/(l.d) at DO 2.320.91 mg/l, IFAS eliminated 92.52%, 94.24%, and 90.07% of COD, LAS, and oil and grease, respectively. The fact that biofilm has effectively broken down and eliminated LAS and oil and grease highlights the significance of IFAS. COD, LAS, oil and grease removal maximized at an organic loading rate of 0.44 g COD/(l.d.) (Eslami et al., 2017). Efficiency was reduced by a subsequent increase in the organic loading rate. At an organic loading rate of 0.44 g COD/(l.d) at DO 2.32±0.91 mg/l, IFAS eliminated 92.52%, 94.24%, and 90.07% of COD, LAS, oil and grease, respectively. The fact that biofilm has effectively broken down and eliminated LAS and oil and grease highlights the significance of IFAS (Waqas et al., 2020).

1.8.2. Removal of nitrogen

IFAS applications for increased nutrient removal, particularly for BNR, have been extensively studied. For the BNR, IFAS is quite successful (Sriwiriyarat & Randall, 2005). High oxygen and nutrient transport are made possible by the mobile media in IFAS (Waqas et al., 2020). For the growth of both heterotrophic and autotrophic nitrifying bacteria, the C/N ratio is important. The competition between autotrophic and heterotrophic bacteria for supplies, oxygen, and space has an impact on nitrification (Bassin et al., 2012; Kim et al., 2011; Onnis-Hayden et al., 2011). Figure 1.9. shows an overview of the IFAS parameters and performances for BNR. Domestic IFAS achieves 33.9–99.93% BNR with an average of 80%; the boxplot illustrates that half of the data fall within this range, from 70% to 90%. It is thought that the value of 33.9% removal is an error. The range of the influent nitrogen is 30–210.5 mg/l, which subsequently influences the selection of other parameters (Huang et al., 2016, 2017). BNR is highly valued by industrial IFAS, as evidenced by the meals with high nitrogen concentrations Figure 1.9.(b). Industrial wastewaters are challenging to clean because they frequently contain phosphorus, ammonium, nitrate, nitrite, volatile elements, and trace compounds (Cai et al., 2013). By achieving 80–100% removals, IFAS has proven its reliability in the treatment of nitrogen rich wastewater. Nitrogen based chemicals are present in significant amounts and an extensive variety in the influents shown in Figure 1.9.(a) (59.08–1500 mg/l). With an average value of 95% and half of the data falling in the 90–100% range, the boxplot shows that nitrogen removals are mostly within the 80–100% zone (Waqas et al., 2020).

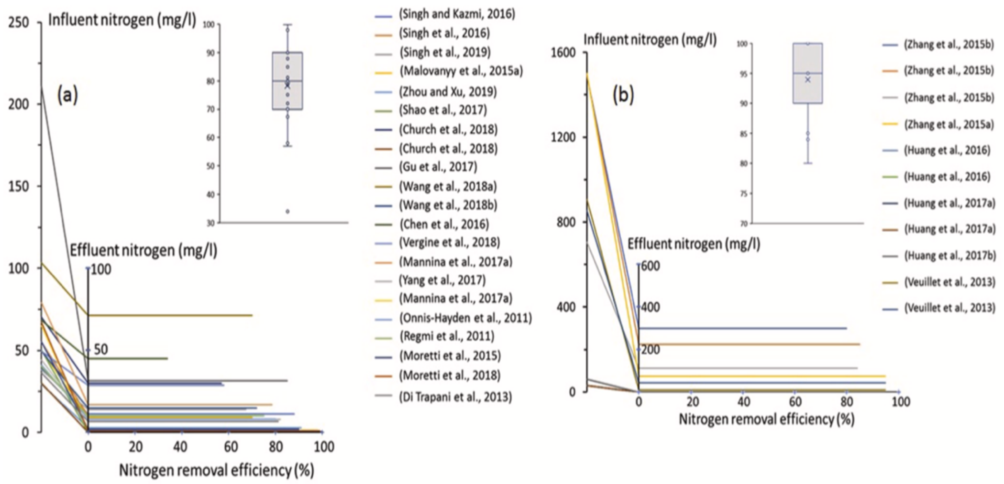


Figure 1.9 : Nitrogen influent and effluent values and removal efficiencies (%) for (a) domestic and (b) industrial IFAS (Waqas et al., 2020).

Many factors influence nitrogen removal, especially the bacterial community (Xia et al., 2008). According to Shao et al., (2017), sufficient nitrification at a C/N ratio of 10:1 resulted in a low effluent nitrate of 30 mg NO3 -N/l. Low C/N ratio reduced denitrification since there was less organic carbon available (Huang et al., 2015). If the C/N ratio is low, the IFAS floc's nitrification rate is higher than the CAS's rate under the same circumstances. It is explained by the seeding effect, which strengthens the floc with the nitrifier-rich biofilm fragment and so enhances nitrification (Di Trapani et al., 2013; Shao et al., 2017). It explains the high removal efficiency of the investigations that are condensed in Figure 1.9. High DO levels and an abundance of AOB in the floc make ammonium more accessible to the microorganisms which increases the nitrite content. A new IFAS ANITA Mox procedure for advanced BNR was proposed by Veuillet et al., (2014) to treat reject water from a mesophilic anaerobic sludge digester. Two IFAS's were fed wastewater that was high in ammonium (NH_4^+-N 907±200 mg/l) and equipped with K5 plastic carrier medium at loading ratios of 43% and 50%. $PO4^{3-}$-P <2 mg/l and NH_4^+-N 10–150 mg/l were the effluents, and they had high nitrogen removal rates of up to 8 g N/m^{2}d. The full scale IFAS achieved nitrogen and ammonium removals of 95% and 85%, respectively, and BNR rates of up to 2.2 kg N/(m^{3}d). AnAOB was more common (96%) in the biofilm, but nitritation by AOB activity was observed in the floc (93% of the total AOB). In addition to increasing BNR, the separation of AOB and anammox bacteria enhances process stability. Anammox bacteria predominate in the biofilm, whereas AOB primarily lives in the floc, as demonstrated by molecular analysis (Waqas et al., 2020). L. Zhang, Zhang, et al., (2015) evaluated the BNR and microbial distribution pattern in the biofilm and the floc while using the nitritation-anammox process to study both at the pilot and full-scale domestic IFAS. At a nitrogen loading rate of 0.7–1.3 kg N/(m^{3}d), the pilot-scale IFAS removed 80% of the nitrogen. In contrast, the full-scale IFAS was able to maintain 85% nitrogen removal at a loading rate of 0.48 kg N/(m^{3}d) of ammonium. The steady increase in ammonium loading rates made it possible to achieve the higher BNR rate.

Because biofilm seeding enhances granular floc, IFAS provides a number of advantages over the anammox biofilm procedure. The AOB activity is facilitated by high DO concentrations and sufficient substrate availability. In order to treat wastewater that is high in ammonium, L. Zhang, Liu, et al., (2015) upgraded a prototype CAS to an IFAS by filling an immobile carrier. Over the course of a two-month extended test, the IFAS maintained an 80% BNR with a loading of 1.2 kgN/(m^{3}d). High anammox bacteria were found in biofilm and granular floc, whereas high AOB was occupied by the flocculent. The floc size distribution indicated the existence of both granular and flocculent floc. Anammox bacteria in IFAS started off growing in the biofilm, separated, and then continued to grow in the floc to support BNR. In comparison to the IFAS-MBBR, the nitrate decomposition and phosphate removal rates in the IFAS fixed-bed bioreactor were much greater, even with a shorter retention time. Because the former had a larger percentage of the biofilm, this benefit was obtained (H. J. Choi et al., 2012). The growth of NOB, primarily Nitrospira and heterotrophic bacteria, was encouraged in the floc by a COD/N ratio of>2.0 (C. Wang et al., 2018). An up-flow anaerobic sludge blanket (UASB) reactor can be upgraded by IFAS to provide high microbial diversity for improved removal of organic micropollutants. Using heterotrophic denitrifiers and aerobic methanotrophs, Arias et al., (2018) operated the IFAS-UASB and achieved 93% COD, 44% TN removal, and 85% methane removal efficiency. In anoxic, anaerobic, and aerobic conditions combined, over 80% of the micropollutants were eliminated. Whereas ibuprofen and bisphenol A experienced anoxic-aerobic conditions of degradation, four micropollutants (naproxen, trimethoprim, sulfamethoxazole, and estradiol) experienced aerobic degradation (Waqas et al., 2020). When paired with IFAS, a self-forming dynamic MBR provided an anoxic environment for enhanced denitrification, lowering the concentration of nitrate in the effluent. The carrier media increase the frequency of cleaning by a factor of three by having an inverse effect on the tendency of mesh clogging (Vergine et al., 2018).

A novel process hybridization technology called microalgae-IFAS (MAIFAS) provides improved effluent quality with minimal energy input. For improved organics oxidation and nutrient absorption, MAIFAS combines bacteria and microalgae. MAIFAS removed 51% of the phosphorus and >99% of the ammonium (Church et al., 2018). Compared to a traditional microalgae photobioreactor, which normally removed 49% of phosphorous and 57% of ammonium, the removal rates were significantly greater (Bilad et al., 2014). Low DO and low carbon concentrations supported the AOB over the NOB in the presence of microalgae. M. Wang et al., (2015) suggested a BNR shortcut that requires low DO and low carbon levels. AOB (1.5% Nitrosomonadaceae) is more common than NOB (0.2% Nitrospira), according to MAIFAS biofilm study. Additionally, according to Sheng et al., (2017), the MAIFAS system can provide biomass for additional uses, although the microalgae collecting component needs.

1.9. Energy Consideration in IFAS

Energy-neutral wastewater treatment is still a long way off, despite the incredible progress made in resource recovery (Papa et al., 2017). The organics in the wastewater hold the chemical energy (Leam et al., 2020; Wibisono & Bilad, 2020). While nitrogenous matter contributes 0.30 kWh/m^3, carbonaceous matter can provide up to 1.66 kWh/m^3 (Wan et al., 2016). Municipal wastewater has four times the potential energy that is needed for the CAS (Yagci et al., 2016). The creation of biogas can facilitate the established anaerobic process for energy recovery (Wan et al., 2016). High organic and nutrient removal, as well as energy neutral or energy positive processes, can be achieved by combining the IFAS-SBR and anaerobic moving bed biofilm reactor (AMBBR) processes (Waqas et al., 2020). In order to treat municipal wastewater for energy recovery. Gu et al., (2017) compared IFAS-SBR with AMBBR in a hybrid A-B configuration of A being the AMBBR and B being the IFAS-SBR Figure 1.10. While the IFAS-SBR recovered nitrogen, the AMBBR converted COD into biogas. In addition to achieving 85% BNR, the system eliminated 85% COD and recovered 0.28 kWh/m^3 of energy. Additionally, the method eliminated 75% of the extra sludge. Advantages in aeration and sludge management were provided by the A-B design. 55% of the COD was transformed into methane by the AMBBR, while 26% of the COD from the primary sludge and 7% from the secondary sludge were converted into methane by anaerobic digestion (Wan et al., 2016).

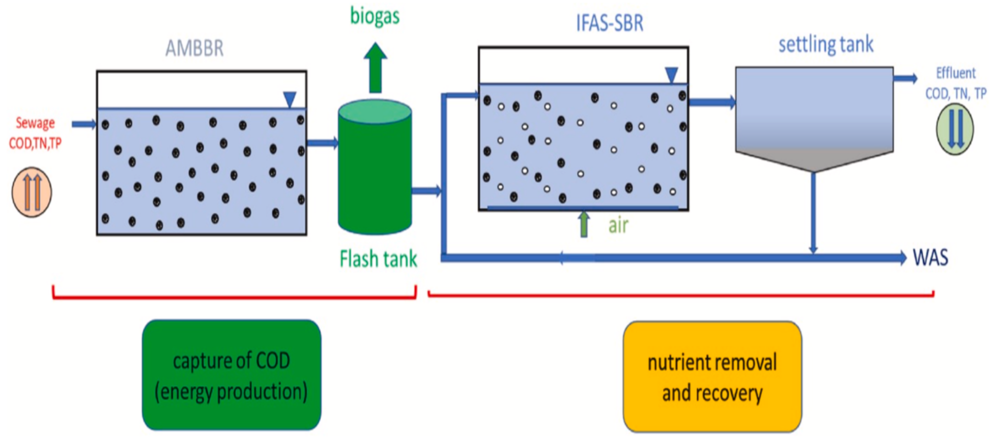


Figure 1.10 : A-B configuration with A-stage as AMBBR for biogas generation and B-stage as IFAS-SBR for nutrient removal and recovery (Waqas et al., 2020).

The excessive production of waste activated sludge (WAS) and high energy consumption are the two main problems facing the CAS. The WAS therapy could cost between 25 and 65 percent of the total (Zhao & Kugel, 1996). AMBBR can reduce WAS by 75% because it produces just 0.1 g-biomass/g-COD, as opposed to 0.3–0.5 g-biomass/g-COD produced by the CAS. Only 30–50% of COD can be removed after treating WAS, which explains the insufficient energy return. The hydrolysis of COD before to digestion, which lowers energy recovery, is a significant issue in anaerobic digestion (Waqas et al., 2020).

1.10. Hybrid IFAS MBR Treatment Technology

Membrane technology and IFAS have been successfully combined to improve treatment effectiveness and overall performance. Regarding process stability, effluent quality, and system compactness, the IFAS-MBR combination has significant benefits. An increase in biomass population and surface area is provided by adding IFAS to an MBR, which promotes the growth of nitrifying and denitrifying bacteria (Vergine et al., 2018). It encourages better removal of nutrients, particularly phosphorus and nitrogen. Ammonia is converted to nitrate and the subsequent denitrification process is facilitated by the IFAS media, which serves as a substrate for the attachment and growth of a biofilm. Combining the two will help carry out strict effluent nutrient discharge limitations in particular (De La Torre et al., 2013).

Variations in the properties of the influent wastewater are tolerated by the microbial population that is steady and robust due to the biofilm on the IFAS media. The membrane's physical separation of the biomass from the treated effluent further improves process stability. It ensures consistent treatment performance even in the presence of fluctuations in the hydraulic and organic loads, preventing the washout of the biomass. The membrane functions as a physical barrier to keep suspended particles and biomass inside the bioreactor. It increases the effectiveness of biological treatment by enhancing solids retention and sludge retention time (SRT). A higher biomass concentration is made possible by combining IFAS with membrane technology, which also reduces the system's footprint and offers a small and effective treatment solution (Naghipour et al., 2022; Phanwilai et al., 2020).

Experiments were conducted by (Mannina, Ekama, Capodici, Cosenza, Di Trapani, & Ødegaard, 2018) to remove carbon, nitrogen, and phosphorus from the IFAS-MBR hybrid system. Throughout the experiments, an average removal efficiency of 98% was achieved, demonstrating the system's outstanding overall COD removal efficiencies. The results are identical to those obtained with the MBR and hybrid MBR configurations (Leyva-Díaz, González-Martínez, et al., 2015). More than 98% of the organic material is removed from both systems using the same loading ratio of carrier media and HRT values (Leyva-Díaz, López-López, et al., 2015). When compared to hybrid MBBR-MBR, which uses different carrier media for each reactor, the organics removal for the IFAS is significantly greater. This is because each of the groups of operating conditions were different: the latter was run at a lower HRT, a lower C/N ratio of 3-5, and a larger membrane pore size 0.1 µm. The IFAS/IFAS-MBR systems' resilience for the removal of organic materials is confirmed by the findings of several researchers (Cuevas-Rodríguez et al., 2015; Leyva-Díaz et al., 2016). Over 90% COD removal efficiency was attained by the MBBR and IFAS, with an effluent concentration of less than 50 mg/L. After removing COD from domestic wastewater, they reached the conclusion that low DO levels are not the limiting issue (Tao & Hamouda, 2019). Even at temperatures below 9°C and with reduced pollutant concentrations (snow melting), the IFAS performance remains unaffected by cold temperatures (Di Trapani et al., 2013). An investigation was conducted into the total efficiency of removing trace organics using three different configurations: MBR, IFAS-MBR, and moving bed membrane bioreactor (MBMBR). The IFAS MBR was operated using a 13 h HRT and a 20 d SRT at a 50% filling ratio. The outcomes were contrasted with MBBR MBR, which has a low value of HRT (6 h) and a lower MLSS concentration, resulting in a worse removal efficiency (De La Torre et al., 2015).

To enhance denitrification, the sludge cake and biofilm production for SFD-MBR combined with IFAS were investigated. At a DO amount of 2-4 mg DO/L, 8 h HRT, and 30 d SRT, a PE carrier with a specific surface area of 489 $m^{2/}m^3$ and a filling ratio of 19% was applied. Similar findings were obtained in productivity correlations, organics oxidation, and ammonium compounds by the SFD-MBR and IFAS combined with SFD-MBR. Although the IFAS-SFD-MBR enhances denitrification and reduces sludge production, it necessitates more frequent mesh cleaning since the carrier media has a negative effect on the tendency of mesh clogging. This results in a three-fold increase in cleaning frequency. The presence of anoxic conditions within the carrier media enhances denitrification, lowering the concentration of nitrate in the effluent, and the associated growth on the carrier media led to decreased sludge generation (Vergine et al., 2018).

To find out how carrier medium affected the reduction of membrane fouling, two MBMBRs were launched into operation. Comparing the MBMBR to the MBR, it was found that the MBMBR's membrane filtration working time (without carrier scouring) increased by 1.5 times. The time was increased by eight times due to the scouring of the carrier media. When the MBR and MBMBR were compared, it was shown that membrane fouling had reduced by 58.8%. Because of carrier medium scouring, the cake layer fouling for MBMBR was reduced to 40.5% (F. Chen et al., 2016).

The structure of the bacterial population and the removal of organics from real municipal wastewater have been investigated using the pilot-scale hybrid IFAS-MBR. Its average TP removal efficiency was 40.4%, whereas its maximum removal efficiency for COD and nitrification was 98% and 98%, respectively. Despite influent fluctuation, the IFAS-MBR pilot plant displayed exceptional COD removal efficiency, with average values of >98%. The result of 98% nitrification indicates the presence of biofilm. A membrane fouling resulting from superficial cake deposition was investigated. Because of an increased EPS proportion, biofilm dissociation enhances the pore-blocking resistance (Mannina et al., 2017).

The aim was to develop a novel A-B configuration using the anaerobic moving bed biofilm reactor (AMBBR) and IFAS-SBR. Stage 'A' of the arrangement would be the AMBBR, which produces biogas that reduces COD, and stage 'B' would be nitrogen removal using IFAS-SBR. With a total energy production rate of 0.28 kWh/m3, this system achieved 85% nitrogen removal and removed around 85% of COD. About 75% less sludge was produced than with traditional ASPs (Gu et al., 2017).

As a result, this combination is perfect for achieving energy-positive or energy-neutral wastewater treatment plant operation. The effectiveness of the MBBR reactor has been investigated and compared with the mainstream wastewater treatment in IFAS provided by the PN/A (Malovanyy, Trela, et al., 2015).

A full scale IFAS plant that uses nitrification to demonstrate nitrogen removal assessment is able to remove more nitrogen related to the conversion of the MBBR to IFAS. 76,000 m^3/day of wastewater are treated by the plant using a modified Ludzack-Ettinger (MLE) arrangement (Regmi et al., 2011).

The IFAS-MBR provides flexibility in system design, allowing different configurations to meet the needs of wastewater treatment. The bioreactor's IFAS media and membrane modules are combined, offering a variety of carrier media and membrane design possibilities. Because of its adaptability, it may be customized to meet site-specific needs, such as influent characteristics, treatment objectives, and space constraints. Numerous benefits are provided by the IFAS-MBR, such as better nutrient removal, increased process stability, greater effluent quality, decreased sludge production, and adaptable system design. Applications requiring thorough wastewater treatment and stringent effluent discharge regulations will especially benefit from this combination (Waqas et al., 2023).

2. MATERIAL AND METHODS

2.1. The Pilot System

The IFAS-MBR processes used in the pilot scale system are controlled by full automation and a SCADA (Supervisory Control and Data Acquisition) system. Within the scope of this thesis, the engineering design and construction of the IFAS-MBR system were carried out in the first two months. During this process, technical 3D drawings and equipment selections were made. The technical drawings of the IFAS-MBR system are provided in Figure 2.1.

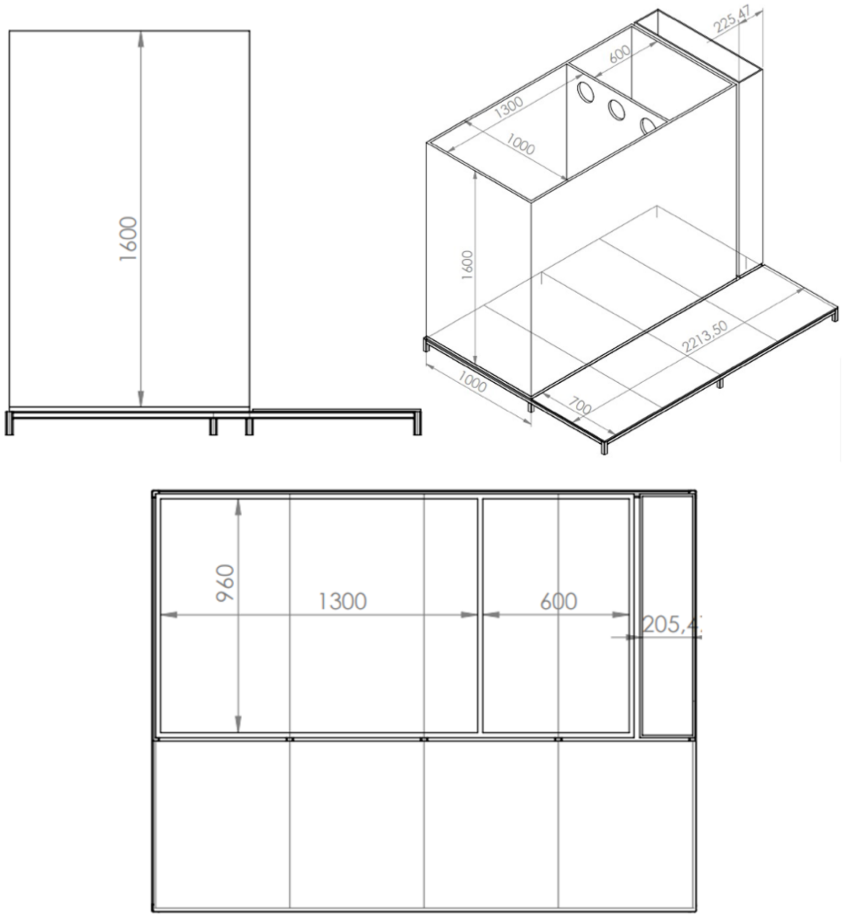


Figure 2.1 : Technical drawings of IFAS MBR system.

The technical drawings of the IFAS MBR system, depicted in 3D (three dimensions), are given in Figure 2.2.

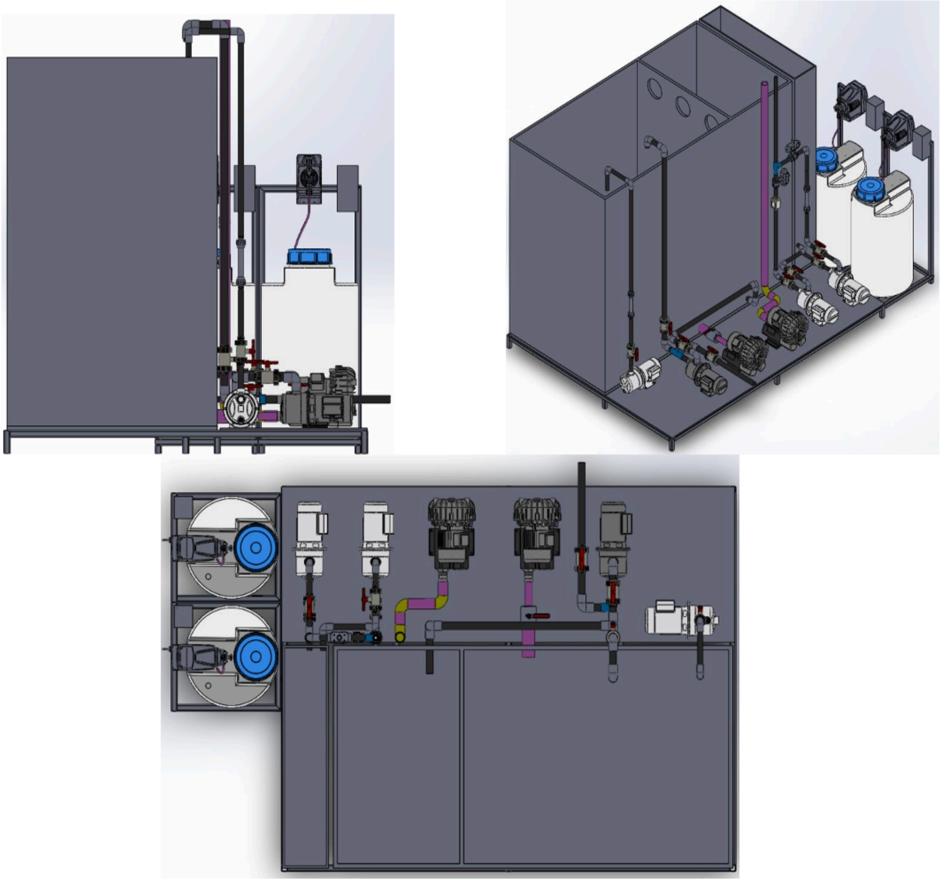


Figure 2.2 : 3D Drawings of IFAS MBR System.

The technical specifications of the IFAS MBR system are summarized in Table 2.1.

Table 2.1 : The technical specifications of the IFAS MBR system.

Unit	Value
Neutrelization Tank	3000L
Aeration Tank	Width: 100cm Length: 120cm Depth: 150cm
MBR TANK	Width: 100cm Length: 60cm Depth: 150cm
Permeate Tank	Width: 100cm Length: 35cm Depth: 150cm

The flow diagram and overall view of the IFAS MBR system and the parallel-operated MBR system are provided in Figure 2.3.

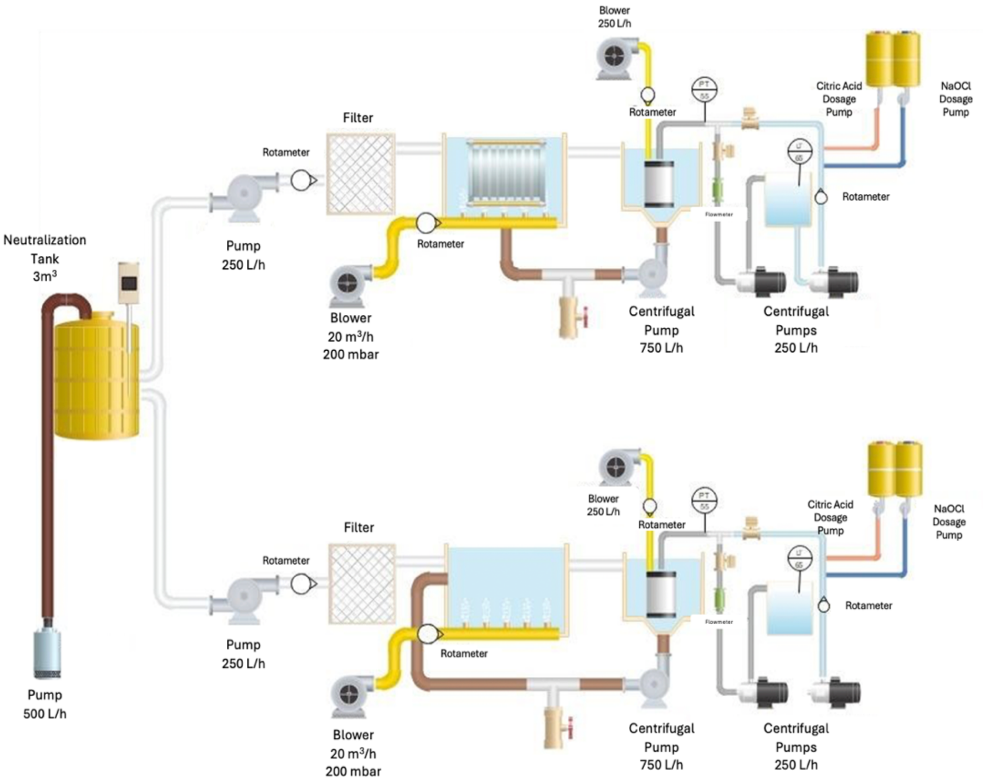


Figure 2.3 : The flow diagram and general views of the IFAS MBR system.

Figure 2.4 : The general overview of the pilot scale IFAS MBR systems.

After the system installation, the carrier material was placed into the aeration (Figure 2.4.) tank of system, followed by filling the tanks with seed sludge. Figure 2.5. shows the IFAS carrier media placed into the aeration tank. Figure 2.6 shows the general appeareance of the pilot system with activated sludge.

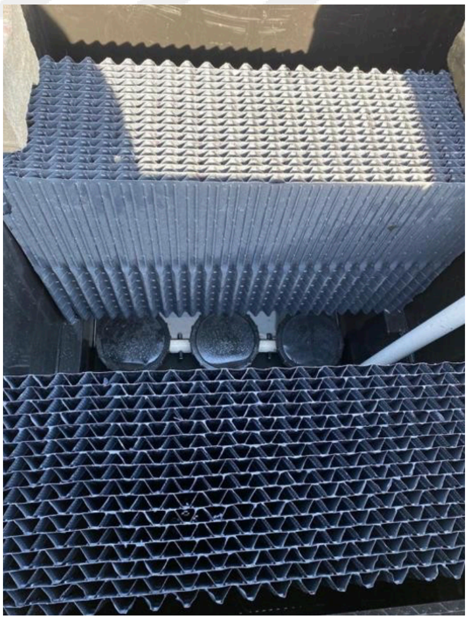


Figure 2.5 : IFAS carrier media located in aeration tank.

Figure 2.6 : The general appearance of the pilot scale IFAS MBR system after the seed sludge has been filled to the reactors.

The pilot scale IFAS MBR system used within the thesis are connected to the SCADA system, enabling all controls to be managed through this SCADA system. Within the MBR system, there are two distinct processes: filtration and backwashing. The entire system layout can be viewed on the SCADA screen, and operational parameters related to the units can be adjusted as needed from this interface. All operations, including backwashing, chemical dosing, valve opening/closing, and pressure adjustments, are carried out through the SCADA control system. The permeate flow rates and pressure values of the membranes in the reactors are continuously measured in real time. These values are displayed and recorded within the SCADA system. SCADA screen shots are provided in Figures 2.7 and 2.8.


Sistem 1 Durum: Mbr Ana Yıkama Yapıyor: 19
Sistem 2 Durum: Mbr Üretimde: 9
KAYIT ZAMANI: 5 Sn

Figure 2.7 : The main SCADA screen of the pilot scale IFAS MBR system.

Figure 2.8 : The SCADA screen of the pilot scale IFAS MBR.

In both the IFAS MBR system, there is one feed pump fort he system. This pump feed wastewater from 3m^3 equalization tank into the system. In the MBR system, the desired sludge level value can be input into the SCADA system for level control within the reactor. As permeate water is withdrawn from the reactor through the membranes, the level drops below the entered value, prompting the system to automatically activate the feed pump. The feed pump continue to operate until the level returns to the desired value, at which point they automatically stop. Figure 2.9. shows the feed pump and equalization tank.

Figure 2.9 : The feed pump of the pilot scale IFAS MBR system.

The air pressure provided to the disc diffusers located beneath the biological tank is adjusted by valves connected to the air line. The appearance of the aeration line with the blower is shown in Figure 2.10.

Figure 2.10 : The aeration line of the pilot scale IFAS MBR system.

In both system, active sludge recirculation from the membrane tank to the aeration tanks has been implemented. Excess sludge is discharged through a valve opened in the middle pipe of the recirculation line. Flowmeters are installed in the recirculation and feed lines, allowing for easy observation of both the feed and recirculation flow rates. The appearance of the flowmeter in the recirculation line is depicted in Figure 2.11.

Figure 2.11 : The recirculation line and flowmeters of the pilot scale IFAS MBR system.

In the MBR tank, pollutants on the membrane are removed by air scouring. Air scouring is conducted by applying aeration at four different points on the modules. The aeration zones of the GENMBR modules are illustrated in Figure 2.12.

Figure 2.12 : The membrane aeration of the pilot scale IFAS MBR system.

Figure 2.13 : The membrane blower and aeration valve of the pilot scale IFAS MBR system.

Measurement of the level in the system is ensured using level sensors. With the assistance of these sensors, the level in the reactor can be measured in real time within the SCADA system. When the level in the membrane tank falls below the required limit, the level sensor automatically detects this condition and activates the feeding signal to supply the system. The appearance of the level sensor is depicted in Figure 2.14.

Figure 2.14 : The level sensor of the pilot scale IFAS MBR system.

The permeate obtained from the IFAS MBR system is collected in the permeate tank. The amount of permeate drawn from the membrane can be adjusted by the capacities of the vacuum pumps. In this method, the SCADA system ensures that the vacuum pump operates at the desired capacity to adjust the flow rate. In the IFAS MBR system, there is one vacuum pump, for the system.

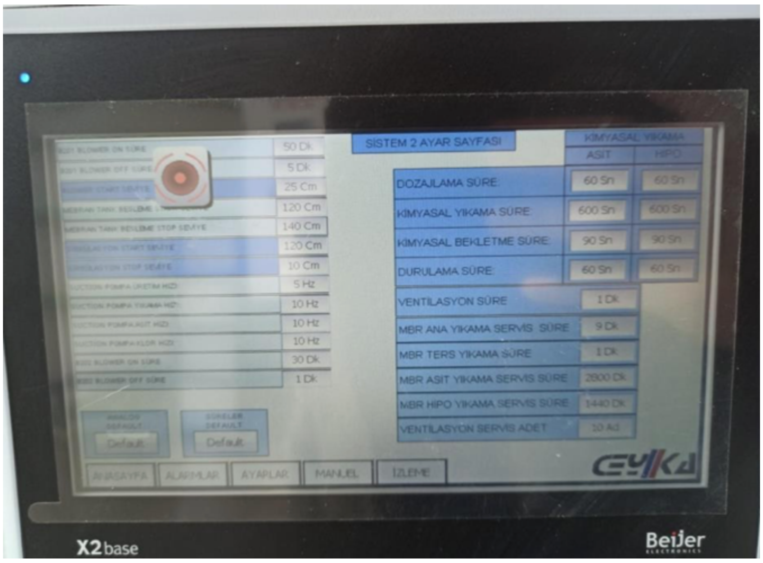
The vacuum pump is used not only to draw permeate from the membrane but also for periodic backwashing using the permeate water at specific intervals (1 time in 10 minutes: 9 minutes filtration, 1 minute backwashing). Within a specific time frame entered into the SCADA system, the vacuum pump operates in the opposite direction of normal operation to perform backwashing instead of vacuuming. This helps prevent clogging and maintains the membrane's filtration efficient at desired levels. The appearance of the vacuum pump is illustrated in Figure 2.15.

Figure 2.15 : The vacuum pump of the pilot scale IFAS MBR system

The flow measurement in the IFAS MBR system is automatically recorded in the SCADA system. These records are subsequently retrieved using a USB flash drive. Similarly, pressure data is also automatically recorded in the SCADA system. Both flow and pressure values can be monitored as separate graphs on the SCADA screen. Additionally, pressure data can be observed from the barometer located on the vacuum line. The flow pressure graphs and the appearance of the manometer are depicted in Figure 2.16.

Figure 2.16 : The SCADA flow-pressure graphs and manometer in the IFAS MBR system.

To control membrane fouling, chemical cleaning is performed at regular intervals. The main purpose of chemical cleaning is to restore the transmembrane pressure to its original state. Accordingly, system undergo cleaning with citric acid ($C_6H_8O_7$) and sodium hypochlorite (NaClO). Citric acid cleaning is conducted every two days (2800 minutes), while sodium hypochlorite cleaning is performed once a day (1440 minutes). The SCADA display of the chemical cleaning durations and the appearance of the chemical dosing pumps and chemical tanks are depicted in Figures 2.17 and 2.18., respectively.


SİSTEM 2 AYAR SAYFASI

	KİMYASAL YIKAMA	
	ASİT	HİPO
DOZAJLAMA SÜRE	60 Sn	60 Sn
KİMYASAL YIKAMA SÜRE	600 Sn	600 Sn
KİMYASAL BEKLETME SÜRE	90 Sn	90 Sn
DURULAMA SÜRE	60 Sn	60 Sn

VENTİLASYON SÜRE 1 Dk
MBR ANA YIKAMA SERVİS SÜRE 9 Dk
MBR TERS YIKAMA SÜRE 1 Dk
MBR ASİT YIKAMA SERVİS SÜRE 2800 Dk
MBR HİPO YIKAMA SERVİS SÜRE 1440 Dk
VENTİLASYON SERVİS ADET 10 Ad

Figure 2.17 : The SCADA screen of chemical cleaning for the pilot scale IFAS MBR system.

Figure 2.18 : The chemical tanks and chemical dosing pumps of the pilot scale IFAS MBR system.

2.2. Membrane Module and Carrier Media

The study utilized domestically produced commercial hollow fiber polyvinylidene fluoride (PVDF) membranes (GEN MBR) (with a pore size of 0.04 µm) in a pilot scale investigation. These GEN MBR modules used during the operation of the process were procured from MEMSIS Environmental Technologies R&D Ltd. Co. a company located in ITU Arı Technopolis. The appearance of the membrane modules in IFAS MBR system is depicted in Figure 2.19.

Figure 2.19 : The GEN MBR membranes used in pilot scale IFAS MBR system

In the system, PVC based sheets were used as the carriers (Figure 2.20.). These carrier materials used during the operation of the process were procured from CEYKA Chemical Industry and Foreign Trade Ltd. Co.

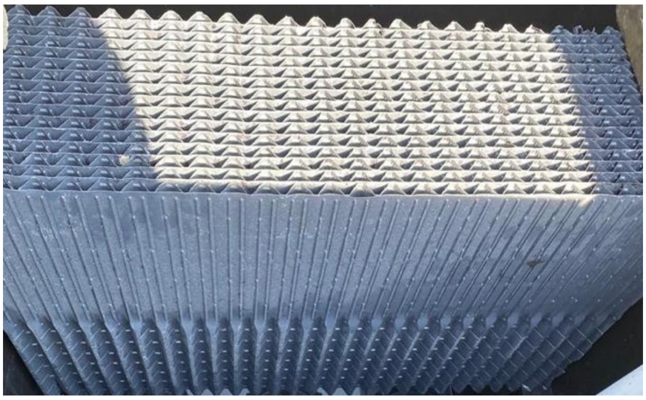


Figure 2.20 : The carrier material used in the pilot-scale IFAS MBR system.

2.3. Analysis Conducted During System Operation

Various analyses were conducted at specified intervals during the operation of the reactors, including in the influent wastewater, within the reactor, and in the effluent. These analyses include COD, Dissolved COD, TSS, VSS, SS, VSS, TN, NH4-N, TP, Particle Size Distribution, DO, pH, turbidity, temperature. The frequency and measurement methods of these analyses are listed in Table 2.2.

Table 2.2 : The parameters measured, measurement points, and measurement frequencies in the operation of the IFAS MBR system

Parameter	Method	Influent	Sludge	Effluent
TS	APHA,2017	-	1/week	-
TVSS	APHA,2017	-	1/week	-
TSS	APHA,2017	3/week	3/week	3/week
TVSS	APHA,2017	3/week	3/week	3/week
COD	APHA,2017	3/week	3/week	3/week

Table 2.2 continuous : The parameters measured, measurement points, and measurement frequencies in the operation of the IFAS MBR system.

Parameter	Method	Influent	Sludge	Effluent
sCOD	APHA,2017	3/week	3/week	3/week
pH	pH probe	3/week	3/week	3/week
Turbidity	Turbidity probe	3/week	-	3/week
Temperature	Temperature probe	3/week	3/week	3/week
DO	DO probe	3/week	3/week	3/week
TN	TOC-VCPN Device	1/week	-	1/week
NH4-N	IC	1/week	-	1/week
TP	Kit	1/week	-	1/week
Particule Size Distrubution	Mastersizer/Zetasizer	1/month	1/month	1/month

2.3.1. Chemical oxygen demand (COD)-dissolved chemical oxygen demand (sCOD)

COD measurements were periodically conducted in the influent wastewater, within the reactor, and in the effluent. The measurements were performed according to standard methods.

Chemicals used:

Standard potassium dichromate solution: 33.3 g of mercury sulfate ($HgSO4$) is dissolved in 500 ml of distilled water, to which 167 ml of concentrated sulfuric acid is added. After cooling, 4.903 g of potassium dichromate, previously dried at 103°C for 2 hours, is added to this solution, and the volume is adjusted to one liter with distilled water.

Silver sulfate sulfuric acid reagent: 5.5 grams of silver sulfate (Ag_2SO_4) is mixed with 1 kg of sulfuric acid, and the mixture is allowed to stand for 1-2 days until the silver sulfate completely dissolves in the acid.

Ferroin indicator solution: 0.695 grams of $FeSO_4.7H_2O$ is dissolved in water, then 1.485 grams of 1,10-phenanthroline monohydrate is added and mixed until dissolved. The volume is adjusted to 100 ml with distilled water.

Standard iron ammonium sulfate solution (0.025 N): 98 grams of $(NH_4)2Fe(SO_4)2{\cdot}6H_2O$ is dissolved in distilled water. Then, 20 ml of concentrated sulfuric acid is slowly added with agitation, the solution is cooled, and the volume is adjusted to 1000 ml with distilled water. This solution must be standardized against standard dichromate solution and its normality determined before each use. The standardization process is carried out as follows:

Standardization: 10 ml of standard $K_2Cr_2O_7$ solution is diluted to 100 ml with 4 mol/L sulfuric acid solution and titrated with DAS. The normality of the standard DAS is calculated using the following formula:

Standard DAS normality = (V1 * N1) / V2 = (10 * 0.24) / V2

Where:

V1 = Volume of dichromate used (ml)

V2 = Volume of DAS consumed (ml)

N1 = Normality of standard potassium dichromate solution (0.24 N)

Equipment Used:

- Glass COD tubes
- Caps for COD tubes
- Automatic pipette
- Thermoreactor

Experiment Procedure:

Samples for COD analysis were taken from inside the reactor, treated effluent, and feed solution. The collected samples were thoroughly mixed, and then 2.5 mL of each sample was transferred to a COD tube using a pipette. For each sample to be measured, at least two sets of sample groups (replicates) should be prepared under the same conditions, with distilled water used as a blank sample.

Next, 1.5 mL of standard dichromate solution and 3.5 mL of silver sulfate sulfuric acid reagent were added to the samples in the tubes, and the caps were closed tightly. The prepared tubes were placed on a table-top electric heater and boiled at 150°C for 120 minutes. After boiling, the tubes were allowed to cool to room temperature, transferred to Erlenmeyer flasks, and Ferroin indicator solution was added dropwise. Then, they were titrated with standard iron ammonium sulfate solution (DAS). By calculating the amount of DAS consumed in the titration, the COD value was determined.

For Dissolved COD measurement, the sample was filtered through a syringe filter with a pore size of 0.45 µm before performing the experiment steps.

Calculation:

$\mathrm{COD} = ((a - b) \times N \times 8 \times 1000) / V_{\mathrm{sample}}$

Where:

a: Volume of standard iron ammonium sulfate solution (DAS) used for the blank (ml)

b: Volume of standard iron ammonium sulfate solution (DAS) used for the sample (ml)

N: Normality of standard iron ammonium sulfate solution (DAS)

V_{sample}: Volume of sample used (ml)

2.3.2. Total suspended solids (TS) - total volatile suspended solids (TVS)

The TSS and TVSS values in the reactors were monitored at regular intervals using the gravimetric measurement method.

Reagents Used:

- Concentrated sulfuric acid
- Concentrated nitric acid
- Phenolphthalein indicator
- 1 N sodium hydroxide

Equipment Used:

- Drying oven

- Desiccator
- Muffle furnace
- Measuring cylinder
- Analytical balance (with a sensitivity of 0.1 mg)
- Crucible

Experiment Procedure:

The crucibles to be used in the experiment are washed thoroughly to remove any residues, dried in an oven at 103-105°C for one hour, and kept in a desiccator to prevent exposure to atmospheric moisture and ensure complete drying. The crucible, which has reached a constant weight, is carefully removed from the desiccator and weighed. A well mixed sample is taken from the estimated TKM value using a measuring cylinder, ensuring at least 50 ml or more of the sample is taken without subjecting it to filtration, and transferred to the crucible. Care is taken to ensure that no residue remains on the edges of the measuring cylinder. The crucibles containing the samples are dried in an oven at 103-105°C for at least 1 hour, then cooled in the desiccator and weighed. The crucible and its contents are then incinerated in a furnace at 500-550°C for 30 minutes, cooled in the desiccator, and weighed again.

Calculation:

TS (mg/L) = (A - B) × 1000 / (Sample volume (ml))

TVS (mg/L) = (A - C) × 1000 / (Sample volume (ml))

Where:

A = Weight of crucible + residue (mg)

B = Weight of crucible (mg)

C = Weight of crucible + weight of inorganic residue (mg)

2.3.3. Suspended solids - volatile suspended solids (TSS-TVSS)

The TSS and TVSS values in the reactors were monitored at regular intervals using the gravimetric measurement method.

Equipment Used:

- Drying oven

- Desiccator
- Ash oven
- Measuring cylinder
- Aluminum dish
- Pen
- Filtration set
- Analytical balance (with 0.1 mg sensitivity)
- Glass fiber filters

Experiment Procedure:

Set up the filtration apparatus. Place the filter paper (previously dried at 103-105°C for 1 hour in the drying oven and cooled in the desiccator, then weighed) into the filtration apparatus. Wet the filter paper with pure water and pass it through a vacuum, then filter the sample of a certain volume that has been well mixed. Ensure that there are no residues left on the edges of the measuring cylinder. After filtration, rinse the walls of the funnel thoroughly with pure water. Continue vacuuming for 1-2 minutes. Carefully transfer the filter paper onto an aluminum or stainless steel plate using tweezers and dry it in the drying oven at 103-105°C for 1 hour. Cool it in the desiccator and weigh it. Burn the filter and any residue in the ash oven at 500-550°C for 30 minutes. Cool it in the desiccator and weigh it.

Calculations:

TSS (mg/L) = (A - B) × 1000 / Sample volume (ml)

TVSS (mg/L) = (A - C) × 1000 / Sample volume (ml)

Where:

A = Weight of filter + residue (mg)

B = Weight of filter residue (mg)

C = Weight of filter residue + weight of inorganic residue (mg)

2.3.4. Total nitrogen (TN)

Total nitrogen analyses were conducted using a Shimadzu TOC-VCPN (Total Nitrogen-Total Organic Carbon Analyzer) instrument (Figure 2.21.).

Figure 2.21 : Shimadzu TOC-VCPN Total Nitrogen-Total Organic Carbon Analyzer

2.3.5. Ammonium nitrogen

Ammonia nitrogen analyses were performed using a Dionex ICS 300 ion chromatography (IC) instrument (Figure 2.22.).

Figure 2.22 : Dionex ICS 300 ion chromatography (IC).

2.3.6. Nitrate nitrogen

Nitrate nitrogen analyses were conducted using a Dionex ICS 300 ion chromatography (IC) instrument.

2.3.7. Total phosphorous (TP)

The TP (total phosphorus) values in the inflows and outflows were monitored at regular intervals. For this purpose, the organic phosphorus determination method was employed to convert organic phosphorus into orthophosphate for total phosphorus analysis.

Equipment Used:

- Heater
- Bunsen burner
- MicroKjeldahl flasks
- Spectrophotometer
- Cuvette

Experiment Procedure:

A sample containing phosphorus within the concentration range measurable by the methods associated with the utilized colorimetric method is measured and placed into a micro-Kjeldahl flask. Add 1 mL of concentrated sulfuric acid and 5 mL of concentrated nitric acid to the flask, and place it into a sample digestion device. Turn on the digestion fan. Continue the digestion process until the solution turns colorless by heating, adding nitric acid until it reaches 1 mL, and then removing the excess nitric acid. After cooling the solution, add 20 mL of distilled water and 0.05 mL (1 drop) of phenolphthalein indicator. Add 6 N sodium hydroxide until a faint pink color appears in the solution. Transfer the resulting solution to a volumetric flask or a flask, if necessary, after filtration to remove particulate matter and turbidity. The sample volume is adjusted to 100 mL using distilled water.

<u>Color Development:</u> 4.0 mL of reagent I from molybdate reagent no. I is added to the sample, thoroughly mixing in each drop. Then, 0.5 mL (10 drops) of stannous chloride reagent I is added. The rate of color development and the intensity of the resulting color depend on the final temperature of the solution, with a 1% increase in color

intensity for every 1°C increase in temperature. Therefore, samples, standards, and reagents should be maintained within 2°C of each other, ideally between 20 and 30°C.

Color Measurement: Approximately 10-12 minutes after the addition of the reagents, absorbance is measured at 690 nm wavelength with a spectrophotometer, accompanied by a blank measurement. The results are then compared with a previously obtained calibration curve. The measurable concentration ranges depending on the path length are approximately as follows: for a 0.5 cm path length, between 0.3 and 2 mg/L; for a 2 cm path length, between 0.1 and 1 mg/L; and for a 10 cm path length, between 0.007 and 0.2 mg/L.

2.3.8. Particle size distribution analysis

The particle size analyses (PSA) of reactor sludges were conducted using the Malvern Instruments Hydro 2000 MU Mastersizer 2000 (Figure 2.23.) instrument (measurement range: 0.6-6000 μm). The PSAs of influent domestic wastewater and effluent from the treatment system were performed using the Malvern Instruments Zetasizer Nano-S (Figure 2.24.) instrument (measurement range: 0.3 nm - 10 μm).

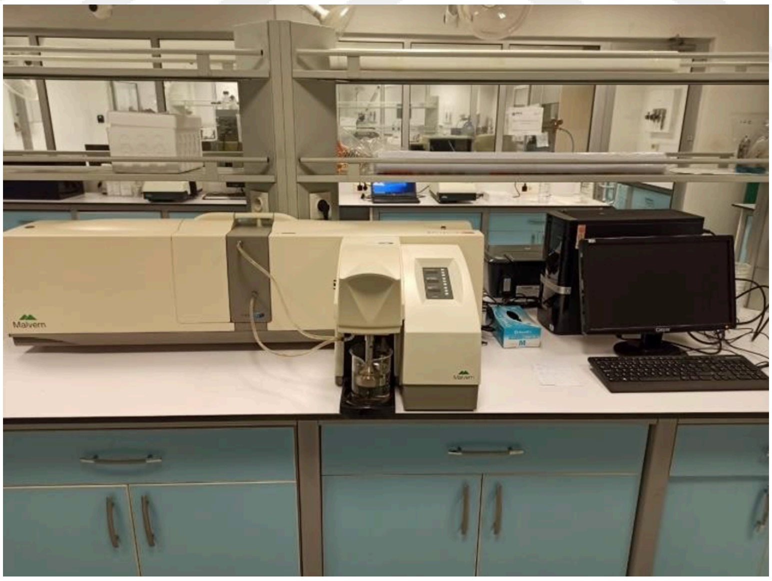


Figure 2.23 : Malvern Instruments Hydro 200 MU Mastersizer 2000 Device

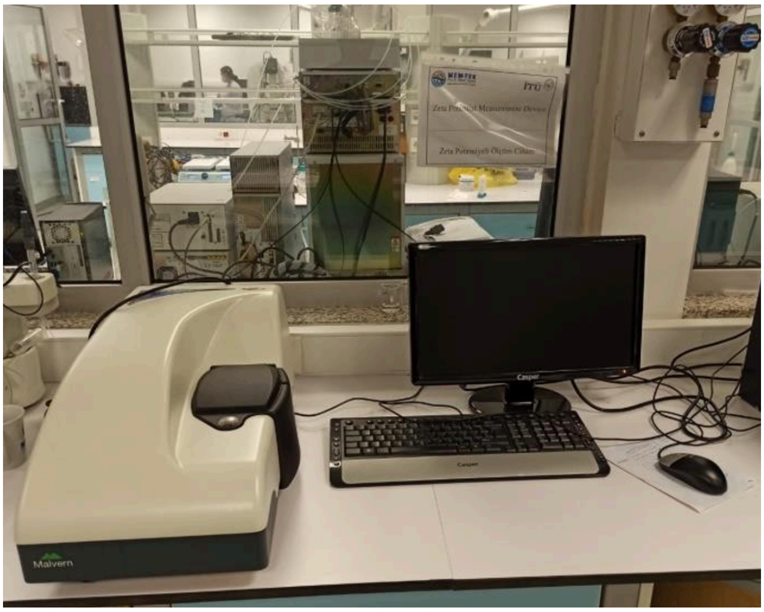


Figure 2.24 : Malvern Instruments Zetasizer Nano-S instrument

2.3.9. Dissolved oxygen probe

Dissolved oxygen measurement in the reactors was conducted using the Hach HQ40d probe (Figure 2.25.).

Figure 2.25 : The multi parameter measurement device and dissolved oxygen probe

2.3.10. pH probe

The pH analyses of the collected samples were measured using the Mettler Toledo SevenCompact pH meter S220 (Figure 2.26.) device.

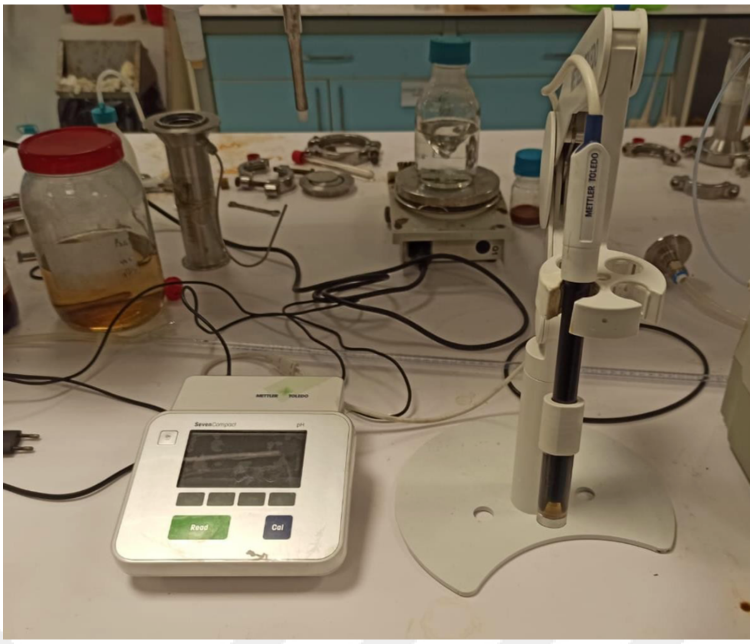


Figure 2.26 : pH Probe

2.3.11. Turbidity probe

The turbidity measurements were conducted using the Hach 2100 Q turbidity measurement (Figure 2.27.) device, with a measurement range of 0-1000 NTU.

Figure 2.27 : Turbidity Probe

2.3.12. Temperature

Temperature measurements were performed using the Hach HQ40d temperature probe.

2.4. Carrier Characterization

2.4.1.Analysis of biofilm thickness using confocal microscopy

Samples (approximately 1x1 cm) were prepared by cutting from the inner part of the carrier material using sterile scissors and directly stained. Staining was performed using the "Live/Dead™ BacLight™ Bacterial Viability Kit". Propidium Iodide provides a red color for dead cells, while Syto dyes provide a green color for live cells. These dyes are stored at -20°C. Immediately after staining, biofilms were analyzed using laser scanning confocal microscopy (CLSM). Images were selected from different locations of each sample. The height of the biofilm was determined by first focusing on the lower layer of the carrier media and marking this position as the origin. The image was then moved until the surface of a cell cluster was focused, and the position of the image was noted. The thickness was measured as the difference between the positions of the images. Samples taken from the carrier material were examined using a Nikon C2 laser scanning confocal (Figure 2.28) microscope (Mahendran et al., 2012).

Figure 2.28 : Nikon C2 laser scanning confocal microscope

2.4.2. The measurement of biomass density on the surface of the carrier media

The surface biomass density relies on the dry weight of the biomass and the surface area provided by the carrier material. Attached biomass growth involved collecting 5 pieces of carrier material from the aeration tank of the IFAS-MBR system, allowing them to drain for 15 to 20 minutes to remove the surface water. After the draining process, the carrier media pieces were dried overnight at 105°C in an oven. The weight of the dried carrier material and biomass was measured and recorded (W1). The dried biomass on the media was then thoroughly cleaned using a brush and tap water until no visible biomass residue remained. The cleaned carrier media was dried again at 105°C for 5 to 6 hours, and its weight was measured (W2). The attached dry solids were calculated as W1-W2 (Kim et al., 2010).

3. RESULTS AND DISCUSSION

3.1. Operational Conditions

The results obtained from the operation of the Hybrid IFAS MBR system within the scope of the thesis are presented in this section. In order to better understand and interpret the gains provided by the IFAS-MBR system, the treatment efficiencies of a system consisting of aeration tank without IFAS carrier media and MBR tank with the same characteristics operated during the operation of the IFAS-MBR system are compared. These two systems were operated for the same duration and under the same operational conditions; the IFAS media-free system is given as the system where the control of the IFAS MBR system is ensured.

The Hybrid IFAS MBR and conventional MBR systems were monitored under different operating conditions for 167 days. Acclimation to different operational conditions, namely medium loading (16 LMH) and high loading (28 LMH), was conducted for sludge ages of 5 days and 20 days. During this period, the wastewater used as feed solution in the systems was sourced from the sewage system within the Istanbul Technical University. Operational conditions of IFAS MBR is given in Table 3.1.

Table 3.1 : Operational Conditions in IFAS MBR System.

Phase	Cycle	Operational Conditions		
		Duration [d]	SRT [d]	HRT [d]
I	1	1-28	∞	7
	2	29-56	∞	4
II	3	57-84	20	7
	4	85-112	20	4
III	5	113-140	5	7
	6	141-167	5	4

The raw wastewater characteristics used in the IFAS MBR system are provided in Table 3.2. It is given that each phases characteristics.

Table 3.2 : Influent Characteristics of IFAS MBR System.

		Phase I	Phase II	Phase III
Parameter	Units		Value	
COD	mg L^{-1}	230,42 ± 68,35	290,1±46,78	259±19,86
SCOD	mg L^{-1}	95±37,70	111,8±28,80	102±10,89
Total Suspended Solids	mg L^{-1}	79,71±31,25	140,29±35,06	190,42±30,20
Total Nitrogen (TN)	mg L^{-1}	39,55± 4,57	37,62± 2,00	35,87± 3,02
Total Phosphorous (TP)	mg L^{-1}	6,005± 0,83	5,7± 0,77	4,89± 1,06
Ammonium Nitrogen (NH_4-N)	mg L^{-1}	19,99±4,02	20,03±3,47	18,22±1,48
Turbidity	NTU	188,50±25,86	182,29±24,32	200,71±19,75

3.1.1. Temperature

Elevated temperatures enhance the removal of organic matter and nutrients by promoting microbial activity and metabolic rates. The temperature significantly influences the biological reactions occurring during wastewater treatment, particularly affecting processes such as nitrification and denitrification. Nitrification, in particular, thrives at higher temperatures. Moreover, temperature plays a crucial role in the adhesion and growth of biomasses on the carrier media within the Integrated Fixed Film Activated Sludge (IFAS) system. Variations in temperature can impact the resilience and stability of microorganisms within IFAS. Sudden temperature fluctuations, such as those experienced during seasonal changes, can disrupt the microbial community and reduce system stability. That is why temperature control in IFAS MBR system is highly important. Figure 3.1 shows temperature changes of the pilot system's IFAS and MBR tank.

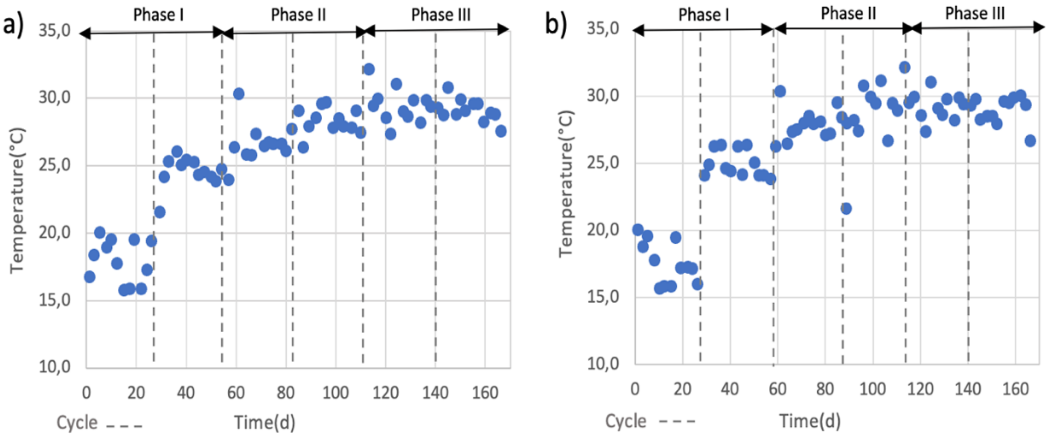


Figure 3.1 : IFAS (a) and MBR (b) tank's temperature values during IFAS MBR operational term

As given in the Figure 3.1. temperature values range are between 15-35°C. The low temperature values in Cycle I is due to winter conditions. Beginning of the operational term it was snowy and temperatures were nearly 5°C. The range of temperatures isn't that low that's why system didin't effect winter conditions that much.

3.1.2. Dissolved oxygen

The activity of aerobic microorganisms responsible for processes like nitrification and organic matter oxidation relies on the availability of oxygen. These microorganisms require dissolved oxygen to sustain their metabolic functions. Adequate oxygen levels are crucial for the efficient oxidation of organic pollutants and the conversion of ammonia to nitrate during nitrification. Nitrifying bacteria require sufficient dissolved oxygen to thrive and perform their functions effectively. Low levels of dissolved oxygen can hinder nitrification, leading to reduced ammonia removal and potential ammonia toxicity. Additionally, the growth of biofilms on carrier media is influenced by dissolved oxygen levels. Higher concentrations of dissolved oxygen promote the formation of thicker and more active biofilms. Robust biofilms enhance treatment efficiency by providing microorganisms with ample surface area for attachment and facilitating pollutant decomposition. Have a good degree of nitrification; dissolved oxygen in biological reactor has great importance. Figure 3.2. shows the dissolved oxygen concentration of IFAS and MBR tank.

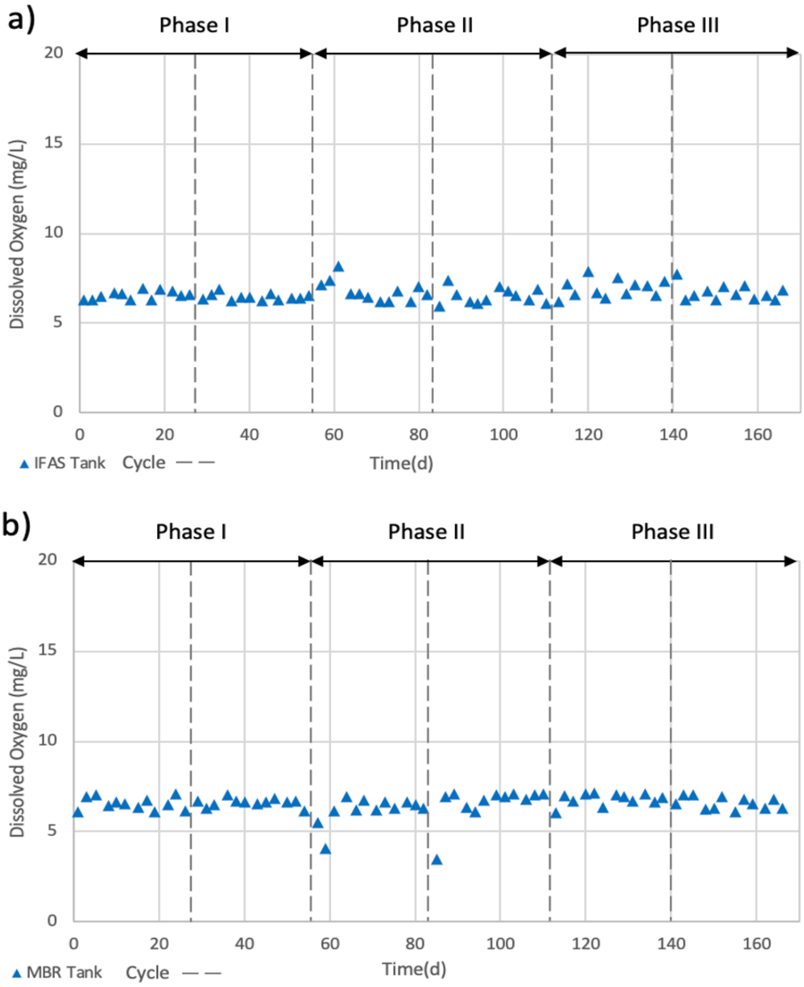


Figure 3.2 : IFAS (a) and MBR (b) tank's dissolved oxygen values during IFAS MBR operational term.

3.1.3. pH values

Trend profile of IFAS (a) and MBR (b) tank pH vaues are given in Figure 3.3.

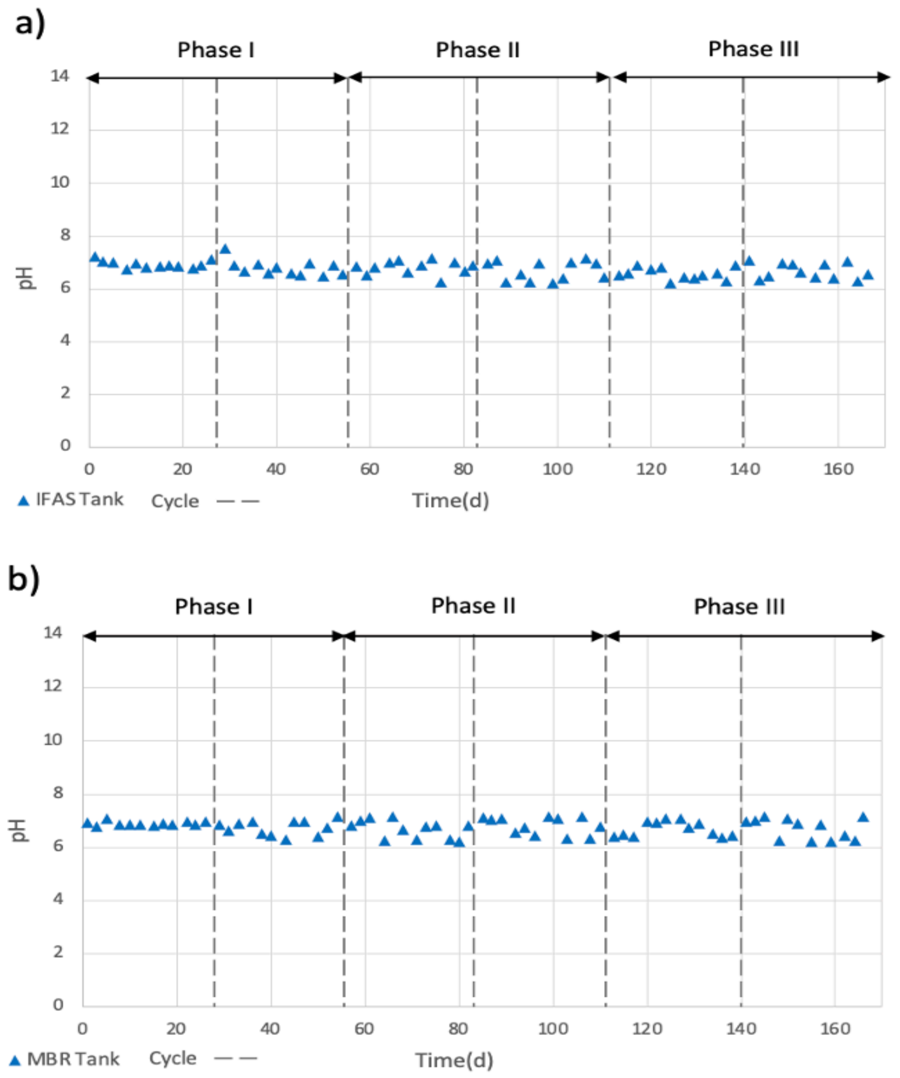


Figure 3.3 : IFAS (a) and MBR (b) tank's pH values during IFAS MBR operational term.

3.2. The Pilot Plant Removal Efficiencies

Table 3.3. shows the average value and standart deviasion of influent and effluent wastewater characteristics.

3.2.1. COD removal

Figure 3.4. shows the patterns of the influent COD (COD_{IN}), soluable COD ($SCOD_{IN}$) concentrations and SCOD/COD values.

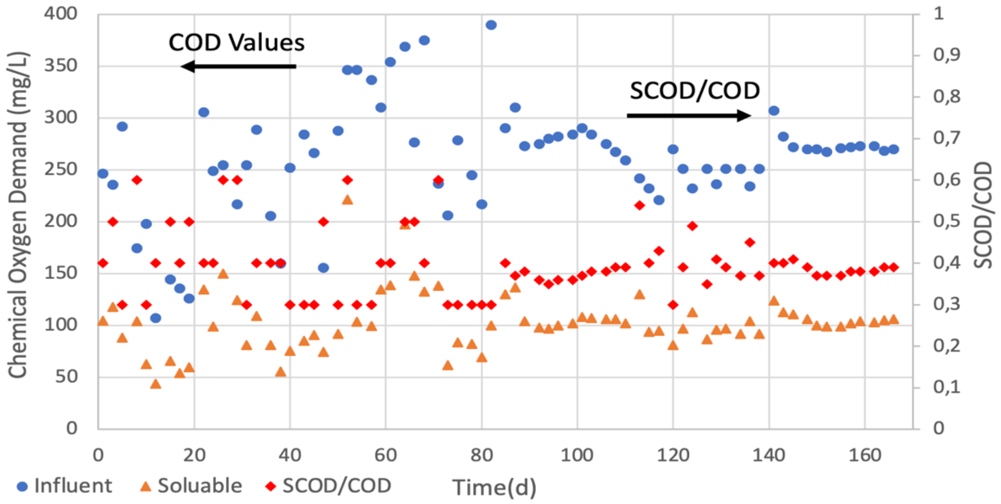


Figure 3.4 : The influent COD (CODIN), soluable COD (SCODIN) concentrations and SCOD/COD values.

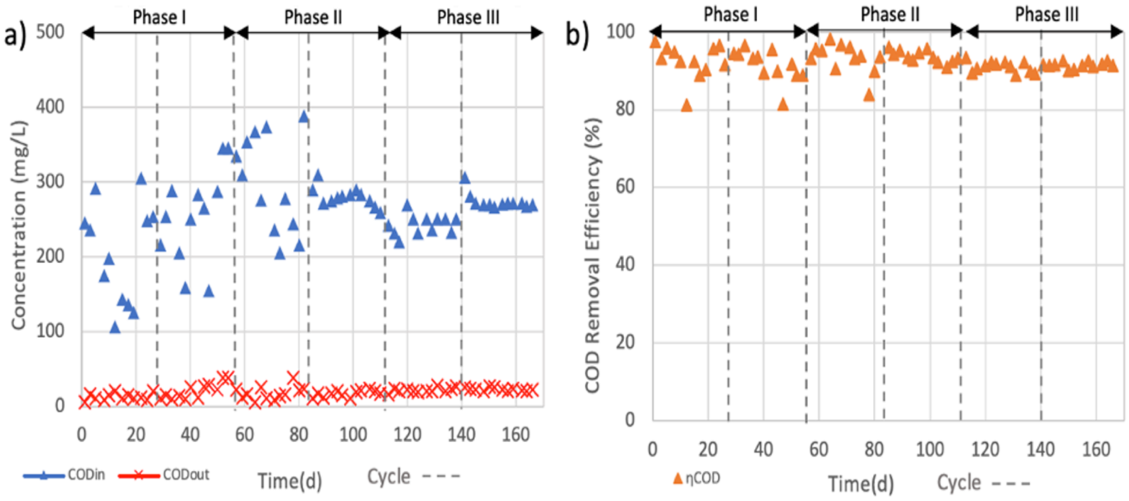


Figure 3.5 : Trend profile of influent, effluent COD (a); pattern of COD removal efficiencies expressed as total COD (ηCOD) removal (b).

Table 3.3 : Average and standart deviasion values of influent and effluent wastewater of IFAS MBR system

		Phase I				Phase II				Phase III			
		Cycle I		Cycle II		Cycle I		Cycle II		Cycle I		Cycle II	
	Unit	Average	SD	Average	SD	Average	SD	Average	SD	Average	SD	Average	SD
COD_{IN}	mg L^{-1}	205,65	67,45	255,19	62,28	299,34	65,01	280,90	12,83	243,48	13,23	274,63	10,96
COD_{OUT}	mg L^{-1}	13,14	4,57	21,32	10,59	18,54	9,11	17,69	4,06	21,92	3,42	23,17	2,41
NH4-N_{IN}	mg L^{-1}	19,37	3,19	20,62	5,16	18,97	1,14	21,06	4,86	17,21	1,20	19,23	0,97
NH4-N_{OUT}	mg L^{-1}	0,58	0,16	0,71	0,26	0,71	0,17	0,79	0,08	2,56	0,64	3,80	0,70
NO3-N_{OUT}	mg L^{-1}	15,11	2,68	16,01	4,21	14,67	0,99	16,30	3,92	11,78	0,46	12,41	0,90
PO4-P_{IN}	mg L^{-1}	6,34	0,77	5,67	0,84	5,33	0,43	6,07	0,91	4,36	1,35	5,43	0,14
PO4-P_{OUT}	mg L^{-1}	2,40	0,40	1,47	0,36	1,84	0,02	2,63	0,20	1,53	0,47	1,53	0,47

Throughout the experiments, high total COD removal efficiency was obtained despite fluctuations in the influent COD concentration. This fluctuations in inlet COD concentration is mainly caused by the term that pilot plant operating. Between Cycle 1-3; campus was generally empty because of the online education that was implemented due to earthquake happened in Turkey. This issue also led to a decrease in the COD concentration in the influent wastewater. The results are given in Figure 3.5. (Phase I (Cyle 1-2): 92%; Phase II (Cycle 3-4): 94%; Phase III (Cycle 5-6): 91%) (Figure 3.5(b)).

3.2.2. Total nitrogen removal

In terms of nitrogen removal, Figure 3.6. shows the pattern of influent and effluent ammonia, effluent nitrate (Figure 3.6.(a)) and the achieved performance for nitrification (η_{nit}), and total nitrogen removal (ηN_{total}). It is worth nothing that the HRT did not significantly influence the nitrification performance of the system. Conversely, SRT change slightly effect the nitrification performance. The ammonium removal was excellent in Phase I (Cycle 1-2) and Phase II (Cycle 3-4) with efficiencies close to 97% for most of the experiments. On the other hand in Phase III (Cycle 5-6), ammonium removal efficiency slightly decreased. Still even in Phase III ammonium removal efficiencies average is 80%. Figure 3.6. (a) shows the influent and effluent ammonium and effluent nitrate values. It can be seen that with the floculations in influent wastewater characteristic; also the effluent and it’s character has changed. Also effluent nitrate values are pretty low (Phase I and Phase II), but still in Phase III the effluent nitrate rate higher than the other two phases. During the experiments, the biofilm growth in the aerobic compartment allowed to maintain a very high nitrification level due to a decrease in SRT.

In contrast with nitrification efficiencies; in the TN removal efficiences were similar between three phases; the average values for Phases I, II, and III were 57, 51, and 52.5%, respectively.

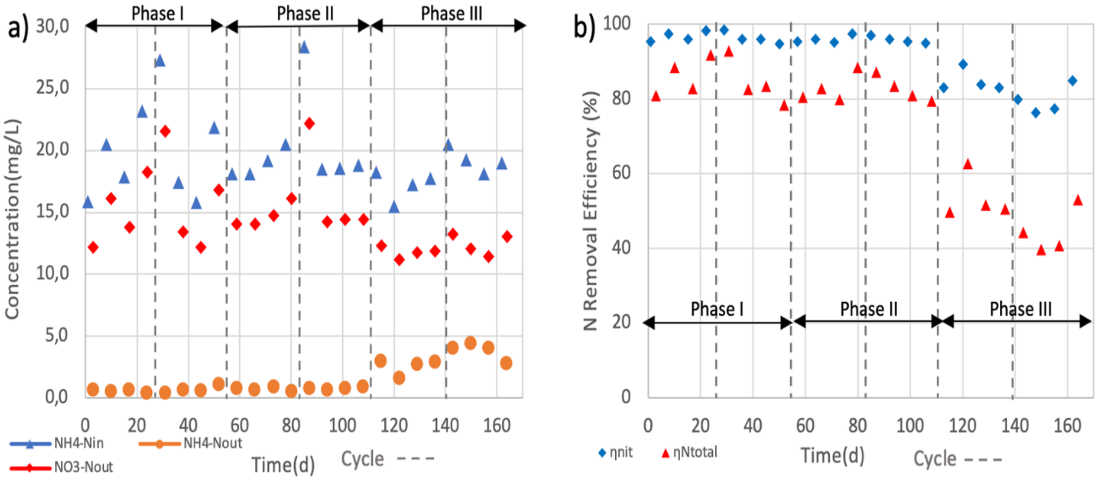


Figure 3.6 : Profile of NH4-NIN, NH4-NOUT and NO3-NOUT (a); performance of nitrification (ηnit) and total nitrogen removal (ηNtotal) (b) during experiments.

3.2.3. Total phosphorous removal

Regarding the removal of phosphorus, Figure 3.7.(a) presents the PO_4-P concentration pattern for influent and effluent, while Figure 3.7.(b) illustrates the PO_4-P removal. Throughout the experiments, there was a small rise in biological P removal and a decrease in SRT. Phase III produced the highest average PO_4-P removal efficiency of 71.1%. This finding appears to support earlier research showing that PAO activity can be hampered by competition for available carbon at high SRTs. In fact, during Phases I and II, the average values for PO_4-P removal efficiencies were 68 and 61%, respectively. Bio P elimination was encouraged by the increased Q_{WAS} in Phases II and III (Mannina et al., 2019).

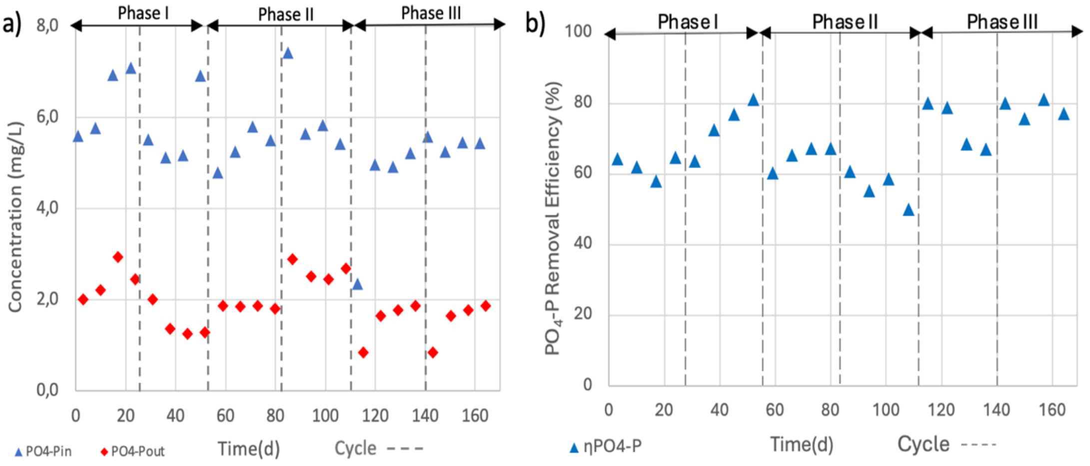


Figure 3.7 : Profile of the influent and effluent PO4-P concentration (a); PO4-P removal (b); inside the aerobic tank.

3.2.4. Total suspended sludge removal

Figure 3.8.(a) shows the total suspended sludge values of influent and effluent wastewater. Figure 3.8.(b) shows the total suspended sludge removal efficiencies.

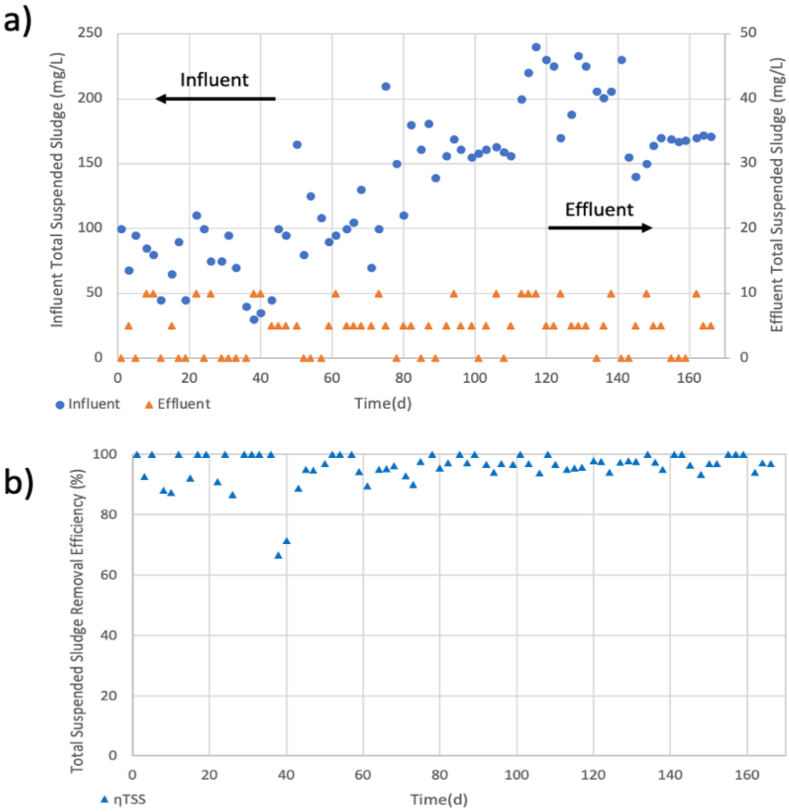


Figure 3.8 : Profile of the influent and effluent TSS concentration (a); TSS removal (b).

3.2.5. Turbidity removal

Figure 3.9.(a) shows the turbidity values of influent and effluent wastewater. It can be understand that beacuse of the biological treatment and membrane filtration; turbidity removal rates nearly % 99 in each Phase (Figure 3.9.(b)).

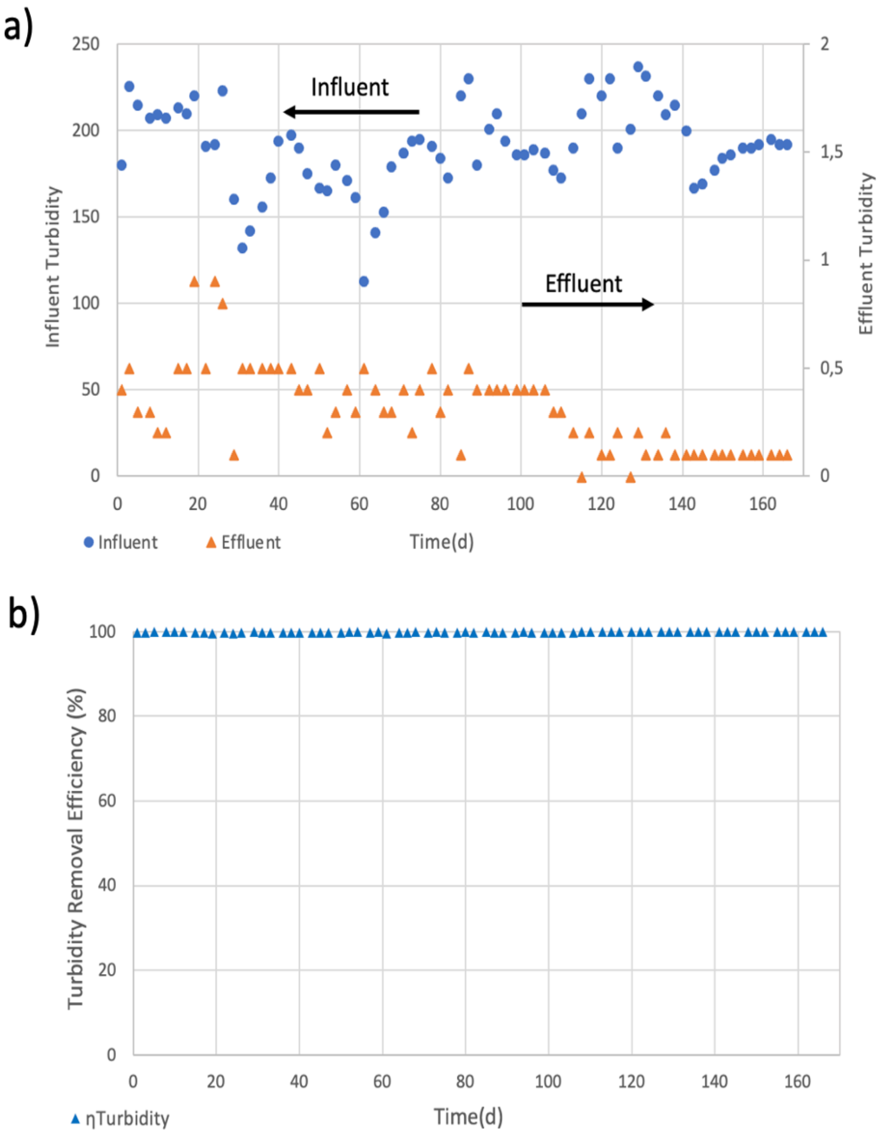


Figure 3.9 : Trend profile of influent, effluent turbidity (a); pattern of turbidity removal efficiencies expressed as total (ηTurbidity) removal (b).

3.3. Biomass Growth and Sludge Properties

3.3.1. Development of suspended biomass and growth of biofilm

The weighted average suspended (g TSSmixed liquor L^{-1}) and volatile biomass concentration profiles inside the IFAS (Figure 3.11.(a)) and MBR tank (Figure 3.11.(b)) (g TSSmixed liquor L^{-1}) during the duration of the studies are shown in Figure 3.11. The volume and concentration within each compartment were taken into account when calculating the weighted average suspended concentration (for both VSS and TSS). Phase I observed a general decrease in the pilot plant's weighted average biomass concentration (Figure 3.11.). The solids' adhesion to the IFAS carrier medium was the reason for the decrease. The withdrawal of sludge to set up SRT causes the suspended biomass in Phase II to continue to decline following continual desludging from the aerobic reactor. In Phase III, there was a notable drop in the MLSS concentrations as a result of the increased sludge withdrawals. By adjusting a pump to ensure its flow rate was daily adjusted according to the rate of biomass growth, the sludge was lost from the aerobic compartment.

The fixed type of IFAS carrier media was the reason for the expected high attached biomass throughout the entire research. Furthermore, slightly higher concentrations of biofilm were seen in the aeration compartments in Phases II and III. This could be a sign of more favorable conditions for biofilm because of the simultaneous decreases in suspended biomass and SRT (resulting from increased sludge withdrawals), which lessen competition for the available substrates. Table 3.4. shows the attached biomass concentrations of media. At the end of the each phase in order to understand attached growth mechanism, carrier samples were took off and calculated the attached biomass concentrations (Figure 3.10.).

Table 3.4 : Attached Biomass Concentrations of Phases

Parameter	Unit	Value
Acclimation Phase	mg L^{-1}	7425
SRT = 20d	mg L^{-1}	11520
SRT = 5d	mg L^{-1}	14850

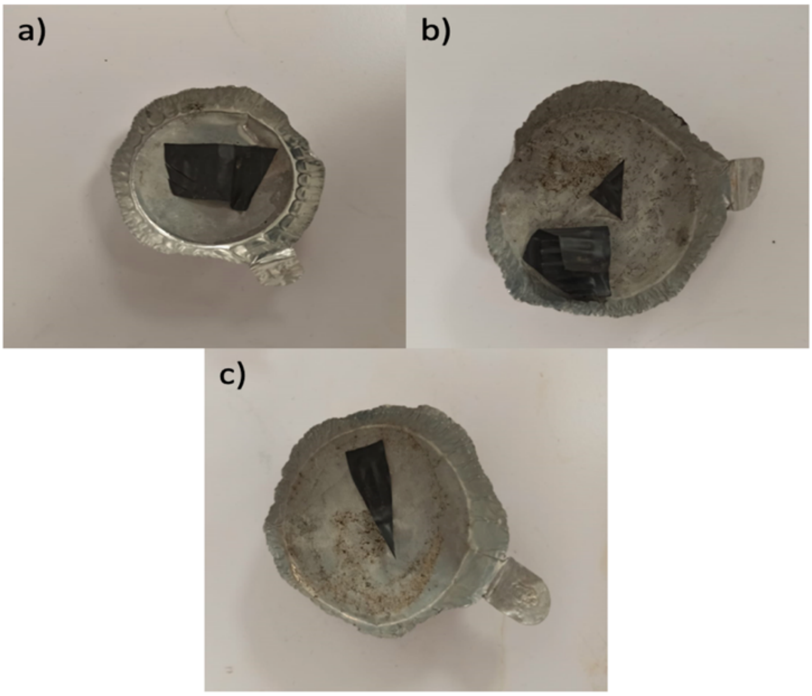


Figure 3.10 : Experimental samples in order to understand attached biomass in each phases; acclimation phase (a); SRT=20d (b); SRT = 5d (c).

3.3.2. Morphology of biofilm

Biofilm growth was shown to be preferential on protected internal surfaces, with some small colonization also happening on external surfaces, according to an analysis of media samples from the samples that are collected from aeration tank. Since external surfaces are exposed to intense liquid and oxygen shear due to aeration; the dispersion of biofilm is expected.

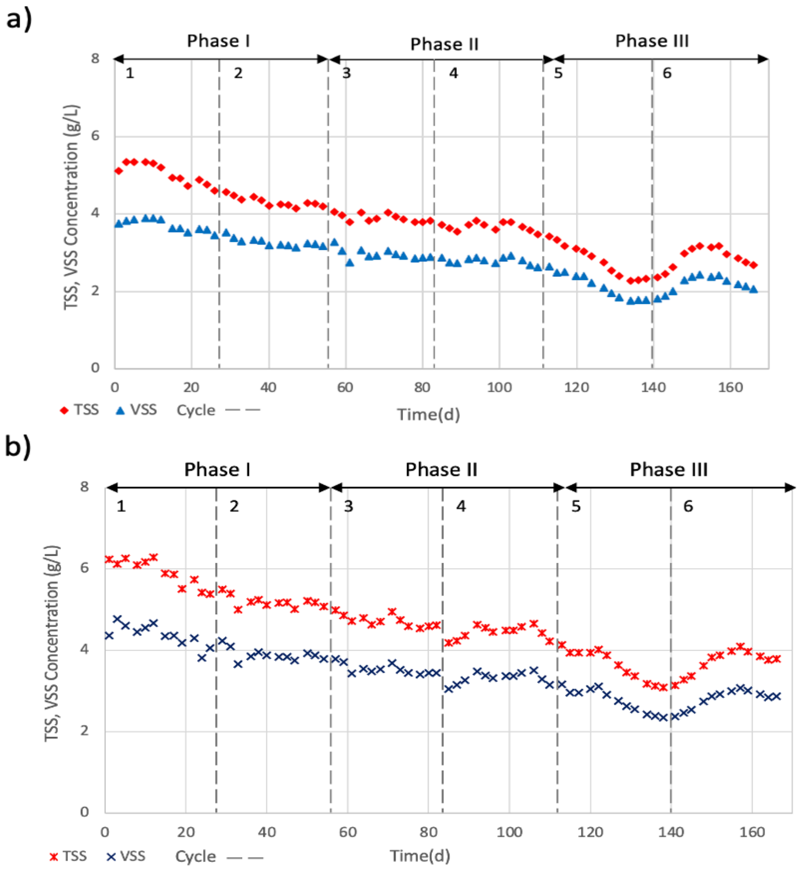


Figure 3.11 : Trend profile of TSS and VSS concentrations of IFAS (a); MBR Tank (b).

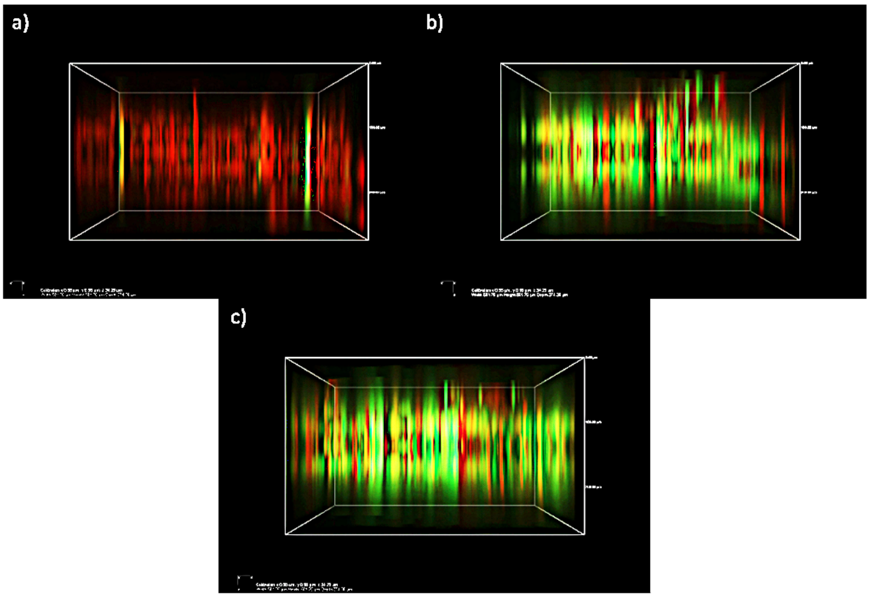


Figure 3.12 : Confocal images in order to understand attached biomass in each phases; acclimation phase (a); SRT=20d (b); SRT = 5d (c).

Confocal images shows that the most of the biomass occured when SRT values decrease. Figure 3.12.(a) shows the Phase I. During Phase I; there is no sludge withdraw SRT value is equal to indefinite. That causes the suspended biomass blocked attached biomass to grow on IFAS carrier media. In Phase II, SRT value equals to 20d and in order to arrange SRT value there is withdraw from the aeration tank and that helped attached biomass grow on the media (Figure 3.12.(b). During Phase III the withdrawed sludge amount is higher than the Phase II. That even helped better to attached biomass to attached and grow on the carrier media (Figure 3.12.(c)).

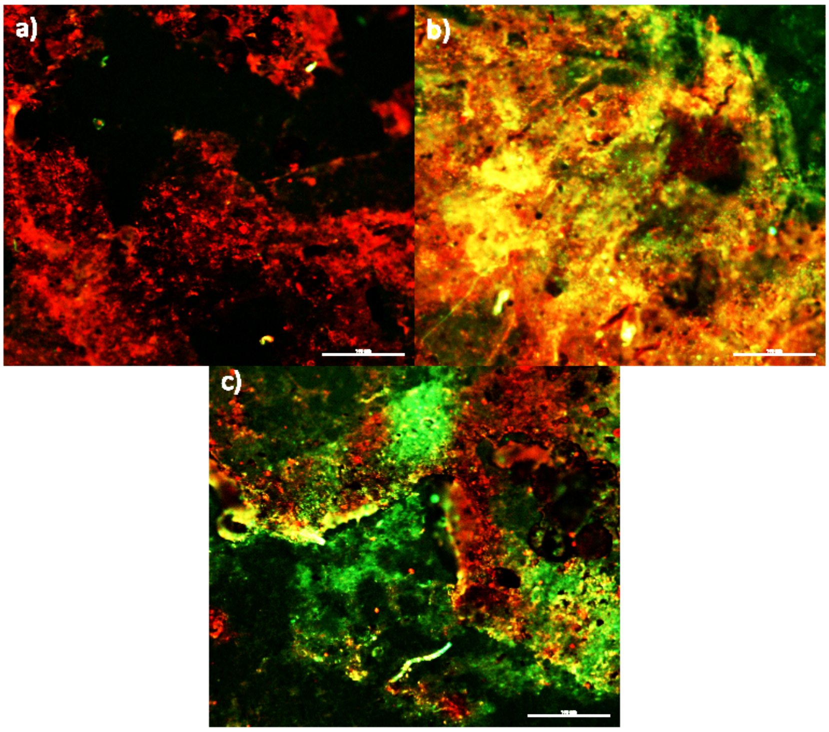


Figure 3.13 : Confocal in order to understand attached biomass in each phases; acclimation phase (a); SRT=20d (b); SRT = 5d (c).

In Figure 3.13., there are confocal images of IFAS MBR plant. Figure 3.13.(a) show the Phase I; (b) Phase II; (c) Phase III.

3.4. Membrane Filtration Properties

Figure 3.14. (a) shows the IFAS-MBR TMP values over time. To compare the membrane fouling properties of IFAS MBR system, results gained from the SCADA system compared with the paralel operated aeration tank followed by mbr tank system

(Figure 3.14.(b)). The paralel system has the same qualification with IFAS MBR except IFAS carrier media placed in the aeration tank.

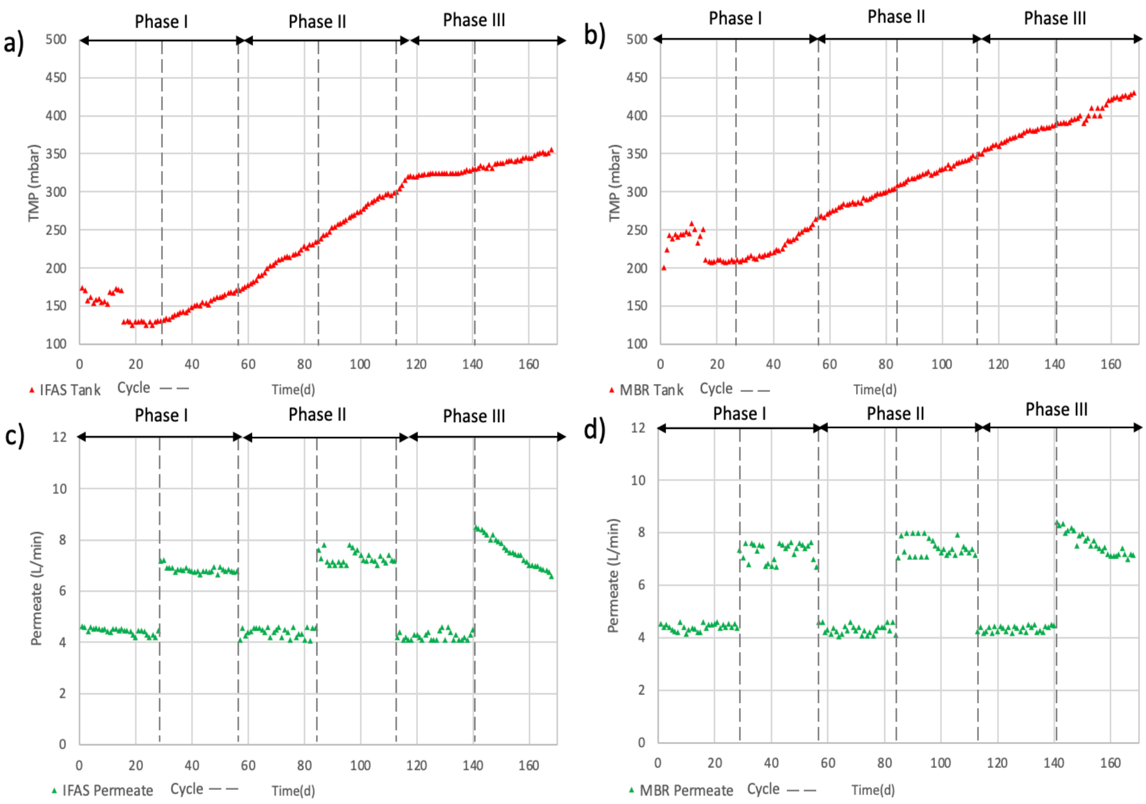


Figure 3.14 : Trend profile of TMP of IFAS MBR (a); TMP of MBR (b); effluent flowrate of IFAS MBR (c); effluent flowrate of MBR (d) systems.

In IFAS systems, biofilm form on the carriers, providing additional surfaces for microbial growth. This reduces the amount of free-floating biomass in the mixed liquor, leading to lower concentrations of suspended solids. Lower suspended solids can decrease membrane fouling and, consequently, reduce TMP. Also presence of biofilms in IFAS systems often leads to better sludge characteristics, such as increased floc size and improved settling properties. Larger flocs are less likely to penetrate the membrane pores, reducing fouling and maintaining lower TMP values.

The fixed-film carriers in IFAS systems can help in redistributing the microbial activity, leading to a more stable and lower fouling rate on the membrane surface. This helps maintain lower TMP over time. IFAS systems typically have better mixing and oxygen transfer characteristics due to the presence of the media. This can enhance the overall efficiency of the biological processes, reducing the load on the membrane and helping to maintain lower TMP values. This qualification can also led higher operating costs due to high amount of oxygen requirement.

IFAS systems can enhance the degradation of organic matter due to the synergy between suspended and attached biomass. This results in lower concentrations of soluble microbial products (SMPs) and extracellular polymeric substances (EPS), which are major contributors to membrane fouling in conventional MBR systems. As can be seen in Figure 3.14 (a) and (b), IFAS MBR system has %40 lower TMP values during operational term. Which this condution leaded to membrane have a longer operational time.

4. CONCLUSION

The IFAS-MBR system demonstrated significant potential and operational flexibility for the biological removal of nutrients when operated at varying mixed liquor SRT levels (undefined, 20, and 5 days). Achieving high removal efficiencies, particularly at low SRTs, underscored its effectiveness.

Throughout the experiments, notably high total COD removal efficiencies (>91%) were consistently observed. Despite the decrease in SRT, a high average nitrification performance (approximately 91%) was maintained, likely attributable to the biofilm's contribution.

At an SRT of 5 days, the system achieved its maximum P removal efficiency (79%). Moreover, as SRT decreased, the average P removal efficiency showed an increasing trend. However, lowering the SRT from indefinite to 5 days generally resulted in deteriorating membrane filtration characteristics, primarily due to membrane fouling.

Future research efforts could focus on the development of novel high-performance carrier media. Additionally, exploring the performance of different types of carrier media under various SRTs and HRTs (especially low SRT values and high C/N loading rates) would be beneficial. The presence of biofilm enabled the system to operate at lower MLSS concentrations, thereby enhancing its ability to mitigate fouling and reduce energy consumption.

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