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PERSPECTIVE

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A mobile-organic biofilm process for wastewater treatment

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Abstract

The mobile-organic biofilm (MOB) process includes mobile biofilms and their retention screens with a bioreactor and liquid and solid separation. The MOB process is inexpensive and easy to integrate with wastewater treatment (WWT) processes, and it provides for high-rate WWT in biofilm or hybrid bioreactors. This paper describes three modes of MOB process operation. The first mode of operation, Mode I, has a mobile-biofilm reactor and a mobile-biofilm retention screen that is downstream of and external to a bioreactor and upstream of liquid and solid separation. Modes II and III have a hybrid (i.e., mobile biofilms and accumulated suspended biomass) bioreactor and liquid and solid separation. Mode II includes a mobile-biofilm retention screen that is downstream of and external to a hybrid bioreactor and upstream of liquid and solid separation. Mode III includes mobile-biofilm retention screening that is external to a hybrid bioreactor and liquid and solid separation, receives waste solids, and relies on environmental conditions and wastewater characteristics that are favorable for aerobic-granular sludge formation. This paper presents a mechanistic approach to design and evaluate MOB processes and describes MOB process: (1) modes of operation, (2) design and analysis methodology, (3) process and mechanical design criteria, (4) mathematical modeling, (5) design equations, and (6) mobile-biofilm settling characteristics and return. A mathematical model was applied to describe a fixed bioreactor volume and secondary-clarifier area with Modes I, II, and III. The mathematical modeling identified key differences between MOB process modes of operation, which are described in this paper.

Practitioner Points

- MOB is a municipal and industrial wastewater treatment (WWT) process that reduces bioreactor and liquid and solids separation process volumes. It may operate with a mobile-biofilm reactor or a hybrid (mobile biofilms and suspended biomass) bioreactor.
- This paper provides a mechanistic basis for the selection and design of a MOB process mode of operation, and it describes MOB process modes of

operation, design criteria, design equations, mathematical modeling, and mobile-biofilm settling characteristics.

- MOB integrated WWT plants exist at full scale and reliably meet their treatment objectives. The MOB process is an emerging environmental biotechnology for cost-effective WWT.

KEYWORDS

hybrid bioreactor, intensification, mobile biofilm, model, wastewater treatment

INTRODUCTION

The mobile-organic biofilm (MOB) process (Nuvoda, USA) for municipal and industrial wastewater treatment (WWT) includes a bioreactor with mobile-biofilm carriers, mobile-biofilm retention screens, and a liquid and solid separation process. It can be operated with a mobile-biofilm reactor or a hybrid bioreactor (i.e., mobile biofilms and accumulated suspended biomass). The MOB process is well suited for continuously flowing WWT and offers an alternative to the plastic-biofilm carriers that are usually associated with integrated fixed film activated sludge (IFAS) and moving bed biofilm reactors (MBBRs) and to aerobic-granular sludge (AGS) that is applied to continuously flowing WWT processes. The MOB process is compatible with a variety of operating schemes and process configurations, it minimizes new infrastructure, and does not require the plastic-biofilm carriers or stainless-steel air diffusers that are associated with IFAS and MBBRs. Mobile biofilms are taken as the biofilm and mobile-biofilm carrier. They can have settling velocities that are comparable with AGS if favorable environmental conditions exist.

Mobile-biofilm retention screens exist external to the bioreactor and liquid and solid separation process and are easy to incorporate into an existing wastewater treatment plant (WWTP). The mobile-biofilm carriers described in this paper are kenaf, a lignocellulosic material, but they can be comprised of different materials (Boltz et al., 2018). Mobile biofilms move freely throughout a well-mixed bioreactor. Screened mobile biofilms can be reintroduced to a WWT process in different locations to promote or avoid the accumulations of specific bacteria and to achieve a variety of other process goals.

The volumetric fill of kenaf in a bioreactor usually does not exceed 8% of the bioreactor volume to avoid clarifier mechanism disruption and air diffusers, pumps, and orifices clogging, unless structures and equipment exist that can accommodate a more substantial mobile-biofilm quantity. Typically, screen(s) with 500-μm orifices retain mobile biofilms, but other screen opening sizes can be applied. Mobile biofilms that are retained by a rotary-drum screen, for example, are pictured in Figure 1. A two-dimensional screen (i.e., circular orifices) is recommended. Commonly, a screen that retains mobile

FIGURE 1 (Left) Mobile-biofilm carriers (i.e., kenaf) are compressed and packed in sacks and are easily integrated with an existing WWT process. (Right) Mobile-biofilm carriers are retained by screens, discharged into a sump, and flow with screen wash water into a location selected for their reintroduction to a WWT process.

biofilms has a hydraulic-loading rate (HLR) that is in the range of 70 to 120 m^3/h/screen and requires a wash-water volumetric flow rate that is in the range of 15 to 35 m^3/day/screen. Typically, wastewater influent to a mobile-biofilm retention screen has less than a 6000-g TSS/m^3 concentration, although additional experience may allow this value to be revised upward. Preliminary treatment usually includes raw-sewage screening. The MOB process may be used with rake or suction-header clarifier mechanisms. Mobile biofilms can be evenly distributed throughout a bioreactor by low-speed mechanical surface aerators, diffused air, mechanical mixers, and pumps. Low-speed mechanical surface aerator design is not usually controlled by mobile-biofilm mixing; therefore, a unit designed to provide adequate dissolved oxygen (DO) will also well mix mobile biofilms and suspended biomass. A minimum air-flow rate of 10 m^3/h/m^2 of reactor floor is recommended to evenly distribute mobile biofilms and suspended biomass throughout a bioreactor that is supplied DO through air diffusers. Anaerobic and anoxic zones that are mixed by mechanical means or pumps require a minimum power input that is in the range of 8 to 12 W/m^3 to well mix the mobile biofilms and suspended biomass. Mechanical mixers and jet inlets are commonly situated near the bottom of relevant tanks because mobile biofilms and suspended biomass tend to settle.

The assignment of pollutants masses that will be transformed by mobile biofilms or accumulated suspended biomass depends on the pollutants forms (e.g., particulate vs. truly dissolved), the mechanisms by which pollutants will be transformed (e.g., hydrolysis vs. respiration), and the rate at which the pollutants are biologically transformed. Therefore, some relevant characteristics of wastewater are described. Municipal wastewater, for example, contains ammonium (NH_4^+), orthophosphate (PO_4^-), and truly dissolved and particulate organics that can be measured as chemical oxygen demand (COD). In this paper, particulate, or slowly biodegradable, COD (denoted X_B) is defined as the material that is retained by a 0.45-μm filter and truly dissolved, or readily biodegradable, COD (denoted S_B) as the material that passes through a 0.45-μm filter after the subject wastewater has been coagulated with zinc (i.e., flocculation and filtration) (Melcer et al., 2003). Commonly, most of the COD in municipal wastewater is due to particulate organic matter. Particulate organics may bioflocculate with suspended biomass. The heterotrophic bacteria that comprise a portion of suspended biomass produces hydrolytic enzymes that are bound to extracellular polymeric substances (EPS) and contribute to the hydrolysis of particulate COD into truly dissolved COD (Boltz & La Motta, 2007). The truly dissolved COD may be fermented and oxidized by bacteria via respiration. Typically, hydrolysis is a rate-limiting step in this sequence.

In addition to wastewater characteristics, the types of heterotrophic bacteria present are relevant to MOB process design and operation. Therefore, the biological selection of a specific type of heterotrophic bacteria is also relevant. Biological selection is defined in this paper as the configuration of a WWT process to create environmental conditions that support desired metabolic and enzymatic transformations and results in the accumulation of desired bacteria and biological forms. Carbon-storing heterotrophic bacteria, for example, are important for AGS formation and may be selected through alternating conditions of organic-substrate feast and famine (Jenkins et al., 2003). Bacteria store organic substrate under the "feast" condition when they can transport organic substrate into their cell at a greater rate than it can be oxidized via respiration. Carbon-storing heterotrophic bacteria polymerize the excess organic substrate and store it inside their cells (e.g., glycogen and poly-hydroxy-alkanoates [PHA]). Bacteria also produce EPS. Intracellular and extracellular polymeric substances have different compositions, but both can be hydrolyzed to a readily biodegradable form through enzymatic reactions (Tokiwa & Calabia, 2004). Carbon-storing heterotrophic bacteria hydrolyze and oxidize intracellular carbon polymers when they experience organic-substrate famine and sufficient electron acceptors (EA), such as DO or nitrate (NO_3^-), are present in the bulk water. Ordinary and carbon-storing heterotrophic bacteria can hydrolyze EPS when the hydrolytic enzymes they produce exists in sufficient quantity, and they can oxidize truly dissolved organic matter when there are sufficient EA. Carbon-storing heterotrophic bacteria have a competitive advantage over ordinary heterotrophic bacteria in WWT processes that create environmental conditions of organic-substrate feast and famine (de Kreuk & van Loosdrecht, 2004). van Dijk et al. (2022) presented a mathematical framework of AGS formation that aligns with the mechanisms described in this paper.

Truly dissolved organic matter is essential to AGS formation and may be in the influent wastewater or result from the hydrolysis of particulate organic matter. Ordinary and carbon-storing heterotrophic bacteria can ferment the truly dissolved organic matter into volatile fatty acids (VFAs). The VFAs can be polymerized and stored by carbon-storing heterotrophic bacteria when feasting on organic substrate, but enough readily biodegradable organic matter is required for heterotrophic bacteria to feast on the organic substrate. A wastewater in which the biodegradable organic matter primarily exists as particles, including colloids, may limit AGS formation.

The MOB process has been demonstrated to intensify biological WWT processes through compact bioreactors and quality solid-settling characteristics (Wei et al., 2021). Mathematical modeling has advanced mobile-biofilm reactors as an emerging technology for the treatments of municipal and industrial wastewaters (Boltz et al., 2017; Sabba et al., 2017). Research completed to date, however, has not defined different modes of MOB process operation nor has it presented a mechanistic basis for the selection and design of different MOB process modes of operation, particularly when a mobile-biofilm carrier model is utilized. This paper presents a mechanistic approach to design and evaluate MOB processes; it describes MOB process: (1) modes of operation, (2) design and analysis methods, (3) design criteria, (4) mathematical modeling, (5) design equations, and (6) mobile biofilms settling characteristics and return.

MODES OF OPERATION

The MOB process has four principal operating configurations that describe bioreactor type and location of mobile-biofilm retention screens. A MOB process can have a mobile-biofilm reactor or a hybrid bioreactor. We define a hybrid bioreactor as one that accumulates mobile biofilms and suspended biomass for desired solids residence times (SRTs). Mobile-biofilm retention screening may exist downstream of a bioreactor and upstream of a liquid and solid separation process or be integrated with waste-solid pipes. Although an operating mode that consists of a mobile-biofilm reactor and mobile-biofilm retention screening that is integrated with waste-solid pipes is viable, it has limited practical applicability. Therefore, this section focuses on describing three modes of operating a MOB process: *Mode I*, *Mode II*, and *Mode III*. Figure 2 illustrates these modes of operation.

Mode I

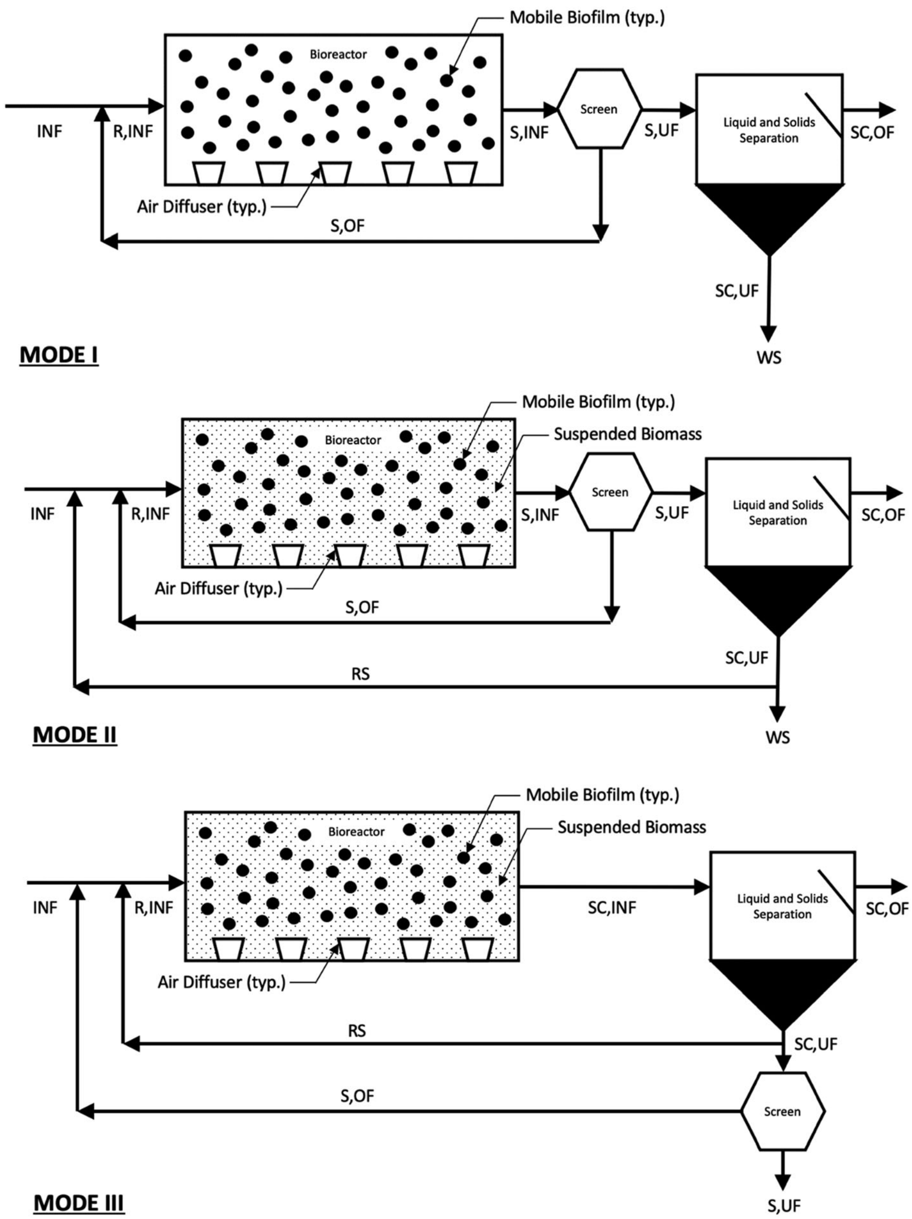
This mode of operation includes a mobile-biofilm reactor, or series of mobile-biofilm reactors, and a liquid and solid separation process. Mobile-biofilm retention screens are located downstream of and external to the bioreactor, and upstream of the liquid and solid separation process. The mobile-biofilm reactor(s) may have internal recirculation and consist of anaerobic, anoxic, and/or aerobic zones or any combination thereof. Mode I does not accumulate suspended biomass by controlled solids wasting. Total suspended solids (TSS) in the mobile-biofilm reactor(s) are, for the most part, composed of mobile biofilms, with solids detaching from mobile biofilms and in the influent wastewater comprising a lesser portion of the TSS in the bioreactor. Bioreactor effluent containing TSS flows from the mobile-biofilm reactor(s) to screens that retain mobile biofilm while the TSS that are smaller than screen orifices and water flow to a liquid and solid separation process.

Mode I requires a greater mobile-biofilm area ($A_{MF,required}$, m^2) to achieve a desired level of WWT when it is compared with other modes of operation and, therefore, it requires a greater kenaf mass than hybrid modes of operation. In this mode of operation, mobile-biofilm retention screens process the bioreactor effluent, which consists of process influent and screen over-flow volumetric flow rates. The mobile-biofilm reactor(s) require a mixing and/or aeration system that evenly distributes mobile biofilm through relevant portions of a mobile-biofilm reactor. The solids loading rate (SLR, kg/day·m^2) that is applied to a liquid and solid separation process in Mode I is minimal when compared with other modes of operation. Mode I is compatible with several different types of liquid and solid separation processes, for example, clarification, chemically enhanced liquid and solid separation, dissolved-air flotation, cloth-disc and granular-media filtration, and membrane filtration. The selection of a liquid and solid separation process may not be generally assigned because it involves several project-specific considerations that include, but are not limited to, site constraints, effluent water-quality standards, budget, and owner preference. Generally, MOB is an intensification approach that is utilized in conjunction with clarification. In the case of clarification, solids that have detached from mobile biofilms may have an average settling velocity that is less than that of ordinary biological flocs. A tank or channel with chemical addition or controlled aeration may exist downstream of the screens and upstream of the liquid and solid separation process to promote chemical or biological flocculation and improve TSS settling velocity (Norris et al., 1982). Chemical dose, contact time, and velocity gradient are key considerations for the design of a chemically enhanced liquid and solid separation process. Bulk-liquid DO concentration, air-bubble diameter, and velocity gradient are key considerations for the design of a re-aeration zone to promote bioflocculation (La Motta et al., 2003). Mode I applies the least SLR and HLR (m^3/day·m^2) to a liquid and solid separation process when compared with other modes of operation.

Mode II

This mode of operation includes a hybrid bioreactor, or series of hybrid bioreactors, and a liquid and solid

FIGURE 2 MOB process modes of operation



separation process that is, usually, a clarifier or membrane filter(s). Typically, suspended biomass is recirculated from a liquid and solid separation process at a volumetric flow rate that is 50% to 60% of the influent volumetric flow rate. Mobile biofilms and carriers retention screening is located downstream of and external to the hybrid bioreactor, and upstream of the liquid and solid separation process. The hybrid bioreactor(s) may have internal recirculation and consist of anaerobic, anoxic, and/or aerobic zones, or any combination thereof. TSS in a hybrid bioreactor are, typically, in the order of 30% to 60% mobile biofilms, but may be more or less. The remaining TSS have detached from mobile biofilms, entered with influent wastewater, or have been accumulated by controlled solids wasting. In this paper, the combination of TSS that have detached from mobile biofilms and are accumulated by controlled solids wasting is referred to as suspended biomass. Mobile biofilms and suspended biomass flow from a hybrid bioreactor to screens that retain the mobile biofilms while allowing suspended biomass and water to flow to a liquid and solid separation process. The SLR that is applied to a liquid and solid separation process in Mode II is greater than Mode I, but less than Mode III. The Mode II SLR is greater than the Mode I SLR because its liquid and solid separation process receives accumulated suspended biomass. The Mode II SLR is less than the Mode III SLR because a Mode III liquid and solid separation process receives mobile biofilms and accumulated suspended biomass. The HLR that is applied to a liquid and solid separation process in Mode II is greater than in Mode I because of under-flow recirculation from a liquid and solid separation process.

Mode II requires a moderate mobile-biofilm carrier mass when it is compared with other modes of operation. Mode II requires less mobile-biofilm carriers than Mode I because mobile biofilms transform only a portion of the electron donors (ED), EA, and other essential nutrients that are in the wastewater; the suspended biomass is responsible for substantial biological transformations. The mobile-biofilm retention screening capacity that is required for Mode II is greater than for Modes I or III because they process the bioreactor influent, screen overflow, and clarifier under-flow recirculation volumetric flow rates. The hybrid bioreactor(s) require a mixing and/or aeration system that evenly distributes mobile biofilms and suspended biomass through relevant portions of a bioreactor.

Mode III

This mode of operation includes a hybrid bioreactor, or series of hybrid bioreactors, and a liquid and solid separation process that is, usually, a clarifier. Mobile-biofilm retention screening is integrated with waste-solid pipes. Modes I and II retain mobile biofilms in a mobile-biofilm reactor and hybrid bioreactor, respectively, by locating mobile-biofilm retention screens downstream of the bioreactor. Mode III retains mobile biofilms in a hybrid bioreactor and clarifier sludge blanket by locating mobile-biofilm retention screens in waste-solid pipes; therefore, Mode III requires mobile biofilms that have excellent settling velocities. In Mode III, mobile biofilms enmesh with suspended biomass and improve overall TSS settling velocity. The hybrid bioreactor(s) may have internal recirculation and consist of anaerobic, anoxic, and/or aerobic zones, or any combination thereof. Mobile biofilms, suspended biomass, and water flows from the hybrid bioreactor(s) to a liquid and solid separation process. Increasing the volumetric flow rate through a liquid and solid separation process under-flow reduces the volume of accumulated solids; thus, the mobile-biofilm carrier mass that is retained in a liquid and solid separation process can be controlled. Suspended biomass accumulates in a hybrid bioreactor through controlled solids wasting, solids recirculation, and biofilm detachment. The SLR that is applied to a liquid and solid separation process in Mode III is greater than in Modes I and II, as discussed above. The HLR that is applied to a liquid and solid separation process in Mode III is greater than Mode I. Mode III will require the least mobile-biofilm carrier mass and screening capacity when it is compared with other modes of operation. The mobile-biofilm carrier mass that is required for Mode III is less than Modes I and II because mobile biofilms transform only a portion of the ED, EA, and other essential nutrients that are in the wastewater. Again, the suspended biomass is responsible for substantial biological transformations. The hybrid bioreactors require a mixing and/or aeration system that evenly distributes mobile biofilms and suspended biomass.

Table 1 lists some MOB installations for municipal and industrial WWT. They include Modes I, II, and III, and summarize design volumetric flow rates, preliminary treatments, process configurations, and WWT goals. The installations that are listed in Table 1 accumulates mobile biofilms with an average settling velocity that is comparable with AGS. Experience suggests that Mode III relies on AGS-forming conditions, which includes the proliferation and accumulation of carbon-storing heterotrophic bacteria. Typically, mobile biofilms constitute at least 25% of the TSS in a Mode III hybrid bioreactor, which is a minimum requirement for the well-settling mobile biofilms to enmesh with suspended biomass and improve the average TSS settling velocity, thus improving liquid and solid separation efficiency. Suspended biomass and solids in the influent wastewater comprise the remaining TSS. In Mode III, clarifiers efficiently retain mobile biofilms, which collect in a sludge blanket and are returned to a hybrid bioreactor. Most mobile biofilms and suspended biomass are recirculated to a hybrid bioreactor with under-flow from a liquid and solid separation process.

A METHOD OF PROCESS DESIGN AND ANALYSIS

A MOB process may be a proposed or existing WWTP component. This section describes means of designing new and analyzing existing MOB processes.

Process design

A MOB process may be designed by following these steps.

1. Assign the pollutants, pollutant forms, and pollutant masses that will be transformed by mobile biofilms.
2. Calculate $A_{MF,required}$ to transform these pollutants.
3. Calculate a mass-based specific surface area that is provided by mobile biofilms ($SSA_{M,MF}$).
4. Calculate a mobile-biofilm carrier mass (M_{MC}) that provides the required mobile-biofilm area.

TABLE 1 Selected MOB installations

Location	Annual-average day flow rate (m^3/d)	Wastewater type	Preliminary/ primary treatments	Process configuration	Mode	Benefits
Frontenac, KS, USA	950	Food processing and municipal	Dissolved-air flotation	CFSTRs in series (3)	I	Increased capacity; BOD_5 and TSS reductions
Norristown, PA, USA	13,250	Municipal	25-mm screens	Extended aeration	II	Increased capacity; BOD_5, TSS, TN, and TP reductions
Roanoke, VA, USA	71,923	Municipal	25-mm screens; primary clarifiers	Extended aeration	III	Increased capacity; BOD_5, TSS, TN, and TP reductions
Moorefield, WV, USA	13,250	Municipal and chicken slaughterhouse	25-mm screens; primary clarifiers	Oxidation ditch	III	Increased capacity; BOD_5, TSS, TN, and TP reductions
Mebane, NC, USA	11,356	Municipal	25-mm screens; primary clarifiers	Extended aeration	III	Increased capacity; BOD_5, TSS, TN, and TP reductions
Rigby, ID, USA	9085	Municipal	25-mm screens; primary clarifiers	Oxidation ditch	III	Increased capacity; BOD_5, TSS, TN, and TP reductions

5. If a hybrid bioreactor, assign the pollutants, pollutants forms, and pollutant masses that will be transformed by suspended biomass.
6. Calculate the suspended-biomass SRT (SRT_{SG}) that is required to transform these pollutants and consider the TSS retention efficiencies of (a) mobile-biofilm retention screens and (b) liquid and solid separation.
7. Calculate the TSS mass that is due to (a) mobile biofilms and (b) suspended biomass (if there is a hybrid bioreactor).
8. Size a mobile-biofilm or hybrid bioreactor and liquid and solid separation process.

The accumulation of suspended biomass by Modes II and III creates an opportunity to utilize suspended biomass and solids recirculation from liquid and solid separation to bioflocculate and then hydrolyze particulate organic matter, which results in most of the particulate organic matter in a wastewater being transformed by suspended biomass. On the one hand, a portion of the truly dissolved organic matter in wastewater may diffuse into mobile biofilms and result in bacteria competing for a common EA and other essential nutrients. On the other hand, the truly dissolved organic matter in wastewater may be useful for nitrogen-oxyanion reductions, fermentation (i.e., transformation of complex organics into a simple organic that we consider to be acetate), and biological selection.

An approach to hybrid-process design is to accumulate more rapidly growing bacteria as suspended biomass and more slowly growing bacteria in biofilms. In this paper, ordinary heterotrophic bacteria are modeled with have a 6.0–1/day specific biomass growth rate (denoted $\mu_{OHB,B}$) when transforming truly dissolved organic matter in a 20°C wastewater. Ammonium may be transformed by nitrifying autotrophic bacteria. We model nitrifying autotrophic bacteria to have a 1.0 1/day specific biomass growth rates (denoted μ_N). The ratio of $\mu_{OHB,B}$:μ_N, for example, is 6, which indicates that a suspended-biomass SRT may be selected for the accumulation of ordinary heterotrophic bacteria and to allow autotrophic nitrifying bacteria to wash out of the process. Then, a mobile-biofilm area may be assigned to accumulate nitrifying autotrophic bacteria, for example.

Calculating $A_{MF,required}$ requires the a priori knowledge of any soluble-substrate *i* flux across a mobile-biofilm surface ($J_{i,MF}$, g/m^2·day). A required mobile-biofilm area is calculated as the mass rate of any soluble substrate *i* through element *j*, or $MR_{i,j}$ ($=Q \cdot S_i$, g/day) divided by the flux of any soluble substrate *i*: $A_{MF,required} = MR_{i,j}/J_{i,MF}$. Usually, it is desirable to achieve a flux across the biofilm surface that is greater than 95% of its surface-area loading rate ($SALR_i$, g/m^2·day), but incomplete transformations by mobile biofilms may be advantageous. Soluble-substrate flux across a mobile-biofilm surface depends on water temperature, the ED and EA concentration in the bulk of the water, the rate at which a substrate diffuses through the biofilm, and the mobile-biofilm area. The soluble-substrate flux across a mobile-biofilm surface may be obtained by testing or, more commonly, through mathematical modeling, an approach taken in this paper.

Several figures are presented to support the development of equations for MOB process design and analysis. Figure 3 represents an embodiment of the MOB process as Mode I. It consists of a mobile-biofilm reactor, mobile-biofilm retention screen that receives the mobile-biofilm reactor effluent, screen over-flow that is returned to the mobile-biofilm reactor, screen under-flow that enters a clarifier, clarifier effluent, and waste solids with a clarifier under-flow. Figure 4 is an embodiment of the MOB process as Mode II. It consists of a hybrid bioreactor, mobile-biofilm retention screen that receives the hybrid-bioreactor effluent, screen over-flow that is returned to the hybrid bioreactor, screen under-flow that enters a clarifier, clarifier effluent, solids recirculation to a hybrid bioreactor with a clarifier under-flow, and waste solids with a clarifier under-flow. Figure 5 is an embodiment of the MOB process as Mode III. It consists of a hybrid bioreactor, clarifier over-flow, solids recirculation to a hybrid bioreactor with a clarifier under-flow, a mobile-biofilm retention screen that receives clarifier under-flow, retained mobile biofilms are returned to a hybrid bioreactor with a screen over-flow, and waste solids with a screen under-flow.

Figures 3–5 identify several MOB process elements that are generally denoted as j. Relevant MOB process elements are the influent ($j =$ INF), bioreactor influent ($j =$ R,INF), bioreactor ($j =$ R), screen over-flow ($j =$ S,OF), screen under-flow ($j =$ S,UF), clarifier over-flow ($j =$ SC,OF), clarifier under-flow ($j =$ SC,UF), return solids ($j =$ RS), and waste solids ($j =$ WS). Each of the elements that are identified in Figures 3–5 have a volumetric flow rate (denoted as Q), soluble-substrate concentration (denoted as S), and TSS concentration (denoted as X). The mobile-biofilm area that is associated with any element j, or $A_{MF,j}$, can be calculated by Equation (1).

$$A_{MF,j} = M_{MC,required} \cdot SSA_{M,MF}. \tag{1}$$

Here,
$M_{MC,required}$ = required mobile-biofilm carrier mass (g)

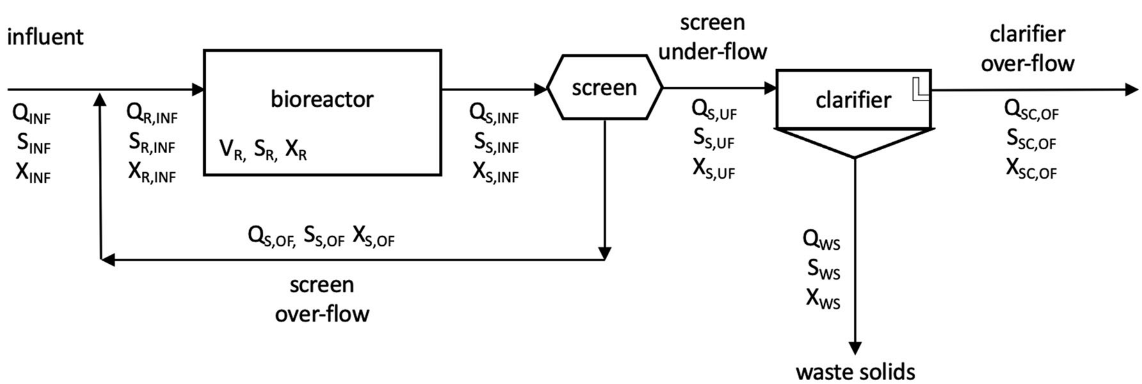


FIGURE 3 MOB process-flow diagram—Mode I

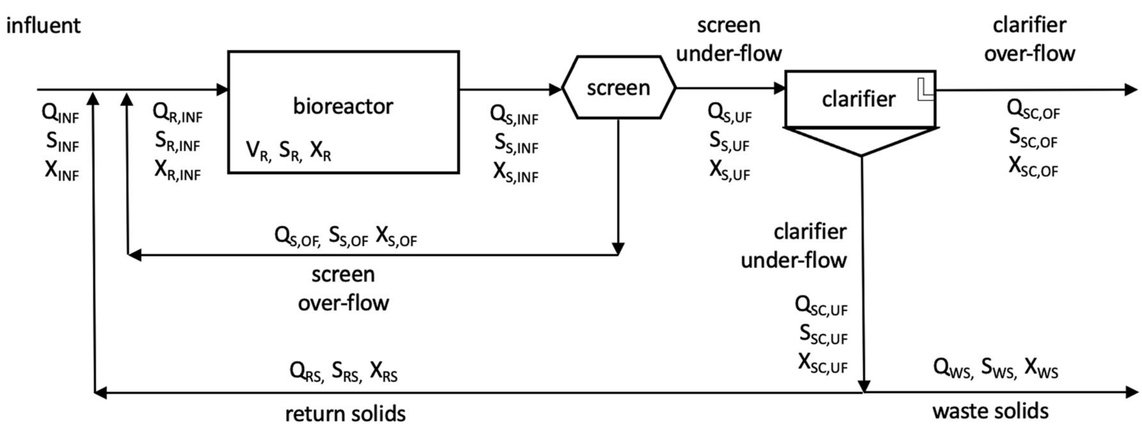


FIGURE 4 MOB process-flow diagram—Mode II

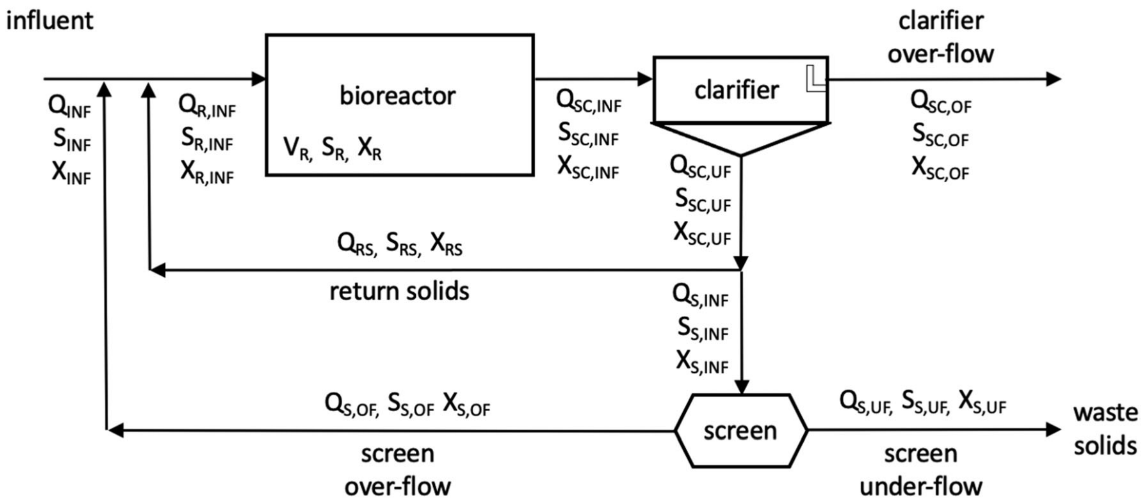


FIGURE 5 MOB process-flow diagram—Mode III.

$SSA_{M,MF}$ = mass-based specific surface area of mobile biofilms (m^2/g)

The TSS concentration in any element *j* (denoted $X_{TSS,j}$) is defined by Equation (2).

$$X_{TSS,j} = X_{TSS,j,SG} + X_{TSS,j,MF}. \tag{2}$$

Here,

$X_{TSS,j,SG}$ = TSS concentration in element *j* due to suspended biomass (g/m^3)

$X_{TSS,j,MF}$ = TSS concentration in element *j* due to mobile biofilms (g/m^3)

$$= X_{TSS,j,MC} + X_{TSS,j,F}$$

$X_{TSS,j,MC}$ = TSS concentration in element *j* due to mobile-biofilm carriers (g/m^3)

$X_{TSS,j,F}$ = TSS concentration in element *j* due to biofilms (g/m^3)

$= \left(\frac{V_{MF,j} - V_{MC,j}}{V_{MC,j} \cdot \rho_{MC}}\right) \cdot X_{TSS,j,MC} \cdot X_{TSS,F}$

$V_{MF,j}$ = biofilm and carrier volume in element *j* (m^3)

$V_{MC,j}$ = mobile-biofilm carrier volume in element *j* (m^3)

$X_{TSS,F}$ = average TSS concentration in a biofilm (g/m^3)

Equation (3) can be used to calculate the fraction of TSS that are due to suspended biomass ($f_{TSS,j,SG}$).

$$f_{TSS,j,SG} = \frac{X_{TSS,j,SG}}{X_{TSS,j,SG} + X_{TSS,j,MF}}. \tag{3}$$

The fraction of a TSS concentration that is due to biofilms ($f_{TSS,j,MF}$) is, by definition, equal to $1 - f_{TSS,j,SG}$.

Process analysis

TSS partitioning can be used to analyze an existing MOB process. TSS accumulate in a MOB process as biofilms, mobile-biofilm carriers, and suspended biomass. To analyze an existing MOB process, consider the wastewater and TSS that are in a mobile-biofilm reactor or a hybrid bioreactor, and evaluate the contributions that the mobile biofilms and suspended biomass make to ED, EA, and other essential nutrients transformations based on observed liquid and solid separation process and screen solid-retention efficiencies. This method includes collecting wastewater and TSS samples from a bioreactor, clarifier over-flow, clarifier under-flow, screen over-flow, and screen under-flow. These samples are then passed through a laboratory-scale screen with an opening size that is equivalent to the mobile-biofilm retention screen openings. TSS that are retained by the screen may be considered mobile biofilms, and the TSS that pass through the screen may be considered suspended biomass. This method of analyzing MOB processes requires the a priori knowledge of the TSS concentration in a bioreactor, clarifier over-flow, clarifier under-flow, screen over-flow, and screen under-flow, and the fraction of measured TSS that is suspended biomass. This information can be used to calculate the mobile-biofilm ($\chi_{SC,MF}$) and suspended-biomass ($\chi_{SC,SG}$) retention efficiencies for liquid and solid separation. The mobile-biofilm ($\chi_{S,MF}$) and suspended-biomass ($\chi_{S,SG}$) retention efficiencies for the screen can also be calculated. Mobile-biofilm (k = MF) and suspended-biomass (k = SG) retention efficiencies by a clarifier, for example, can be calculated by Equation (4).

$$\chi_{SC,k} = \frac{MR_{k,SC,INF} - MR_{k,SC,OF}}{MR_{k,SC,INF}}. \quad (4)$$

Here,

$MR_{k,SC,INF} = Q_{SC,INF} \cdot X_{k,SC,INF}$ = clarifier influent mass rate (g TSS/day)

$= Q_{SC,INF} \cdot X_{TSS,SC,INF} \cdot f_{TSS,SC,INF,SG}$ [for suspended biomass]

$= Q_{SC,INF} \cdot X_{TSS,SC,INF} \cdot (1 - f_{TSS,SC,INF,SG})$ [for mobile biofilms]

$MR_{k,SC,OF} = Q_{SC,OF} \cdot X_{k,SC,OF}$ = clarifier over-flow mass rate (g TSS/day)

$= Q_{SC,OF} \cdot X_{TSS,SC,OF} \cdot f_{TSS,SC,OF,SG}$ [for suspended biomass]

$= Q_{SC,OF} \cdot X_{TSS,SC,OF} \cdot (1 - f_{TSS,SC,OF,SG})$ [for mobile biofilms]

Mobile-biofilm and suspended-biomass retention efficiencies by a screen are calculated by Equation (5).

$$\chi_{S,k} = \frac{MR_{k,S,INF} - MR_{k,S,UF}}{MR_{k,S,INF}}. \quad (5)$$

Here,

$MR_{k,S,INF} = Q_{S,INF} \cdot X_{k,S,INF}$ = screen influent mass rate (g TSS/day)

$= Q_{S,INF} \cdot X_{TSS,S,INF} \cdot f_{TSS,S,INF,SG}$ [for suspended biomass]

$= Q_{S,INF} \cdot X_{TSS,S,INF} \cdot (1 - f_{TSS,S,INF,SG})$ [for mobile biofilms]

$MR_{k,S,UF} = Q_{S,UF} \cdot X_{k,S,UF}$ = screen under-flow mass rate (g TSS/day)

$= Q_{S,UF} \cdot X_{TSS,S,UF} \cdot f_{TSS,S,OF,SG}$ [for suspended biomass]

$= Q_{S,UF} \cdot X_{TSS,S,UF} \cdot (1 - f_{TSS,S,UF,SG})$ [for mobile biofilms]

The clarifier under-flow TSS concentration ($X_{TSS,SC,UF}$) and TSS concentration of the clarifier return solids ($X_{TSS,RS}$) are assumed equal. Modes I and II have a TSS concentration in the screen influent that is assumed equal to the TSS concentration in the bioreactor effluent. Mode III has a TSS concentration in the screen influent ($X_{TSS,S,INF}$) that is assumed equal to the clarifier under-flow TSS concentration ($X_{TSS,SC,UF}$).

DESIGN CRITERIA

In a MOB process, mobile biofilms grow on kenaf particles, which are pictured in Figure 6a. Mobile biofilms that have grown on kenaf particles are pictured with AGS and suspended biomass sampled from the Moorefield WWTF (West Virginia, USA) in Figure 6b. Means by which mobile biofilms produce and coexist with AGS may be reviewed in van Benthum et al. (1996) and van Dijk et al. (2022). Kenaf is a lignocellulosic material with a dry density (ρ) that is in the range of 150 to 250 kg/m^3 (Voulgaridis et al., 2000; Xu et al., 2004). A Brunauer–Emmett–Teller (BET) analysis revealed that processed kenaf provides 1.75 m^2 of surface area per gram of kenaf. However, the kenaf $SSA_{M,MF}$ is much less than the area that was determined by a BET analysis because biofilm growth on the exterior of kenaf particles constitutes a majority of the biofilm (Figure 6b). The $SSA_{M,MF}$ can be calculated by considering that processed kenaf particles resemble spheroids with 250-μm minimum (a_{MC} and b_{MC}) and 500-μm maximum (c_{MC}) dimensions. Mobile-biofilm carrier mass is the product of its density, or ρ_{MC}, and the volume of the shape that approximates the mobile-biofilm carrier (e.g., spheroids). Similar methods were applied by van Benthum et al. (1996) to evaluate a bench-scale air-lift reactor with basalt carriers and Daigger et al. (2007) to analyze ordinary biological flocs in a bench-scale reactor, but they assumed that the mobile biofilms and biological flocs were spherical. Applying a spheroid shape to mobile biofilms and carriers, $SSA_{M,MF}$ can be calculated by Equation (6).

$$SSA_{M,j,MF} = \frac{A_{\frac{MF}{carrier},j}}{M_{MC}} = \frac{4 \cdot \pi \cdot \left(\frac{a_{MF}^p \cdot b_{MF}^p + a_{MF}^p \cdot c_{MF}^p + b_{MF}^p \cdot c_{MF}^p}{3} \right)^{\frac{1}{p}}}{\rho_{MC} \cdot \frac{4}{3} \cdot \pi \cdot a_{MC} \cdot b_{MC} \cdot c_{MC}}. \quad (6)$$

Here,

$A_{MF/carrier,j}$ = mobile-biofilm area due to mobile-biofilm carriers in element *j* (m^2)

M_{MC} = mobile-biofilm carrier mass (g)

a_{MC} = mobile-biofilm carrier dimension, minimum (m)

b_{MC} = mobile-biofilm carrier dimension, minimum (m)

c_{MC} = mobile-biofilm carrier dimension, maximum (m)

a_{MF} = biofilm and mobile-biofilm carrier dimension, minimum (m) = $a_{MC} + L_{MF}$

b_{MF} = biofilm and mobile-biofilm carrier dimension, minimum (m) = $b_{MC} + L_{MF}$

c_{MF} = biofilm and mobile-biofilm carrier dimension, maximum (m) = $c_{MC} + L_{MF}$

L_{MF} = biofilm thickness (m)

p = empirical coefficient = 1.6075

ρ_{MC} = mobile-biofilm carrier density (g/m^3)

A volume-based specific surface area provided by mobile biofilms in an element *j*, or $SSA_{V,j,MF}$ (m^2/m^3), is the product of a mass-based specific surface area provided by mobile biofilms, or $SSA_{M,j,MF}$, and the concentration of mobile-biofilm carriers in an element

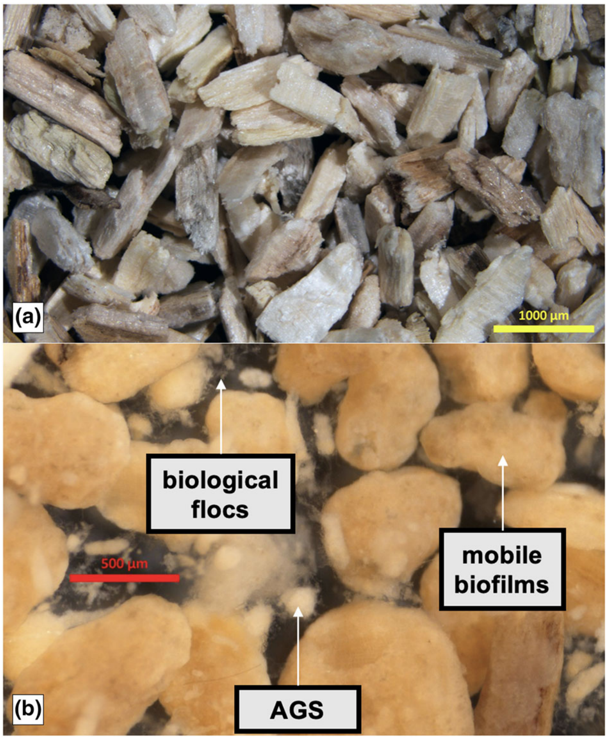


FIGURE 6 (a) Mobile-biofilm carriers (i.e., kenaf) and (b) mobile biofilms among biological flocs and aerobic-granular sludge (AGS)

j (i.e., $SSA_{V,j,MF} = SSA_{M,j,MF} \cdot X_{TSS,j,MC}$). To express $SSA_{V,j,MF}$ in terms of mobile-biofilm carrier volume in an element *j* (denoted as $SSA_{V,j,MF,Fi}$), one may divide $SSA_{V,j,MF}$ by the ratio of mobile-biofilm carrier volume to the volume of element *j*, or $Fi_{MC,j}$ (m^3/m^3) (i.e., $SSA_{V,j,MF,Fi} = SSA_{V,j,MC} \div Fi_{MC,j}$). The total volume of mobile-biofilm carriers in an element *j*, or $V_{MC,j}$ (m^3), can be calculated as the product of the mobile-biofilm carrier concentration in element *j*, or $X_{TSS,j,MC}$ (g/m^3), and the volume of element *j*, or V_j (m^3), divided by mobile-biofilm carrier density, or ρ_{MC} (g/m^3) (i.e., $V_{MC,j} = (X_{TSS,j,MC} \cdot V_j) \div \rho_{MC}$). Relevant calculations and additional analyses that evaluate mobile-biofilm carrier shape may be reviewed in the Supporting Information. Equation (6) is a conservative estimate of $SSA_{M,MF}$ because mobile biofilms do not have smooth surfaces. The mobile-biofilm carrier mass that is needed to provide a required biofilm area, or $M_{MC,required}$, in Modes I and II can be calculated by Equation (7).

$$M_{MC,required} = \frac{A_{MF,required}}{SSA_{M,MF}}. \qquad (7)$$

Equation (7) neglects mobile biofilms that are not in a bioreactor due to internal recirculation and screen over-flow because their residence time in process pipes are negligible when compared with their residence time in a bioreactor. Mode III, however, operates with a portion of the mobile biofilms in a liquid and solid separation process (e.g., in a clarifier sludge blanket). The design method presented in the paper is predicated on the idea that a required mobile-biofilm area, or $A_{MF,required}$, exists in a bioreactor at any time. The mobile-biofilm carrier mass that is needed to provide a required biofilm area, or $M_{MC,required}$, in Modes I and II can be calculated by Equation (8).

$$M_{MC,required} = \frac{A_{MF,required}}{SSA_{M,MF}} + V_{SB} \cdot X_{TSS,SB} \cdot f_{TSS,SB,MF}. \qquad (8)$$

Here,
V_{SB} = sludge-blanket volume (m^3)
$X_{TSS,SB}$ = sludge-blanket TSS concentration (g/m^3)
$f_{TSS,SB,MF}$ = fraction of sludge-blanket TSS concentration due to mobile biofilms (–)

The plastic-biofilm carriers that are utilized in IFAS and MBBR are state of the art. An example plastic-biofilm carrier (e.g., K5; Veolia, France) is formed of high-density polyethylene (HDPE) and has an 800-m^2/m^3 volume-based specific surface area ($SSA_{V,PC}$) (McQuarrie & Boltz, 2011). The plastic-biofilm carrier known as K5 has a 7-m^2/kg mass-based specific surface area ($SSA_{M,PC}$) (Roman, 2021). Therefore, a 1000-m^3 reactor that has a 0.49 volumetric fill of plastic-biofilm carriers has a 392,000-m^2 biofilm area. Assuming a 250-kg/m^3 kenaf density, 200-μm biofilm thickness, and 250-μm minimum (a_{MC} and b_{MC}) and 500-μm maximum (c_{MC}) dimensions, Equations (1) and (6) may can be applied to calculate a 0.11-m^2/g $SSA_{M,MF}$. Therefore, a 1000-m^3 bioreactor with $\Phi = 0.98$ and a 3636-g TSS/m^3 mobile-biofilm carrier (as kenaf) concentration ($X_{TSS,R,MF}$) has an approximately 392,000-m^2 mobile-biofilm area. Comparing calculations, 56,000 kg of HDPE and 3636 kg of kenaf (covered by a 200-μm-thick biofilm) are required to provide the same biofilm area in a 1000-m^3 bioreactor, which is a 15-to-1 mass ratio.

MATHEMATICAL MODELING

Mathematical modeling of MOB processes configured as Mode I, Mode II, and Mode III was performed. The modeled wastewater contains truly dissolved organic matter and ammonium (denoted S_{NH4}). A modeling objective was to simulate and compare different MOB process modes of operation. In addition, mathematical modeling results provide an informational basis for the examples that appear in the Supporting Information. A mobile-biofilm model by Boltz et al. (2017) and a WWTP simulator (Sumo, Dynamita, France) was used to model a fixed bioreactor volume and clarifier area as Modes I, II, and III. A model of ordinary heterotrophic bacteria (denoted X_{OHB}) and nitrifying autotrophic bacteria (denoted X_N) respirations, syntheses, endogenous decays, and endogenous-decay products hydrolyses was encoded and applied. The modeled ordinary heterotrophic bacteria utilize truly dissolved organic matter, or rbCOD, as an ED and DO as an EA. The modeled nitrifying autotrophic bacteria oxidize ammonium to nitrate (denoted S_{NO3}) and utilize DO as an EA. Endogenous-decay products are modeled as particulate inert COD (denoted X_I) and organic matter, or slowly biodegradable COD, which can be hydrolyzed into rbCOD by biomass-associated hydrolytic enzymes. A process, kinetic, and stoichiometric matrix, summary of kinetic expressions, kinetic and stoichiometric parameters, and biofilm-model parameters are presented as the Supporting Information. A numerical, one-dimensional (1-D) biofilm model was applied (Wanner et al., 2006). Additionally, a good biofilm reactor modeling practice (GBRMP) by Rittmann et al. (2018) was applied. Biofilm thickness, or L_F, was modeled in response to a user-defined detachment rate (b_{det}, 1/day) and to achieve a desired TSS concentration inside a simulated mobile biofilm. A 120,000-g TSS/m^3 concentration was modeled inside the biofilm (denoted $X_{TSS,F}$), which was applied based on observations by van Benthum et al. (1996). The mobile-biofilm carriers are assumed to have the same dimensions and support equivalent biofilm thicknesses.

Particles, quantified here as TSS, attach to and detach from mobile-biofilm surfaces. The biofilm mass resulting from synthesis is greater than the biofilm mass that is lost through endogenous decay and hydrolysis. Therefore, healthy biofilms have a net detachment of TSS from their surfaces. Particles were modeled to detach from mobile-biofilm surfaces at a rate of 0.1/day. Particle attachment to mobile-biofilm surfaces was not modeled. Table 2 summarizes simulated conditions including volumetric flow rates, influent wastewater characteristics, the bioreactor, mobile-biofilm carriers, screens, and liquid and solid separation. Each scenario was simulated to achieve 99.5% rbCOD and ammonium transformations, or better. Table 3 summarizes mathematical modeling results. Application of the design equations in this paper to the modeled Mode III MOB process are presented as the Supporting Information. Several trends emerge from the mathematical modeling that are summarized in Table 3.

1. The mobile-biofilm carrier masses that are required to meet a common WWT objective are 1.1 g for Mode I, 0.9 g for Mode II, and 0.7 g for Mode III, and the suspended-biomass SRTs are 4.5 days for Mode III and 3.8 days for Mode II. Accumulating suspended biomass reduces the mobile-biofilm carrier mass that is required to meet a WWT objective.
2. The rbCOD fluxes across mobile-biofilm surfaces are 10.5 g/day·m^2 for Mode I, 2.5 g/day·m^2 for Mode II, and 1.5 g/day·m^2 for Mode III, and the ammonium fluxes are 3.2 g/day·m^2 for Mode III, 1.5 g/day·m^2 for Mode II, and 0.9 g/day·m^2 for Mode I. An increasing portion of rbCOD is transformed by suspended biomass as SRT_{SG} increases, and the portion of rbCOD that is transformed by mobile biofilms decreases. Consequently, there is less competition between ordinary heterotrophic bacteria and nitrifying autotrophic bacteria for the common EA, namely, DO, in mobile biofilms as SRT_{SG} increases.
3. The clarifier SLRs are 151 kg/day·m^2 Mode III, 68 kg/day·m^2 for Mode II, and 7 kg/day·m^2 for Mode I.
4. The clarifier HLRs are 30 m/day for Modes II and III and 20 m/day for Mode I.
5. The mass ratio of organic matter transformed by mobile biofilms to the total mass of organic matter transformed by suspended biomass and mobile biofilms is in the order of Mode I > Mode II > Mode III.
6. The mass ratio of ammonium that has been transformed by mobile biofilms to the total mass of ammonium transformed by suspended biomass and mobile biofilms is greater than 90% for Modes I, II, and III.
7. The observed yields of TSS ($Y_{TSS,obs}$) are approximately 0.5 g TSS/g COD_S for Modes, I, II, and III.

An increasing apparent surface-area loading rate of any soluble substrate *i* that is applied to a mobile-biofilm surface ($SALR_i$) is usually associated with an increasing flux of the substrate, or $J_{i,MF}$, until a maximum possible substrate flux has been achieved. Increasing a $SALR_i$ beyond a maximum possible substrate flux reduces substrate-transformation efficiency in a mobile-biofilm reactor, consistent with the simulated ammonium fluxes, or $J_{NH4,MF}$, but it is not consistent with the simulated rbCOD fluxes, or $J_{B,MF}$. The apparent values of rbCOD SALR, or $SALR_B$, are in the order of Mode III > Mode II > Mode I. However, modeled rbCOD fluxes are in the order of Mode I > Mode II > Mode III. Noteworthy, the modeled rbCOD fluxes significantly decrease in Modes II and III when they are compared with the Mode I rbCOD flux.

Why does rbCOD flux significantly decrease despite an increased $SALR_B$?

Modes II and III rely on transformations by mobile biofilms and suspended biomass. When competing for the same ED and EA, bacteria that accumulate as suspended biomass will have a competitive advantage over the bacteria that accumulate in mobile biofilms; the suspended biomass has less diffusional resistances than

TABLE 2 Summary of MOB process mathematical modeling inputs

Parameter	Symbol	Mode I	Mode II	Mode III
Volumetric flow rate (m^3/day)				
Influent	Q_{INF}	2000	2000	2000
Bioreactor influent	$Q_{R,EFF}$	2025	3025	3025
Screen under-flow	$Q_{S,UF}$	2000	3000	80
Screen over-flow	$Q_{S,OF}$	25	25	25
Clarifier influent	$Q_{SC,INF}$	2000	3000	3025
Return solids	Q_{RS}	0	1000	1000
Waste solids	Q_{WS}	100	100	N.A.
Effluent	Q_{EFF}	1900	1900	1920
Influent WW concentrations (g/m^3)				
rbCOD	$S_{B,INF}$	900		
Ammonium-nitrogen	$S_{NH4,INF}$	80		
TSS	$X_{TSS,INF}$	0		
Bioreactor				
Volume (m^3)	V_R	1000		
Bulk-liquid DO concentration (m^3)	S_{O2}	6.0		
Organic-loading rate (kg COD_S/day·m^3)	OLR	1.8		
Ammonium-loading rate (g N/day·m^3)	ALR	160		
Biofilms and mobile-biofilm carriers				
Mobile-biofilm carrier density (kg/m^3)	ρ_{MC}	250		
Detachment rate (1/day)	b_{det}	0.1		
Displacement factor (m^3/m^3)	Φ	0.98		
Screen				
Mobile-biofilm retention efficiency (–)	$\chi_{S,MF}$	0.98		
Suspended-biomass retention efficiency (–)	$\chi_{S,SG}$	0.02		
Clarifier				
Mobile-biofilm retention efficiency (–)	$\chi_{SC,MF}$	1.0		
Suspended-biomass retention efficiency (–)	$\chi_{SC,SG}$	1.0		
Area (m^2)	A_{SC}	100		

biofilms. Therefore, the reducing rbCOD fluxes are due to transformations by suspended biomass. A Mode II simulation indicates that mobile biofilms transform 14% of the rbCOD despite comprising 50% of the TSS in a hybrid bioreactor. The simulation for Mode III indicates that mobile biofilms transform 4% of the rbCOD despite comprising 23% of the TSS in a hybrid bioreactor. These observations are explained by the accumulation of suspended biomass that transforms most of the organic matter in the simulated wastewater. The modeled SRT_{SG} is in the order of Mode III > Mode II > Mode I and mobile-biofilm area is in the order of Mode I > Mode II > Mode III. Increasing quantities of rbCOD are transformed by suspended biomass as SRT_{SG} increases, which results in $SALR_B$ reducing and ammonium flux increasing. Mode II and III simulations indicate that the modeled mobile biofilms are ideal for accumulating the relatively slow-growing bacteria such as nitrifying autotrophic bacteria.

DESIGN EQUATIONS

A steady-state mass balance on any soluble substrate *i* (S_i) in a continuous-flow-stirred-tank reactor (CFSTR) is presented as Equation 9 (Boltz et al., 2009).

$$0 = \left(Q_{R,INF} \cdot S_{R,INF,i}\right) - \left(Q_{R,EFF} \cdot S_{R,EFF,i}\right) - \Phi \cdot V_R \cdot \left(r_{MF,i} + r_{SG,i}\right). \quad (9)$$

Here,

TABLE 3 Summary of MOB process mathematical modeling results

Parameter	Symbol	Mode I	Mode II	Mode III
Hydraulic-retention time (day)	HRT	0.5	0.3	0.3
Suspended-biomass SRT (day)	SRT_{SG}	N.A.	3.8	4.5
Mobile-biofilm average SRT (day)	SRT_{MF}	10	10	10
Concentrations (g/m^3)				
rbCOD, bioreactor influent	$S_{B,INF}$	900	595	595
rbCOD, effluent and waste solids	$S_{B,EFF}$	2.0	0.9	0.7
TSS, bioreactor	$X_{TSS,R}$	5000	5000	5000
TSS, effluent	$X_{TSS,EFF}$	0	0	0
TSS, waste solids	$X_{TSS,WS}$	8600	9000	11,500
Mobile biofilms in the bioreactor				
TSS, suspended biomass (g/m^3)	$X_{TSS,R,SG}$	352	2488	3838
TSS, mobile-biofilm carriers (g/m^3)	$X_{TSS,R,MC}$	1131	935	700
TSS, biofilms (g/m^3)	$X_{TSS,R,F}$	3517	1577	462
TSS, mobile biofilms/TSS (g/g)	$X_{TSS,R,MF}/X_{TSS,R}$	0.93	0.50	0.23
Biofilm thickness (μm)	L_F	293	200	100
TSS concentration inside biofilm (g/m^3)	$X_{TSS,F}$	120,000	120,000	120,000
Specific surface area, mass (m^2/g)	$SSA_{M,R,MF}$	0.15	0.11	0.07
Specific surface area, vol. R (m^2/m^3)	$SSA_{V,R,MF}$	166	100	48
Volumetric fill (m^3/m^3)	$Fi_{MC,R}$	0.0045	0.0037	0.0028
Specific surface area, vol. MC (m^2/m^3)	$SSA_{V,R,MF,Fi}$	36,888	27,243	17,143
Mobile-biofilm area, required (m^2)	$A_{MF,required}$	166,286	100,800	48,000
SALR, rbCOD ($g\ COD_S/day{\cdot}m^2$)	$SALR_B$	10.8	17.9	37.5
Flux, rbCOD ($g\ COD_S/day{\cdot}m^2$)	$J_{B,MF}$	10.5	2.5	1.5
SALR, ammonium ($g\ N/day{\cdot}m^2$)	$SALR_{NH4}$	0.96	1.59	3.33
Flux, ammonium ($g\ N/day{\cdot}m^2$)	$J_{NH4,MF}$	0.93	1.54	3.23
Clarifier				
Solid-loading rate ($kg/day{\cdot}m^2$)	SLR_{SC}	7.3	68	151
Hydraulic-loading rate ($m^3/day{\cdot}m^2$)	HLR_{SC}	20	30	30
Mass ratio due to mobile biofilms, S_B	$M_{B,MF}/M_{B,T}$	0.97	0.14	0.04
Mass ratio due to suspended biomass, S_B	$M_{B,SG}/M_{B,T}$	0.03	0.86	0.96
Mass ratio due to mobile biofilms, S_{NH4}	$M_{NH4,MF}/M_{NH4,T}$	0.97	0.97	0.99
Mass ratio due to suspended biomass, S_{NH4}	$M_{NH4,SG}/M_{NH4,T}$	0.03	0.03	0.01
Observed yield ($g\ TSS/g\ COD_S$)	$Y_{TSS,obs}$	0.48	0.50	0.51

$Q_{R,INF}$ = bioreactor influent volumetric flow rate (m^3/day)

$Q_{R,EFF}$ = bioreactor effluent volumetric flow rate (m^3/day)

$S_{R,INF,i}$ = bioreactor influent soluble-substrate i concentration (g/m^3)

$S_{R,EFF,i}$ = bioreactor effluent soluble-substrate i concentration (g/m^3)

Φ = displacement factor (–) $= \frac{V_j - V_D}{V_j}$.

V_j = volume of element j (m^3)

V_D = bulk-water volume displaced by mobile-biofilm carriers (m^3)

$r_{MF,i}$ = rate of soluble-substrate i transformation by biofilm ($g/day{\cdot}m^3$)

$r_{SG,i}$ = rate of soluble-substrate i transformation by suspended biomass ($g/day{\cdot}m^3$)

In a CFSTR, $Q_{INF} = Q_{EFF}$.

Biofilms and suspended biomass have different SRTs in Mode II and III MOB processes. The average

SRT of biofilms is a function of the rate at which solids detach from their surfaces. The average SRT of mobile biofilms is influenced by screen and liquid and solid separation process solid-retention efficiencies. Screens are more than 95% efficient for retaining mobile biofilms, which is consistent with the reported efficiency of screens for retaining densified biological flocs greater than a 250-μm equivalent spherical diameter (Van Winckel et al., 2019). While the loss of mobile biofilms through screens will have an impact on mobile-biofilm SRT, we do not consider this sink because the average mobile-biofilm carrier SRT is much greater than the average mobile-biofilm SRT. The suspended-biomass SRT is influenced by screen and clarifier solids-retention efficiencies, solid-wasting rate, and biofilm-detachment rate. A way of calculating suspended-biomass and mobile-biofilm SRTs is described in this section.

Solid-residence time

The suspended-biomass SRT, or SRT_{SG}, can be calculated for operational and control purposes as the mass of suspended biomass in the bioreactor divided by the suspended biomass that is lost in the waste solids and clarifier over-flow. The SRT_{SG} described in this paper includes the contribution of mobile-biofilm detachment and may be calculated by Equation (10).

$$SRT_{SG} = \frac{M_{SG,R}}{MR_{SG,WS} + MR_{SG,SC,OF} - MR_{MF,det}}. \quad (10)$$

Here,

$M_{SG,R}$ = suspended biomass in the bioreactor (g)

$= \Phi \cdot V_R \cdot X_{TSS,R,SG}$

$MR_{SG,WS}$ = mass rate of suspended biomass in the waste solids (g/day)

$= Q_{WS} \cdot X_{TSS,WS} \cdot f_{TSS,WS,SG}$ Mode II

$= Q_{S,UF} \cdot X_{TSS,S,UF} \cdot f_{TSS,S,UF,SG}$ Mode III

$MR_{SG,SC,OF}$ = mass rate of suspended biomass in the clarifier over-flow (g/day)

$= Q_{SC,OF} \cdot X_{TSS,SC,OF} \cdot f_{TSS,SC,OF,SG}$

$= Q_{R,INF} \cdot X_{TSS,R} \cdot f_{TSS,R,SG} \cdot (1 - \chi_{S,SG}) \cdot (1 - \chi_{SC,SG})$ Mode II

$= Q_{R,INF} \cdot X_{TSS,R} \cdot f_{TSS,R,SG} \cdot (1 - \chi_{SC,SG})$ Mode III

$MR_{MF,det}$ = mass rate of mobile-biofilm detachment (g/day)

$= X_{TSS,MF} \cdot L_{MF} \cdot A_{MF} \cdot b_{det}$

Q_{WS} = waste solids volumetric flow rate (m^3/day)

$Q_{S,UF}$ = screen under-flow volumetric flow rate (m^3/day)

$f_{TSS,WS,SG}$ = waste solids suspended-biomass fraction of TSS (–)

$= \frac{X_{TSS,WS,SG}}{X_{TSS,WS,SG} + X_{TSS,WS,MF}}$

$f_{TSS,S,UF,SG}$ = screen under-flow suspended-biomass fraction of TSS (–)

$= \frac{X_{TSS,S,UF,SG}}{X_{TSS,S,UF,SG} + X_{TSS,S,UF,MF}}$

$X_{TSS,WS,SG}$ = waste-solid TSS concentration passing 500-μm screen (g TSS/m^3)

$X_{TSS,WS,MF}$ = waste-solid TSS concentration retained by 500-μm screen (g TSS/m^3)

$X_{TSS,S,UF,SG}$ = screen under-flow TSS concentration passing 500-μm screen (g TSS/m^3)

$X_{TSS,S,UF,MF}$ = screen under-flow TSS concentration retained by 500-μm screen (g TSS/m^3)

Example SRT_{SG} calculations for modeled Modes II and III are included in the Supporting Information.

Mobile-biofilm average SRT

Biofilms are subject to strong mass-transfer resistances; thus, substrate concentration gradients exist, primarily, in a direction that is perpendicular to the mobile-biofilm surface. Consequently, biofilms have a range of specific growth rates. Yet the SRT concept can be applied to a steady-state biofilm by recognizing that its SRT is an average of the entire biofilm (SRT_{MF}) (Rittmann & McCarty, 2020). The calculation of SRT_{MF} is useful when modeling MOB processes because it provides an indication of the modeled biofilm properties and their alignment with generally accepted information and process-design intent. Assuming steady-state biofilms and that the mobile-biofilm mass lost through a screen is negligible, SRT_{MF} can be calculated by Equation (11).

$$SRT_{MF} = \frac{M_{MF,R}}{MR_{MF,det}} = \frac{\Phi \cdot V_R \cdot X_{TSS,R,MF} \cdot SSA_{M,MF} \cdot L_{MF} \cdot X_{TSS,MF}}{X_{TSS,MF} \cdot L_{MF} \cdot A_{MF,R} \cdot b_{det}} = \frac{1}{b_{det}}. \quad (11)$$

Here, $M_{MF,R}$ is the mobile-biofilm mass in a bioreactor (g).

MOBILE-BIOFILM SETTLING CHARACTERISTICS AND RETURN

Modes I and II retain mobile biofilms in a bioreactor; therefore, mobile-biofilm settling velocities are not relevant to liquid and solid separation process performance. A MOB process configured as Mode III, which depends on AGS-forming conditions, may have mobile biofilms with a 30-min sludge volume index (SVI_{30}) of 30 ml/g and a SVI_{30}-to-5-min sludge volume index ratio (SVI_{30}/

SVI_5) of 1; these SVI_{30} and SVI_{30}/SVI_5 values are consistent with those reported for AGS (Wei et al., 2021). In Mode III, mobile biofilms comprise a minimum of 25% mobile-biofilm carriers to improve average TSS settling velocity. Figure 7 pictures graduated cylinders that contain suspended biomass (left) and mobile biofilms and AGS (right) sampled from the Moorefield WWTP (West Virginia, USA). The water and TSS sample was taken from this full-scale WWTP, which is configured as a Bardenpho process integrated with MOB as Mode III. Pictured to the left are suspended biomass, or TSS passing a 500-μm screen, after a 5-min settling period, and to the right are mobile biofilms, or TSS retained by a 500-μm screen, after a 5-min settling period. In a MOB process, mobile-biofilm surfaces are exposed to significant shear stresses by mechanical mixing, aeration, and pumping. These shear stresses are essential to the development of compact mobile biofilms and AGS. Generally, mobile-biofilm carriers alone do not improve the average settling velocity of TSS.

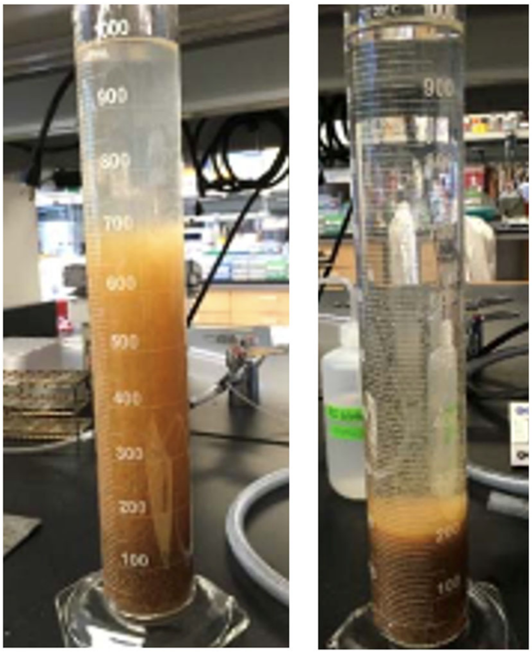


FIGURE 7 Images of mobile-biofilm and suspended-biomass samples taken from the Moorefield WWTF (West Virginia, USA), which is a MOB process that is configurated as Mode III. (Left) TSS passing a 500-μm screen, or suspended biomass, after 5 min of settling. (Right) TSS retained by a 500-μm screen, or mobile biofilms and AGS, after 5 min of settling

A location may be selected to reintroduce the mobile biofilms that are retained by screens to a MOB process that benefits its performance. We describe two scenarios in this section: (1) side-stream treatment and (2) wet weather and WWT. Supporting process-flow diagrams are provided in the Supporting Information.

Wastewaters originating from sources other than the influent wastewater are sometimes referred to as side streams. They commonly have volumetric flow rates that are less than the influent volumetric flow rate and have higher ED or EA concentrations. Side-stream WWT benefits include a reduced bioreactor volume and the possibility of utilizing biological transformations that are otherwise inhibited (e.g., anammox) (Grady et al., 2011). The mobile biofilms that are retained by screens may flow into a side-stream bioreactor and then a hybrid bioreactor with the side-stream bioreactor effluent. While mobile biofilms and carriers are retained, suspended biomass flows through the screen to a clarifier, thus, efficient WWT may occur in an economically viable manner, if enough ED, EA, and A_{MF} exists.

Wet-weather flow at a WWTP occurs during rain events. The rain infiltrates a wastewater collection and conveyance system and may result in, for example, a

TABLE 4 Summary of key equations for the design and analysis of MOB processes

No.	Description	Symbol	Equation	Units
1	Mobile-biofilm area required to transform soluble substrate *i* in element *j*	$A_{MF,required}$	$=\frac{MR_{i,j}}{J_{i,MF}}$	m^2
2	Mobile-biofilm specific surface area	$SSA_{M,MF}$	$=\frac{4\cdot\pi\cdot\left(\frac{a_{MF}^p\cdot b_{MF}^p+a_{MF}^p\cdot c_{MF}^p+b_{MF}^p\cdot c_{MF}^p}{3}\right)^{\frac{1}{p}}}{\rho_{MC}\cdot\frac{4}{3}\cdot\pi\cdot a_{MC}\cdot b_{MC}\cdot c_{MC}}$	m^2/g
3	Mobile-biofilm carrier mass needed to provide a required mobile-biofilm area	$M_{MC,required}$	$=\frac{A_{MF,required}}{SSA_{M,MF}}$ (Modes I and II) $=\frac{A_{MF,required}}{SSA_{M,MF}}+V_{SB}\cdot X_{TSS,SB}\cdot f_{TSS,SB,MF}$ (Mode III)	g
4	TSS concentration in element *j* due to mobile-biofilm carriers	$X_{TSS,j,MC}$	$=\frac{M_{MC,j}}{\phi\cdot V_j}$	g/m^3
5	TSS concentration in element *j* due to biofilms	$X_{TSS,j,F}$	$=\left(\frac{V_{MF,j}-V_{MC,j}}{V_{MC,j}\cdot\rho_{MC}}\right)\cdot X_{TSS,j,MC}\cdot X_{TSS,F}$	g/m^3
6	TSS concentration in element *j* that is due to mobile biofilms and suspended biomass	$X_{TSS,j}$	$=X_{TSS,j,SG}+X_{TSS,j,MC}+X_{TSS,j,F}$	g/m^3
7	Suspended-biomass SRT (Modes II and III)	SRT_{SG}	$=\frac{M_{SG,R}}{MR_{SG,WS}+MR_{SG,SC,OF}-MR_{MF,det}}$	day

fivefold increase in the volumetric flow rate that is influent to a WWTP. Rain infiltration to a wastewater collection and conveyance network usually dilutes the wastewater that is influent to a WWTP. MOB process screens are limited by HLR; therefore, sizing screens to process volumetric flow rates that are associated with wet weather will increase equipment requirements and monetary costs. A MOB process may be configured for WWT during dry and wet weather by controlling the location where mobile biofilms are reintroduced to a secondary process. Consider a bioreactor that is followed by a screen and a suspended-growth reactor. While mobile biofilms are retained by the screen, suspended biomass flows through it and into the suspended-biomass bioreactor. The mobile-biofilm may be mixed with the influent wastewater. Any influent volumetric flow rate that is greater than the dry-weather volumetric flow rate will bypass the hybrid bioreactor and flow into the suspended-biomass bioreactor, which may be anoxic or aerobic. Influent WWT during wet weather will benefit from contact stabilization and the protection of mobile biofilms.

CONCLUSIONS

The MOB process is a relatively new option for municipal and industrial WWT that includes mobile biofilm and their retention screens with a bioreactor and liquid and solid separation. Three modes of operation are described in this paper. Mode I has a mobile-biofilm reactor and a mobile-biofilm retention screen that is downstream of and external to a mobile-biofilm reactor and upstream of a liquid and solid separation process. Modes II and III have a hybrid bioreactor and a liquid and solid separation process. Mode II includes a mobile-biofilm retention screen that is downstream of and external to a hybrid bioreactor and upstream of a liquid and solid separation process. Mode III includes a mobile-biofilm retention screen that is external to a hybrid bioreactor and liquid and solid separation process, receives waste solids, and relies on environmental conditions and wastewater characteristics that are favorable to AGS formation. Principal conclusions of the work presented in this paper include:

1. Selecting a MOB process operating mode depends on influent wastewater characteristics and WWT objectives. Mode III requires enough truly dissolved organic matter for the development of AGS-like mobile biofilms that have excellent settling characteristics. This constraint does not exist for Modes I and II. The WWT objectives and effluent water-quality goals will influence the types of biological transformations that will be incorporated for all three modes and, consequently, the relative functional roles of mobile biofilms and suspended biomass.
2. MOB process analysis and design is based on appropriate mass-balance equations that account for mobile biofilms and suspended biomass, along with the TSS retention efficiency of mobile-biofilm retention screens and liquid and solid separation. In addition to mobile biofilms, AGS may result from mobile biofilms and interact with them and suspended biomass. Table 4 presents a summary of key equations.
3. Existing WWTPs that have integrated a MOB process can be analyzed and upgraded, and new WWTPs can be designed to integrate a MOB process by appropriately coupling mass-balance equations and partitioning the biological transformation of pollutants that are in wastewater.
4. Biological process, numerical 1-D biofilm, and mobile-biofilm models can be used in conjunction with the design methods presented in this paper to analyze and design MOB processes.
5. Well-designed hybrid bioreactors accumulate slow-growing bacteria in biofilms and faster-growing bacteria as suspended biomass. Hybrid bioreactors have a SRT_{SG} to accomplish one, or more, biological transformations and $A_{MF,required}$ to accomplish others. A primary mechanism is the significantly greater resistance to mass transfer of soluble substrates into a biofilm when compared with the ordinary biological flocs that comprise suspended biomass.

The objective of this paper is to offer readers a mechanistic understanding of the MOB process, and how to use key equations to analyze and design MOB processes. This understanding is expected to increase the application of MOB processes and continue to expand the collective knowledge and application of mobile biofilms as an emerging environmental biotechnology for municipal and industrial WWT.

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AUTHOR CONTRIBUTIONS

Joshua P. Boltz: Conceptualization; methodology; writing-review and editing; software; formal analysis; writing-original draft; investigation. **Glen T. Daigger:** Methodology; writing-review and editing; investigation; conceptualization.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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