Aerobic granular sludge: the future of wastewater treatment

Y. V. Nancharaiah[1,2,*], M. Sarvajith[1,2] and T. V. Krishna Mohan[1]

[1]Water and Steam Chemistry Division, Bhabha Atomic Research Centre, Kalpakkam 603 102, India
[2]Homi Bhabha National Institute, BARC Training School Complex, Anushakti Nagar, Trombay, Mumbai 400 094, India

Water, food and energy security are interlinked and central to sustainable development. Wastewater is a key element in the water–food–energy nexus, and recovery of resources can link water, nutrient and energy cycles. Effective treatment of wastewater is essential for public health and sanitation, water reclamation, preventing environmental pollution and protecting water resources. Furthermore, the treated wastewater is a potential resource and its reuse will partially offset supply and demand in water-stressed areas. A century-old activated sludge (AS) process is still widely employed, though not sustainable in terms of large land footprint, higher costs and complex designs for achieving biological nutrient removal. The recently developed aerobic granular sludge (GS) process is a better replacement for AS and promises sustainable wastewater treatment for at least the next century. The GS process uses familiar sequencing batch reactor technology for simultaneous removal of organic carbon, nitrogen, phosphorus and other pollutants from wastewater. Among the available biological treatment options, GS process is the most preferred choice because of smaller land footprint, lower costs and effective wastewater treatment. Accumulating research shows that the GS technology has gained enormous popularity; it is increasingly considered for capacity extension as well as new wastewater treatment plants in domestic and industrial sectors.

Keywords: Activated sludge, aerobic granulation, sequencing batch reactor, wastewater treatment.

BIOLOGICAL treatment is an integral part of wastewater treatment plants (WWTPs) used for purifying sewage and industrial wastewater. By convention, biological treatment of wastewater is achieved using activated sludge (AS) process which requires large land footprint for bioreactors (aeration tanks) and secondary clarifiers (settling tanks). AS plants become much more complex by way of multiple process units and necessitate recirculation flows when modified for achieving biological nutrient (nitrogen and phosphorus) removal. The AS technology is a century-old biological process which is widely used in WWTPs across the world[1]. In this process, microbial growth is maintained in the form of flocculent activated sludge for wastewater treatment. AS is a mixed microbial community feeding on the biodegradable substrates present in the wastewater. Due to loose microbial structure and poor settling properties of AS, secondary clarifiers are essential for separating the sludge and treated wastewater. Moreover, partition in the aeration tank or introduction of additional tanks is required for maintaining anaerobic, anoxic and aerobic conditions if biological nutrient removal is envisaged[2]. Thus, major drawbacks of conventional AS technology are requirement of large land footprint, associated capital costs, complex process design and energy for recirculation of biomass and wastewater[3]. Requirement of large land footprint is mainly due to the use of flat bioreactors for treatment and large secondary clarifiers for gravity-based separation of flocculent AS and treated wastewater[4]. To overcome the sludge separation issue, membrane-based technologies (i.e. membrane bioreactors) have been successfully developed but not yet widely implemented because of (i) high capital costs, (ii) high energy costs and (iii) membrane fouling problems[5]. In recent years, it became possible to address the sludge separation issue by engineering the microbial community in the form of a compact and dense aerobic granular sludge (GS), which is becoming a standard for the future of aerobic wastewater treatment.

Since its first observation in sequencing batch reactors[6], GS has attracted enormous interest because of its potential to transform the future of aerobic WWTPs. GS is distinct from AS in terms of compactness, particle size, settling velocities, extracellular polymeric substances (EPS) matrix and microbial community structure[7–9]. This form of sludge allows gravity-based separation of biomass and treated wastewater in the bioreactor itself, contributing to significant reduction in land footprint and costs. During the last two decades, the GS technology has been evaluated in laboratory- and pilot-scale studies[10–12]. Few GS systems are already available at full scale for treating sewage combined with industrial wastewater[13–15]. GS technology is now seen as the most advanced and promising biological method for aerobic WWTPs.

The aim of this study was to present sewage treatment status in India, to provide an overview of different biological treatment systems and GS technology for advanced wastewater treatment. The GS technology was

*For correspondence. (e-mail: yvn@igcar.gov.in)

compared with the widely applied AS process and other compact biological methods, i.e. moving bed bioreactors (MBBRs) and membrane bioreactors (MBRs). Biological treatment methods have been described and compared in terms of treatment efficiency, land footprint and costs for facilitating the users and policy makers to exercise suitable option while planning WWTPs.

Sewage treatment status in India

About 70–80% of water supplied for domestic use enters the sewers after use as sewage. While turning the water into sewage, a multitude of organic and inorganic pollutants in both particulate and soluble form are introduced. Table 1 provides an overview of pollutants present in the sewage. It is evident that the pollutants are lower than 2% (%w/w) and the rest is water in the sewage. However, suitable treatment of sewage is necessary to remove pollutants, avoid pollution of natural water, provide sanitation, recover water and nutrients. According to the Constitution of India, the subject of sewage treatment falls under the purview of the State List as part of public health and sanitation[16]. It is widely acknowledged that the discharge of untreated or improperly treated wastewater (i.e. sewage, industrial effluents) is the major cause for pollution of surface and ground water resources[16].

Figure 1 shows sewage generation and treatment capacities of different states in India[17]. According to the Census of India, 2011, about 377,105,760 people live in urban areas (class I and class II cities), accounting for 31.16% of the total population of the country. Total sewage generation in class I and class II cities was estimated to be 75,020 million litres per day (MLD) in 2017. However, the available sewage treatment plants (STPs) can process only 26,066.31 MLD as of July 2018. About 83% of the existing plants are only operational for treating sewage (source: report on 'Sewage treatment market in India 2018'). This indicates that about 71.2% (about 53,385 MLD) of sewage generated in the urban cities of India does not receive any kind of treatment (Figure 2). This large gap between sewage generation and treatment capacity is the main reason for pollution of water bodies. In fact, the Central Pollution Control Board (CPCB) has urged for increasing sewage treatment capacity to improve the water quality of rivers and lakes. Recent governmental programmes, like Swachh Bharat Abhiyan, Namami Gange, etc. have made significant headway to augment sewage networks and treatment capacity in urban areas for improving the health of water resources. The current sewage treatment scenario in India offers enormous scope for business opportunities. There is a need for developing compact, effective and affordable technologies for increasing the treatment capacity closer to the sewage production levels.

Existing STPs are equipped with different biological treatment technologies such as oxidation ponds, AS process, sequencing batch reactors, biofilm reactors or membrane bioreactors. By and large, the conventional AS process is the most widely applied treatment system in India covering up to more than 50% of the total installed capacity. However, the current state of knowledge shows that the AS process is no longer considered sustainable, from an economic and environmental perspective. Due to lower land footprint and costs, sequencing batch reactor technology is increasingly considered for newer plants, especially in urban India.

Table 1. Overview of pollutants present in sewage collected from sewage treatment plant, Kalpakkam

Parameter	Value*
COD (mg/l)	112–425
BOD (mg/l)	90–226
Ammonia-N (mg/l)	9.0–24
Nitrate-N (mg/l)	0.3–0.8
Nitrite-N (mg/l)	0.3–1.0
Phosphorus-P (mg/l)	1.6–6.5
Total suspended solids (mg/l)	520–1100
Total CFUs (per 100 ml)	$3.4–4.0 \times 10^9$
Total coliforms (CFUs /100 ml)	$3.1–3.6 \times 10^8$
Faecal coliforms (CFUs/100 ml)	$1.6 \times 10^6–2.4 \times 10^7$

*Data represent measurements made during 2015–2018. COD, Chemical oxygen demand; BOD, biochemical oxygen demand; CFU, colony forming units.

Microbial communities: bioflocs, biofilms and granules

Environmental engineers and scientists have recently celebrated the centenary year (2014) of AS. In 1914, Ardern and Lockett described AS which was later adopted worldwide for aerobic wastewater treatment. Suspended biomass generated during the aeration phase was separated out from the treated wastewater and recycled for treating another batch of wastewater. The sludge that was generated and settled out at the end of the aeration phase was termed 'activated'. It is essentially a microbial community which separates out from treated wastewater by flocculation under quiescent conditions. AS flocs are irregularly shaped and not more than 100 μm in size. They are characterized by loose microbial structure and often dominated by filamentous microbes[18]. In addition to functional capabilities (contaminant removal), settling properties of biomass is a key parameter in biological wastewater treatment. The settling properties are quantified in terms of sludge volume index (SVI), which is defined as the volume (ml) occupied by 1 g of sludge after 30 min settling period. The SVI_{30} of AS is usually higher at 100 ml/g. It is not feasible to maintain high biomass concentrations (>4 g/l) in conventional AS plants while

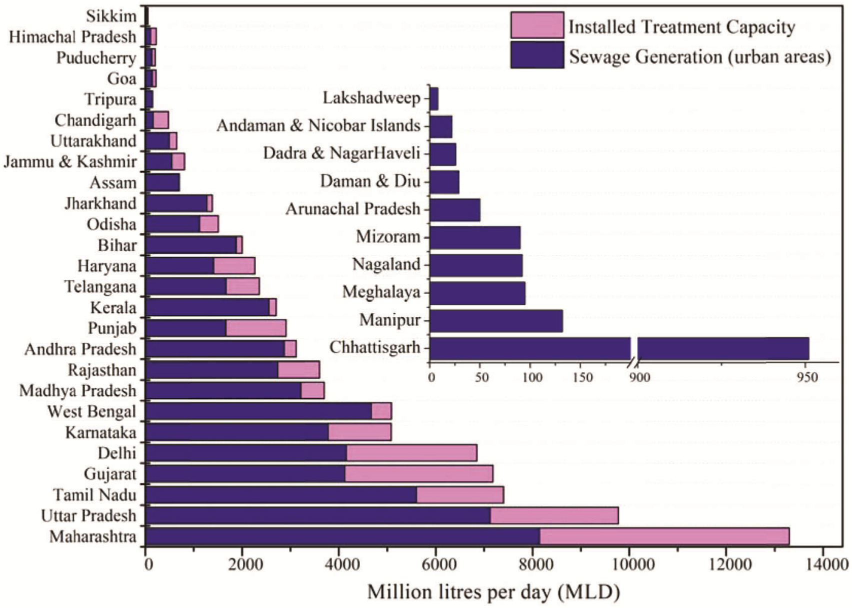

Figure 1. State-wise distribution of sewage generation and treatment capacity in India (data sourced from ref. 17).

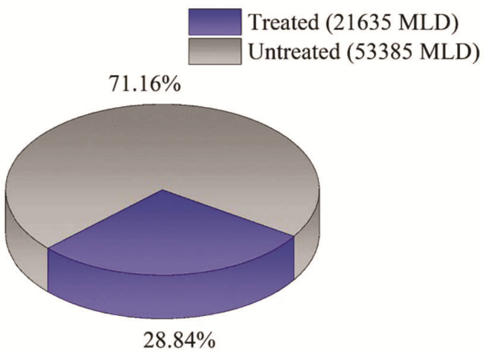

Figure 2. Sewage generation and treatment capacity in class I and class II cities.

treating low-strength wastewater like sewage. This is due to loose microbial structure and lower settling velocities of AS. Unlike conventional AS plants, membrane bioreactors and sequencing batch reactors allow increasing the concentration of AS in the bioreactor tanks.

Biofilms are microbial communities enmeshed in a self-produced extracellular biomolecular matrix comprising carbohydrates, proteins and extracellular DNA[19]. Biofilm growth is a natural living style for numerous microorganisms in diverse environments. Microorganisms in biofilm growth mode are useful for biodegradation of diverse pollutants and bioremediation[20]. These beneficial biofilms can be developed either on a solid static surface or on suspended carriers for wastewater treatment. Biofilm growth is an effective means for biomass retention and for increasing volumetric conversion capacities while treating diluted waste streams[21]. Therefore, biofilm reactors are suitable for retaining slow-growing microorganisms (e.g. nitrifiers), maintaining high biomass concentration and treating diluted waste streams such as sewage and some industrial effluent[22]. Trickling filters, rotating biological contactors, biological aerated filters and constructed wetlands are some of the conventional biofilm processes for wastewater treatment. MBBRs and membrane aerated biofilm reactors are new biofilm technologies for wastewater treatment[23]. Though biofilms simplify separation of biomass from the treated wastewater, removal of detached biomass is required for minimizing suspended solids in the treated wastewater prior to discharge.

Granules are physically distinct, macroscale biomass particles with definite shape and separate out from the water column by sedimentation under quiescent conditions (Figure 3). Granules are characterized by enhanced settling properties with lower SVI values (often below 50 ml/g) and higher settling velocities. As the granules quickly sink in the water column, SVI_{30} has been revised to SVI_5 (SVI after 5 min settling) for GS systems. The SVI_5 of granules is almost similar to SVI_{30}, while SVI_5 is much larger than SVI_{30} for bioflocs. Figure 4 shows a comparison of AS and GS. Superior settling velocities and compact microbial structure of granules make it possible to integrate separation of biomass and treated wastewater in the treatment tank itself. Due to lower SVI values and effective biomass retention, it is possible to achieve two to four-fold higher biomass concentration in GS process compared to AS process.

Biological treatment options

The components of WWTPs can be grouped under primary, secondary and tertiary treatment systems. Physical and

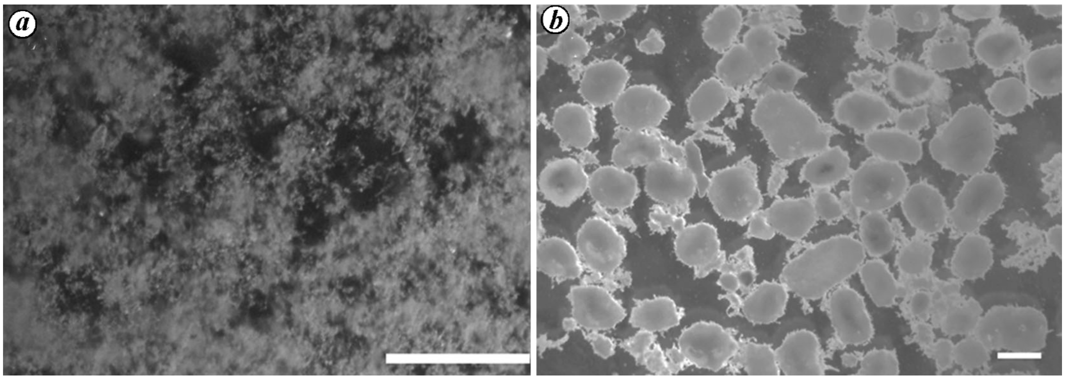

Figure 3. Morphology of (***a***) activated sludge and (***b***) aerobic granlar sludge. Scale bar: 1 mm.

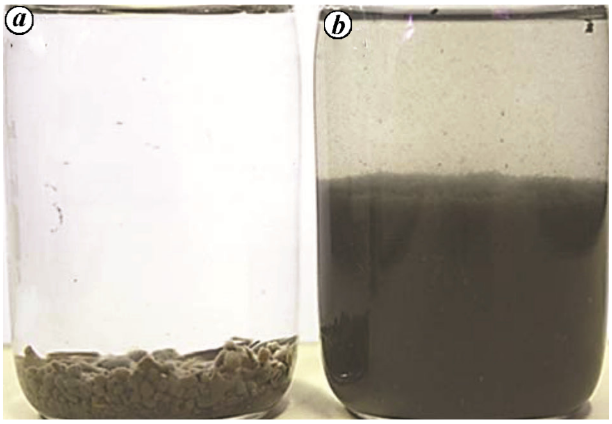

Figure 4. Comparison of volume occupied by equal amounts of (***a***) granular sludge and (***b***) activated sludge after settling.

chemical methods are used in the primary and tertiary treatment systems[24,25]. Whereas biological processes are used in the secondary treatment, which plays a key role in removing most of the pollutants, such as organic carbon, reactive nitrogen (ammonium, nitrate and nitrite), phosphorus and other pollutants from wastewater[8,25]. Several factors such as land footprint, cost, treatment efficacy, knowhow availability and process reliability are considered while selecting the appropriate treatment technology (Table 2).

Biological treatment of wastewater involves two important tasks: (i) removal of contaminants from wastewater, and (ii) separation of microbial biomass and treated wastewater. Originally, the AS process was designed only for lowering organic matter (biochemical oxygen demand) by heterotrophic microorganisms. Later, it was modified for removing nitrogen (N) and phosphorus (P) from the wastewater. Integration of biological N and P removal necessitates introduction of multiple process units and recirculation flows (Figure 5). This is because biological removal of N and P requires different redox conditions such as aerobic, anoxic and anaerobic conditions[25]. Due to smaller size and loose microbial structure, it may not be possible to maintain different redox microenvironments in AS under aerated condition. Therefore, different redox conditions are maintained through multiple process units. After biological treatment, AS is separated from the treated wastewater by means of flocculation, which requires a dedicated clarifier tank. Thus, AS plants require large land footprint and associated capital costs for wastewater treatment. Aeration and recirculation of biomass and water between bioreactor tanks consume considerable amount of energy[26]. Therefore, reliance on AS-based WWTPs is considered economically and environmentally unsustainable[27].

Other popular technologies such as MBBRs, MBRs and sequencing batch reactors (SBRs) have been developed for designing compact WWTPs[28]. In the case of MBBR, microbial growth is mainly in the form of biofilms on moving carriers. Due to continuous treatment process, secondary clarifier is used for separating coexisting AS and detached biofilm–biomass from the treated sewage respectively, in AS and MBBR-based WWTPs. In MBR, membrane is used for separating AS and treated wastewater. Therefore, secondary clarifier is not needed for MBR-based WWTPs[28]. Unlike other technologies, SBR is a batch process but continuity in treatment is achieved by employing parallel tanks. In SBR, both treatment of wastewater and separation of AS from the treated wastewater (by flocculation) are achieved in the single tank. Thus, both MBR and SBR-based WWTPs require lower land footprint and are promising for use in cities.

GS technology for aerobic wastewater treatment

GS is a distinct form of microbial biomass and is characterized by compact microstructure and lower SVI values[8,9,29,30]. It mainly comprises of compact macroscale biomass particles which can quickly sink from the wastewater to the bottom of the tank by sedimentation under quiescent conditions[31,32]. Operation of bioreactor in SBR mode is most suited for GS formation and its stability. Formation of GS in aerobic SBR was first reported in 1997 from The Netherlands[6]. Since then, GS has

Table 2. Important factors for the selection of treatment technologies

Parameter	Goal
Land footprint	Minimum land requirement
Capital costs	Minimum and optimum utilization
Operating costs	Lower energy requirement
Operation and maintenance	Simple, flexible, minimal complexity and lower expenditure
Quality of treated sewage	Treated wastewater should conform to discharge limits
Reliability	Long-term stability and sustainable treatment
Fluctuating loads in sewage	Process should withstand fluctuations in organic and hydraulic loading rates
Toxic chemicals/metals	Process should tolerate toxic pollutants

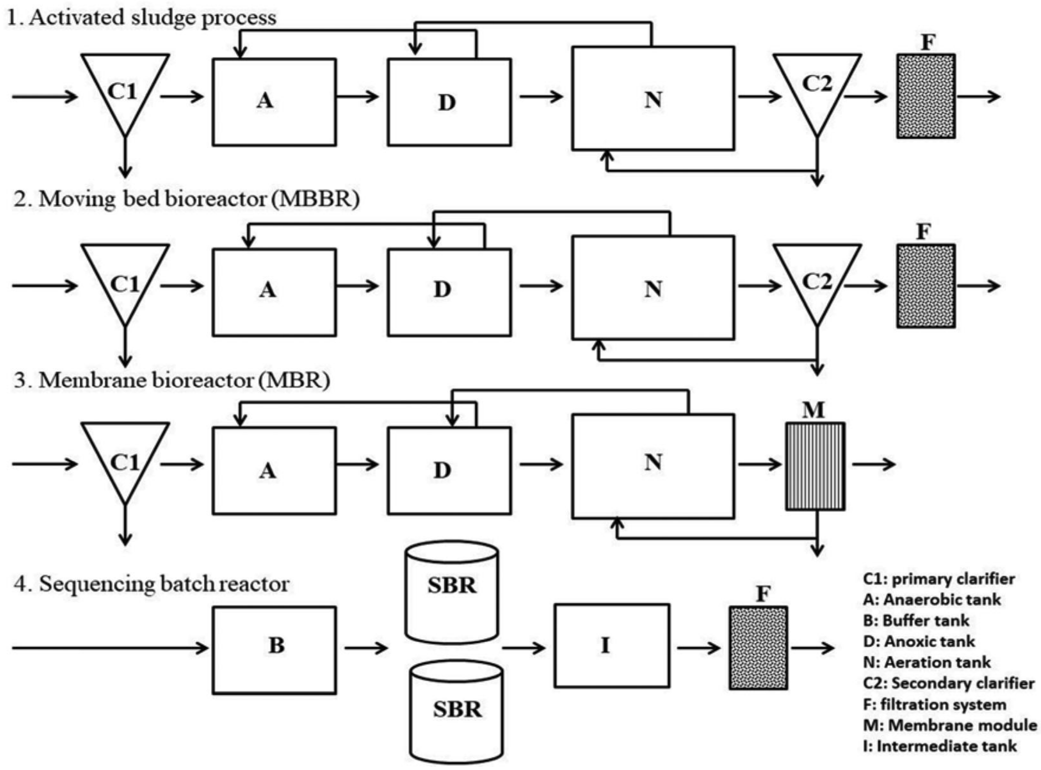

Figure 5. Comparison of different biological treatment processes.

attracted research attention (Figure 6) for its promising technological applications in domestic and industrial wastewater treatment[9].

Research has shown that GS performs better than AS (Table 3) in removing contaminants from the wastewater[33]. GS has been demonstrated to degrade a variety of toxic and recalcitrant organic compounds such as azo dyes, phenols, metal chelating agents, organophosphorus compounds, nitroaromatic compounds, anilines and pharmaceuticals in laboratory-scale bioreactors[34–38]. Formation of GS and wastewater treatment were also demonstrated in aerobic pilot-scale bioreactors[39–41]. A full-scale GS plant has been set-up in The Netherlands for treating mixed wastewater comprising 65% sewage and 35% industrial (slaughter house) wastewater[13]. Another full-scale plant has been set-up in China for treating mixed wastewater with 30% sewage and 70% industrial wastewater from printing and dyeing, chemical, textile and beverage industries[14]. Studies on full-scale GS plants reported long start-up periods of up to 10 months for achieving reasonable granulation (80% of biomass in the form of granules). It is to be noted that these full-scale plants were used for treating wastewater consisting of significant proportion (30–70%) of industrial effluents. It appears that long start-up periods are required for GS formation, and for establishing nitrogen and phosphorus removal when this technology is considered for sewage treatment.

Several strategies have been proposed for the development of GS as well as to minimize start-up period under real sewage conditions. Mixing of industrial wastewater with sewage[40,42], or addition of acetate to

Table 3. Comparison of characteristics between activated sludge and granular sludge

Characteristics	Activated sludge	Granular sludge
Particle size (mm)	<0.1	>0.1
Microstructure	Loose and flocculent	Dense and compact
Settling velocities (m h^{-1})	~10	~90
SVI (ml/g)	Above 100	Often below 50
SVI	Very different at 5 and 30 min	Similar at 5 and 30 min
Microenvironments	Not possible to have distinct redox conditions within a floc	Aerobic, anoxic and anaerobic regions within a single granule is possible

SVI, Sludge volume index.

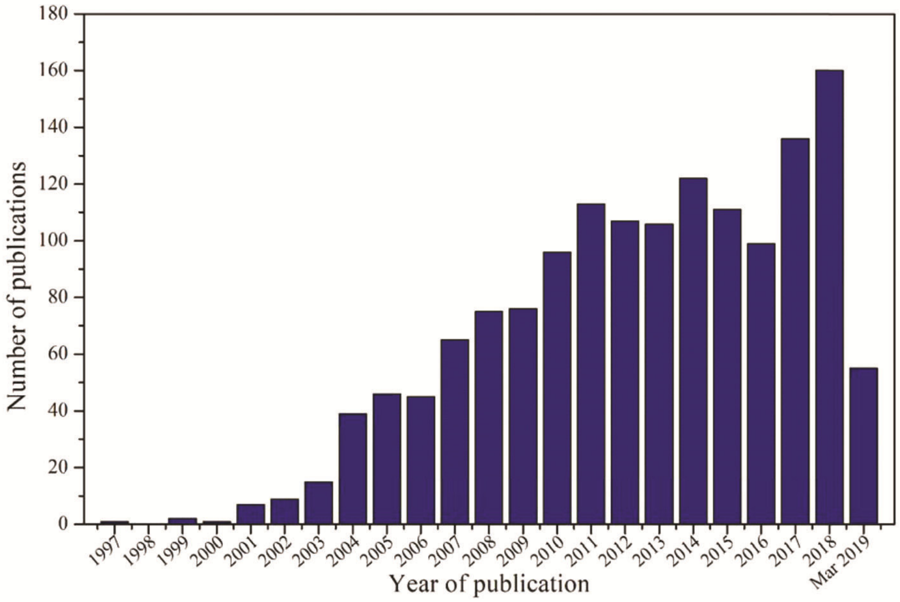

Figure 6. Year-wise distribution of publications on aerobic granular sludge for wastewater treatment (Scopus-indexed publications with keywords 'aerobic granules', 'aerobic granular sludge', 'aerobic granular biomass', 'aerobic granular microbes', or 'aerobic microbial granules' as on March 2019 are included).

sewage[43,44] was reported. Addition of particles of granular activated carbon has been reported for the rapid development of GS[45–47]. Addition of zeolite and magnetite (Fe_3O_4) powder was shown to promote granule formation from AS[48,49]. However, all these studies have been carried out using synthetic effluent with either glucose or acetate as the carbon source. Therefore, neither these substrates nor their concentrations are representative of real sewage. Though these studies are useful for getting an insight into the granulation process, the results cannot be directly extrapolated to granulation under treatment of real sewage. Thus, it is desirable to develop newer strategies for cultivating functional GS under real sewage conditions.

Comparison of treatment efficiency, land footprint and costs

Bioreactor operating condition, such as anaerobic feeding coupled to short settling period prior to decanting are imposed for forming GS from bioflocs[8,32,50]. These operating conditions allow selection of slow-growing microbes such as nitrifiers, polyphosphate accumulating-organisms and glycogen-accumulating organisms in the form of compact and dense granules[32,47]. Settling velocities of granules are much higher than that of bioflocs, and are responsible for enhanced biomass retention in the bioreactor. Both granular structure and increased biomass levels are responsible for achieving higher biological nutrient (N and P) removals in GS plants. Due to large particle size (about 0.2 mm and higher) and compact microstructure, it is possible to maintain aerobic, anoxic and anaerobic microenvironments within an individual granule even during aeration phase[51,52]. Maintenance of different redox conditions in granules facilitates occurrence of oxidation and reduction reactions simultaneously and contributes to simultaneous C, N, and P removal from wastewater[26–43]. Biomass concentration of 10 g/l and higher is feasible in GS plants due to effective biomass retention[13,30,42,43]. Therefore, biomass concentrations are much higher in GS plants compared to conventional

AS plants. Higher biomass concentrations can achieve effective and rapid removal of contaminants and improve volumetric conversion capacities.

GS is capable of performing all biological reactions for effective removal of organic carbon, nitrogen and phosphorus from wastewater in a single bioreactor tank. In addition, separation of GS and treated wastewater is carried out in the same bioreactor tank. The characteristics of GS make sure that no secondary clarifiers, and separate anoxic and aerobic compartments are required. Thus, land footprint of the GS process is significantly reduced compared to the conventional AS process. A reduction of up to 75% in the land footprint has been estimated[13,53]. Recently, Bengtsson *et al.*[3] also reported that the GS process requires 40% to 50% smaller footprint compared to the conventional AS process. Due to enhanced settling properties of GS, bioreactors can be operated at 10 g/l and higher biomass concentration. This can significantly increase the treatment capacity of the plant. Therefore, the GS process requires smaller footprint (20–30%) as against conventional SBR based on AS. The footprint of the GS system is comparable to that of MBR, the other compact treatment option. Due to effective retention, MBRs can also achieve high biomass concentration and offer efficient treatment. Though MBRs are compact and give better effluent quality, they require costly membrane and face membrane-fouling problems[54].

Due to single reactor tank design, the number of tanks and mechanical equipment required for the GS process is much less compared to the AS process. Secondary clarifier tanks, biomass and effluent recirculation systems of the AS process are not required for the GS process. Moving decanters normally used for withdrawing the treated wastewater in conventional SBRs are not essential for the GS systems. Nereda®[53] uses simultaneous filling–drawing for decanting the treated wastewater from full-scale GS bioreactors[13]. Due to plug-flow pattern, decanting of treated wastewater with minimum suspended solids has been reported. High biomass concentration of the GS system may contribute to substantial reduction in bioreactor volume. All these aspects are directly factored in lowering the capital expenditure (CapEx) of the GS process-based WWTPs. Operation and maintenance expenditure (OpEx) of these WWTPs are expected to be lower due to (i) reduction in equipment, (ii) lower energy for aeration, and (iii) no movement of biomass and effluent between the treatment tanks. Lower sludge production and sludge management practices are the additional aspects contributing to lower energy requirement of the GS plants. Recent estimates suggest up to 30% lower energy consumption for the GS process compared to other AS technologies, when similar depth tanks are used for the bioreactors[3]. Lower energy costs of the GS process are because of no return sludge pumping and recirculation of wastewater for nitrogen removal. The energy demand for aeration in the GS and AS systems appears to be different. Pronk *et al.*[13] reported a lower energy consumption of up to 48% in full-scale GS process than AS process. Energy savings were partly due to lower electricity demand for aeration because of deeper water treatment tanks in the GS process leading to more efficient oxygen transfer. But, the energy for aeration becomes comparable between the GS and AS processes if treatment tanks of similar depth are used[3].

MBR-based WWTPs are proven to be energy intensive mainly because of two reasons: (i) they require high rate of sludge return pumping, and (ii) high aeration rate at the membranes to minimizing fouling. The energy demand for an MBR is roughly 50–70% higher than that of the GS process[3].

GS technology in India

The GS technology is being successfully implemented at full scale and currently promoted as Nereda®[53] wastewater treatment technology. A full-scale GS plant has been set-up in The Netherlands for treating mixed sewage stream containing significant fraction (35%) of slaughter-house wastewater[13]. Though it is increasingly considered for treating sewage, the full-scale GS systems have been mainly applied for treating mixed sewage. Even while treating sewage mixed with significant proportion of industrial wastewater, long-term operation of plants has been reported for achieving granulation and establishing nutrient (N and P) removal. In spite of issues with respect to granulation and stability, the GS process is a promising method due to advantages like lower land footprint, lower costs, effective nutrient removal and lower sludge production compared to AS-based systems (Table 4). As of now, there are no full-scale GS plants treating either sewage or industrial wastewater in India.

GS research has gained popularity among the scientific community across the world (Figure 6) for developing sustainable technologies for aerobic treatment of industrial and domestic wastewater[9]. Formation of GS was studied in laboratory-scale bioreactors for biological removal of various organic and inorganic pollutants of interest to nuclear fuel cycle operations[18,35,36]. Research showed that stable GS can be developed for biological removal of various organic (i.e. tributyl phosphate, *n*-butanol, dibutyl hydrogen phosphate, 2,4-dinitrotoluene, nitrilotriacetic acid, *p*-nitrophenol, textile dye and acetonitrile) and inorganic (i.e. ammonia, nitrate and phosphorus) contaminants[18,34–36,55,56]. Research shows that GS is a better choice for removing recalcitrant or toxic pollutants from wastewater arising from industrial processes, including nuclear fuel cycle operations. GS is becoming a future standard for developing effective bioremediation and wastewater treatment solutions.

Various types of industrial wastewater (i.e. textile, dairy, pharmaceutical, hospital and effluents of nuclear

Table 4. Capabilities and advantages of granular sludge technology

Functional capabilities
Simultaneous COD, N and P removal from wastewater
Simple operational strategy for N and P removal
Pollutant removal via both biological oxidation and reduction reactions
Phosphorus removal via enhanced biological phosphorus removal
High biomass retention for faster treatment
Tolerant to toxic contaminants, shock loadings and environmental perturbations
No sludge bulking issues
Advantages
Compact and fast-settling biomass allowing smaller bioreactor volume
No secondary clarifiers
Smaller land footprint for the plant and savings on capital costs
Lower sludge production and easy sludge dewatering
Lower energy costs due to minimal recirculation flows

fuel fabrication) were treated using GS in laboratory-scale bioreactors to demonstrate the utility of the technology[28,32,50]. To demonstrate its utility in sewage treatment, pilot-scale plants have been set-up for treating real sewage under tropical climate conditions (https://www.ndtv.com/india-news/nuclear-engineers-fighting-water-pollution-with-sewage-treatment-plant-1768223). Pilot-scale studies demonstrated that the GS technology is suitable for aerobic biological treatment of sewage under tropical climate conditions. Alternative new strategies are being developed to reduce the start-up period for granulation and establishing nutrient (N and P) removal while treating sewage and saline wastewater. The mechanisms by which microbes form aggregates and granules in water are not yet understood. It is our endeavour to underpin the mechanisms behind granulation and to develop innovative biotechnological processes for sustainable wastewater treatment.

Future directions

The GS technology has proven to be a suitable option for aerobic biological treatment of sewage and a variety of industrial effluents. Nevertheless, most of the GS research has been carried out in laboratory-scale sequencing batch reactors using synthetic wastewater with defined substrates and well-controlled operating conditions, which are not true representatives of real sewage and prevailing environmental conditions. Accumulated evidence indicates that the formation of GS is feasible in moderate to high-strength industrial wastewater. Challenges exist in cultivating GS from activated sludge, especially while treating real sewage which is low strength in terms of biodegradable organic carbon. Previous studies in pilot- and full-scale systems reported several issues while treating real sewage: (i) very long start-up periods of 10 and 13 months for achieving ≥85% granulation[10,14], and (ii) smaller sized granules (0.2–1.3 mm) which may limit simultaneous nitrification and denitrification. Therefore, this necessitates development of newer strategies for improving granulation under sewage conditions. Further research is necessary for understanding granulation mechanisms, developing GS cultivation strategies, and sustainable excess sludge management practices for fully exploiting granular sludge technology.

Currently, SBR technology is considered for STPs in urban India. However, these plants still rely on AS for wastewater treatment. With certain modifications in layout and operation, these AS SBRs can be converted to GS systems. Since GS is superior to AS in removing contaminants and tolerating fluctuations in influent and environmental conditions, it is promising for both capacity extensions and new STPs.

Conclusion

The conventional AS process is no more considered sustainable for wastewater treatment due to large land footprint, higher costs and complex process designs for achieving nutrient (nitrogen and phosphorous) removal biologically. GS is emerging as a new standard for sustainable biological wastewater treatment and for meeting stringent effluent discharge limits. GS is distinct from that of AS in terms of large particle size, compact microstructure, retaining slow-growing functional microbes, biopolymer composition, high settling velocities and lower sludge volume index values. The GS process is advantageous over the AS process in effective removal of contaminants, tolerability to changes in influent/environmental perturbations and lower sludge production. Accumulating evidence indicates that the GS process is suitable for treating sewage and several industrial effluent. Currently, the GS process is the most favourable biological treatment option considering advanced wastewater treatment coupled with lower land footprint and costs. The GS technology could be the better choice for both new treatment plants and capacity extension of existing wastewater treatment plants in the coming years, to decrease the gap between sewage generation and treatment capacity in India.

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