अपशिष्ट जल उपचार

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संधारणीय अपशिष्ट जल उपचार हेतु संकर कणिक अनुक्रमण बैच रिएक्टर (एचजीएसबीआर)

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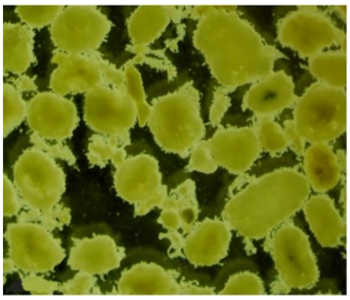

बायोग्रैन्यूल की डिजिटल तस्वीर

सारांश

घरेलू एवं औद्योगिक अपशिष्ट जल से दूषित पदार्थों को प्रभावी ढंग से हटाने के लिए hgSBR एक सघन जैविक उपचार प्रणाली है। यह प्रत्येक बैच के साथ फीड-बैच मोड में प्रचालित की जाती है जिसमें भरण, वातन, नि:सादन एवं क्षय चरण शामिल होते हैं। प्रक्रम स्थिति जैव-मणिका (बायोफिल्म और कणिका) के रूप में अपशिष्ट जल-सूक्ष्मजीव से समुच्चय और कार्यात्मक रोगाणुओं का चयन एवं संवर्धन करती है जो सीओडी, बीओडी, अमोनियम, फॉस्फेट, ठोस और मल कोलीफॉर्म को स्वीकार्य स्तर तक कम कर देते हैं जिससे उपचारित अपशिष्ट जल का सुरक्षित विसर्जन या पुनः उपयोग होता है। कल्पाक्कम टाउनशिप में घरेलू अपशिष्ट जल के उपचार के लिए पूर्ण क्षमता का प्रदर्शन संयंत्र 150 m^3/day और 1500 m^3/day (~ 3200 घर) उपचार क्षमता पर काम कर रहे हैं। इस प्रौद्योगिकी को पूरे भारत में लगभग 28 परियोजनाओं में परिनियोजित किया गया है, जिसमें आवासीय परिसर, विद्यालय, सेना शिविर और प्रयागराज में महाकुंभ 2025 शामिल हैं। प्रगत जैविक उपचार एवं पर्यावरणीय स्थिरता (निम्न भूमि पदचिह्न और लागत) को ध्यान में रखते हुए, देश में अपशिष्ट जल के बुनियादी ढांचे में सुधार के लिए अन्य मुख्य अपशिष्ट जल उपचार प्रौद्योगिकियों की तुलना में जैविक कणों पर आधारित hgSBR लाभकारी हैं।

Wastewater Treatment

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Hybrid Granular Sequencing Batch Reactor (hgSBR) for Sustainable Wastewater Treatment

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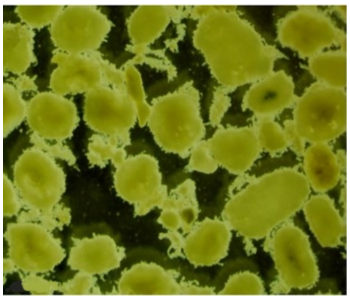

Digital photograph of biogranules

ABSTRACT

The hgSBR is a compact biological treatment system for effectively removing contaminants from domestic and industrial wastewaters. It is operated in fed-batch mode with each batch comprising of fill, aeration, settling and decant phases. The process conditions select and enrich aggregating and functional microbes from wastewater-microbiome in the form of bio-beads (biofilms and granules) which decrease COD, BOD, ammonium, phosphate, solids and faecal coliforms to acceptable levels making safe discharge or reuse of treated wastewater. Full-scale demonstration plants are in operation at 150 m^3/day and 1500 m^3/day (~3200 households) treatment capacities for treating domestic wastewater in Kalpakkam Township. The technology has been deployed in about 28 projects across India including residential complexes, schools, army camps, and Maha Kumbh 2025 at Prayagraj. In view of advanced biological treatment and environmental sustainability (lower land footprint and costs), the biogranules-based hgSBR is advantageous over the other mainline wastewater treatment technologies for improving wastewater infrastructure in the country.

KEYWORDS: *Aerobic granular sludge, Biofilms, Biogranules, Nutrient removal, SBR, Water reuse.*

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Introduction

Effective wastewater treatment is essential to providing sanitation, safeguarding public health, and protecting environment. Activated sludge process (ASP) adopted in 1914 has been the most widely used biological process in wastewater treatment plants (WWTPs) [1]. However, it is no more attractive because of large land footprint, re-circulation flows, inefficient nutrient removal and sludge-bulking challenges. To address these challenges, various biological treatment technologies including moving bed bioreactor (MBBR), membrane bioreactor (MBR), membrane biofilm reactor (MBfR) and sequencing batch reactor (SBR) have been developed. SBR is a fed-batch process offers fine control on treatment and attractive for both centralised and decentralized wastewater treatment.

Microbial communities such as activated sludge flocs, biofilms or biogranules (granular sludge) achieve biological treatment in WWTPs. Formation of biogranules (referred to aerobic granular sludge (AGS), granular activated sludge (GAS) or aerobic granules in literature) was first reported in 1997 for aerobic wastewater treatment [2]. In the last two decades, biogranules have emerged as a favoured option because of robust biodegradation, resilience to toxic pollutants, excellent settling properties and sustainability in terms of lower land footprint and costs. Combination of SBR with biogranules offers compact treatment with advanced biological treatment in WWTPs.

Biogranules Research at BARC

The biogranules represent microbial aggregates comprising of phylogenetically diverse microorganisms self-immobilized in an extracellular polymeric substances (EPS) matrix, distinct from activated sludge flocs. Initial research had focused on cultivation of biogranules under different process conditions, identifying key bioreactor operation conditions and biodegradation of organic and inorganic contaminants of importance to nuclear fuel cycle operations. Formation of biogranules is a developmental process involves induction of bacterial aggregation, formation of tiny aggregates, retention and growth of aggregates into millimetre sized distinct granules. The bioreactor operating conditions such as slow and static feeding, short settling time, aeration rate etc., were found to be critical for cultivation and stability of granules. This research showed that bacteria-laden granules (Fig. 1a and 1b) can be cultivated for biodegradation of several organic compounds including tributyl phosphate, *n*-butanol, dibutyl hydrogen phosphate, nitrilotriacetic acid, 2,4-dinitrotoluene, *p*-nitrophenol, textile dye and acetonitrile [3-7]. Biogranules also removed inorganic pollutants such as ammonium, nitrate, phosphorus, heavy metals and metal oxyanions [9-11]. This work showed that biogranules are suitable for biodegradation or biotransformation of recalcitrant as well as toxic pollutants relevant to industrial processes including nuclear fuel cycle operations.

For larger societal benefit, studies on biogranules-based treatment of domestic wastewater was pursued from 2016 onwards. To address cultivation of biogranules under low-strength domestic wastewater, de novo cultivation of biogranules directly from water or wastewater-borne microbiome with and without carrier material (granular activated carbon) was developed [12-15]. This approach enabled rapid cultivation of biogranules from autochthonous bacteria of sewage and seawater for achieving simultaneous removal of organic carbon, ammonium and phosphate under normal and saline conditions. De novo granulation utilizes the indigenous bacteria that are already thriving in the wastewater or contaminated environment, minimized the time needed for enrichment. Moreover, use of granular activated carbon particles as carrier facilitated enrichment of functional microbes, i.e., ammonium oxidizing bacteria (AOB) and polyphosphate accumulating organisms (PAOs). This is advantageous for establishing partial nitrification-denitrification (PND) and enhanced biological phosphorus removal (EBPR) pathways for removing ammonium and phosphate, respectively. An Indian patent was granted in 2021 for this invention on de novo granulation for bio-beads development and wastewater treatment [16].

Biogranules-based sewage treatment was further evaluated under different conditions including (i) lower temperatures [17], (ii) toxic heavy metals and metal oxyanions, and (iii) antibiotics [18]. These studies suggested resilience and robustness of biogranules to perform biological nutrient removal under varied temperatures (15 to 30^{o}C), in the presence of heavy metals ((Zn(II), Cu(II)), metal oxyanions (chromium, selenite) and antibiotics (oxytetracycline, ciprofloxacin). The data confirmed occurrence of nitrification, denitrification and enhanced bio-P removal pathways in granular bioreactors operated at different temperatures ranging from 15 to 30^{o}C [17] and also in the presence of lower concentrations of toxic emerging contaminants.

hgSBR process development

Initial field-scale tests were carried out in 10 to 100 L

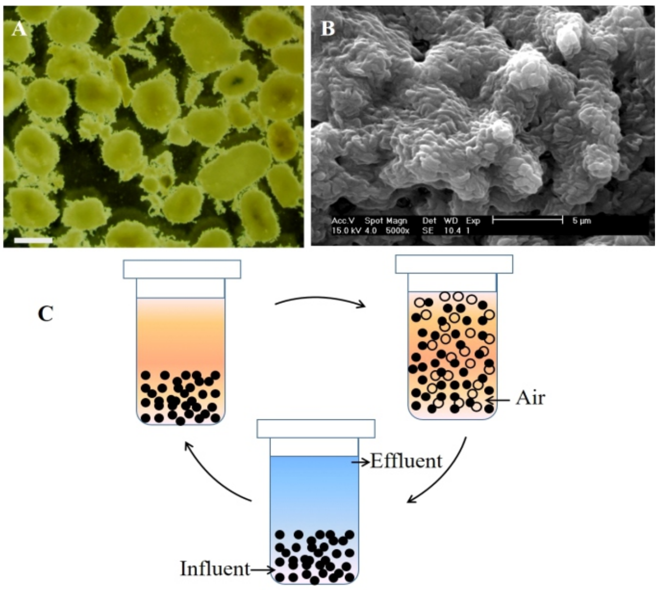
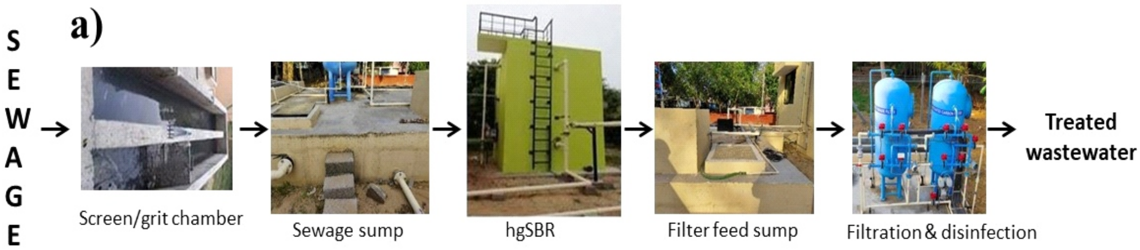
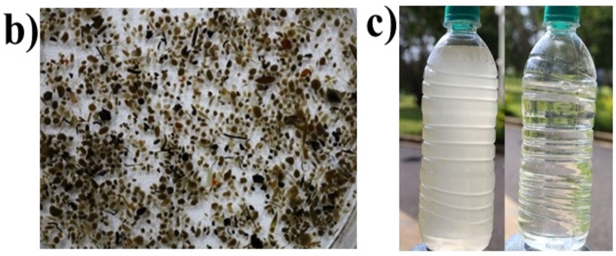


Fig.1: A) Digital photograph of biogranules, scale bar = 1 mm. B) SEM image of a biogranule. C) hgSBR cycle used for cultivating biogranules.





d)

Parameter	Sewage	Treated wastewater
COD (mg/l)	400 – 600	<20
BOD (mg/l)	150 – 250	<10
Total Nitrogen (mg/l)	13 – 30	<10
Total Phosphorus (mg/l)	4 – 6	<1
Faecal Coliforms (/100 mL)	10^6	<200
pH	7 – 8	7.5 – 8.5

Fig.2: a) Typical process flow of a biogranules-based sewage treatment plant. b) Biogranules (0.2 – 0.5 mm) formed during sewage treatment. c) Sewage before and after treatment using 4 h batch. d) Water quality before and after biological treatment.

volume bioreactors for treating real domestic wastewater. Subsequently, pilot-scale studies were performed in 2 m^3 volume bioreactors with 16.8 m^3/day treatment capacity for evaluating sustained sewage treatment. These studies demonstrated formation of biogranules, enrichment of functional microbes, establishment of nutrient removal pathways and efficient treatment of real domestic wastewater under tropical climate [19,20].

For achieving biological treatment, hgSBR is operated intermittently in fill and draw mode with each batch (cycle) of treatment comprising of filling (static), mixing (aeration), settle and/or decant, and idle phases (Fig.1c). The biological conversions (COD/BOD removal, nitrification, denitrification, phosphate accumulation etc.) are partitioned between the anaerobic and aerobic phases applied during each cycle. The length of cycle and individual phases in each cycle can be adjusted based on influent characteristics and treated effluent quality requirements. Appropriate sizing of tanks and hydraulic flows can be adjusted based on the treatment capacity since hgSBR process is suitable for small, medium and large scale wastewater treatment plants.

Fig.3: Photographs of some hgSBR-STPs. A) 1500 m^3/day plant at Kalpakkam township. B) 500 m^3/day plant used during Maha Kumbh 2025 at Prayagraj. C) 150 m^3/day plant at Surat. D) 400 m^3/day plant at Sangmaner.

hgSBR technology deployment

The knowhow of hgSBR technology was made available to private companies from 2020 onwards [21]. To demonstrate the patented process at reasonable scale and facilitate its commercialisation, two full-scale demonstration plants with treatment capacities of 150 m^3/day and 1500 m^3/day were installed for treating real sewage at Kalpakkam Township. Fig.2 shows typical process flow (Fig. 2a) of hgSBR-STP, morphology of biogranules (Fig. 2b) and sewage treatment performance (Fig. 2c and 2d). In fact, these full scale hgSBR-STPs have contributed to augmenting sewage treatment infrastructure of the township and facilitated technology demonstration to practitioners, and companies involved in developing and providing wastewater treatment infrastructure.

Because of advantages like lesser footprint, reliable and effective treatment, several private companies have entered into technology transfer agreement with BARC for technology commercialization. Presently, it is implemented in over 28 wastewater projects at different places across India majorly for treating domestic wastewater (Fig. 3). Notably, BARC's hgSBR was chosen as the sole technology by Uttar Pradesh (UP) Jal Nigam for providing sanitation during Maha Kumbh 2025 at Prayagraj. As part of this endeavour, 3 numbers of hgSBR-based Sewage Treatment Plants (STPs) each with 500 m^3/day treatment capacity were installed at Sector 10, 13 and 16 in Maha Kumbh Mela area, Prayagraj and used for treating the sewage (black water) collected by the trucks from temporary toilets. The biologically treated wastewater was subjected to ozone treatment and released into a discharge canal. Presently, this technology has been deployed in residential townships, schools, and army camps for providing treating domestic wastewater or mixed wastewater for safe environmental discharge or reuse of treated wastewater in non-potable applications.

Comparison with other technologies

Side-by-side comparison of biogranules-based process with conventional activated sludge process revealed up to 40–70% reduction in land footprint [22-24]. However, the land footprint reduction in biogranules-based process in comparison to activated sludge-SBR is mainly due to a reduction in the volume of the treatment tank is also significant and up 20 - 30% lower [23]. The land footprint of biogranules-based system is comparable to that of MBR, which is not attractive due to high installation and operational costs because of use of membrane and its biofouling [23,24].

Conclusions

The biogranules research has provided accumulating evidence on reliable formation of biogranules under different process conditions and technological applications for sustainable treatment of domestic and industrial wastewater. The dual combination of bio-beads and SBR operation permits achieving effective biological ammoniacal-nitrogen and phosphate removal essential for avoiding eutrophication in the receiving water bodies. The technology is futuristic for providing new generation wastewater treatment with advantages including lower land footprint, lower energy costs, efficient biological nitrogen and phosphate removals and lesser sludge generation. However, further research addressing granulation mechanisms, identifying key structural biopolymers and optimum aeration rate may help in further improvement. Presently, biogranules-based treatment is largely applied for treating domestic wastewater. Since biogranules exhibit robust metabolism and resilience compared to activated sludge flocs, it is desirable to evaluate biogranules-based system at across different scales for implementing in effluent treatment plants. The fate of emerging pollutants including antibiotics, pharmaceutical compounds, and metal contaminants in biogranules-based systems need to be evaluated in the coming years.

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