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SHORT RESEARCH AND DISCUSSION ARTICLE

A pilot-scale study of a novel system for simultaneous nitrogen and carbon removal: technological advancement of a structured bed reactor with intermittent aeration (SBRIA) in real domestic sewage treatment

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Abstract
This study outlines the development of an effective pilot-scale simultaneous denitrification and nitrification (SDN) system using intermittent aeration for the removal of carbon and nitrogen from real domestic sewage. Given the limited research in this area, the main objective was to evaluate the overall performance of the SBRIA system on a pilot scale and show its benefits in domestic wastewater treatment. The structured bed reactor with intermittent aeration (SBRIA) notably achieved 57% efficiency in removing total nitrogen without requiring external carbon sources. It also demonstrated impressive removal rates of 56% for total chemical oxygen demand (COD_T) and 82% for biochemical oxygen demand (BOD_5), indicating its effectiveness in degrading organic matter. In addition, the SBRIA showed high pH control and managed the consumption of alkalinity without the need for an alkalizer, maintaining consistent mean values of 7.7 ± 0.8 for pH and 166.8 ± 79.8 $mg \cdot L^{-1}$ for alkalinity. The system also proved resilient against toxic shocks caused by significant variations in influent characteristics. This study offers valuable insights and compelling results into a cost-effective and efficient treatment approach using an innovative technology not previously applied at the pilot scale. Its potential to remediate polluted water is substantial.

Keywords Simultaneous nitrogen and carbon removal · Structured bed reactor · Intermittent aeration · Sewage treatment · Pilot scale

Introduction

Nitrogen compounds are vital nutrients for life's growth and activities. Yet, their unregulated release into water ecosystems causes eutrophication—a major environmental issue. To avert pollution and meet standards, nitrogen removal from wastewater is crucial. Developing nations often discharge untreated domestic wastewater, prioritizing organic matter removal. Thus, controlling eutrophication via effective domestic sewage treatment poses a universal challenge for researchers (Rout et al. 2021; Oliveira et al. 2022).

A cost-effective solution suitable for developing countries is employing systems that achieve nitrogen removal via simultaneous nitrification and denitrification (SND) (Correa et al. 2023). This process has merits over traditional methods as operational ease, energy efficiency, cost-effectiveness, and obviating external carbon requirement for denitrification. These benefits result in reduced operational costs (Rout et al. 2021; Oliveira et al. 2023). Therefore, reactor configurations that employ the SND process have garnered attention for the remediation of domestic wastewater.

The structured bed reactor with intermittent aeration (SBRIA) effectively promotes simultaneous nitrification and denitrification (SND) in a single stage, enabling efficient removal of organic carbon and nitrogen. This capability has been consistently demonstrated in numerous bench-scale studies utilizing the SBRIA reactor configuration (Moura et al. 2018; dos Santos et al. 2021; Oliveira et al. 2022).

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Given the limited studies conducted at the pilot scale and the potential variability in results when scaling up reactor improvements, employing this technology in pilot-scale trials for treating actual domestic wastewater represents an innovative approach. This underscores the importance of further research in this field to facilitate the engineering implementation of SBRIA. Therefore, endeavors like the current work in pilot-scale studies are essential to acquire more suitable operational parameters and achieve efficiencies closer to those observed in bench-scale experiments.

This study presents a preliminary report on an innovative reactor configuration for treating real domestic sewage, based on the simultaneous nitrification and denitrification (SND) process, utilizing a single-unit reactor with intermittent aeration. The objective was to evaluate the overall performance of the pilot-scale SBRIA system and demonstrate that this technology can effectively and efficiently offer substantial benefits in the field of domestic wastewater treatment.

Materials and methods

Sourcing and characterization of sewage

The sanitary sewage used in this study originated from a wastewater treatment plant named Bortolan, located in Poços de Caldas, Minas Gerais, Brazil. The sewage underwent a preliminary treatment prior to being directed to the biological stage in the pilot-scale reactor. Table 1 presents the main characteristics of used sewage.

Pilot scale SBRIA setup and operation

The SBRIA comprised a cylindrical fiberglass vessel with an internal diameter of 1.8 m and a total height of 5.095 m (with a working height of 4.95 m). Within the reactor, four 1.0-m modules containing prismatic structures of polyurethane foam measuring 30 × 30 mm are installed, as depicted in Fig. 1. This configuration resulted in a total volume of 12.296 m^3, a working volume of 8.37 m^3, and a bed porosity of 66%. The foam rods were securely attached to a structure made of fiberglass and polypropylene. The SBRIA was inoculated with sludge obtained from an upflow anaerobic sludge blanket reactor (UASB) treating raw sewage in Poços de Caldas, Minas Gerais, Brazil.

The raw sewage was continuously fed into the reactor through the base using an Abs Sulzer submersible pump. The treated sewage exited the reactor at the top, approximately 4.75 m from the input point. The reactor was operated at room temperature for a duration of 105 days, without recirculation. The hydraulic retention time (HRT) was set at 10 h, employing intermittent aeration in a 3-h cycle. Within each cycle, aeration was carried out for 2 h using a Nexco blower model, followed by 1 h of non-aeration. This operational setup was in accordance with previous studies by Moura et al. (2018) and Oliveira et al. (2022). Continuous aeration was only carried out during the reactor start-up period and was discontinued once high nitrification efficiency was achieved.

Table 1 Characterization of the sewage affluent in pilot scale reactor

Main parameters	Concentration ($mg \cdot L^{-1}$)
Carbon oxygen demand (COD)	576.7 ± 238.6
Biochemical oxygen demand (BOD_5)	486.0 ± 214.6
Alkalinity	423.2 ± 194.9
pH	7.9 ± 0.8
Ammoniacal nitrogen (NH_4^+-N)	26.0 ± 9.2
Nitrite (NO_2^--N)	0.2 ± 0.4
Nitrate (NO_3^--N)	2.8 ± 3.2
Nitrogen total Kjeldahl (NTK)	45.6 ± 28.5
Total solids (TS)	607.8 ± 187.4

Analytical methods

Treated sewage samples were collected at least once a week for pH, alkalinity, total Kjeldahl nitrogen (TKN), ammoniacal nitrogen (NH_4^+-N), nitrite nitrogen (NO_2^--N), nitrate nitrogen (NO_3^--N), filtered chemical oxygen demand (COD_F), total chemical oxygen demand (COD_T), and biological oxygen demand (BOD_5) analyses, according to the protocols outlined in the Standard Methods for the Examination of Water and Wastewater (APHA 2023).

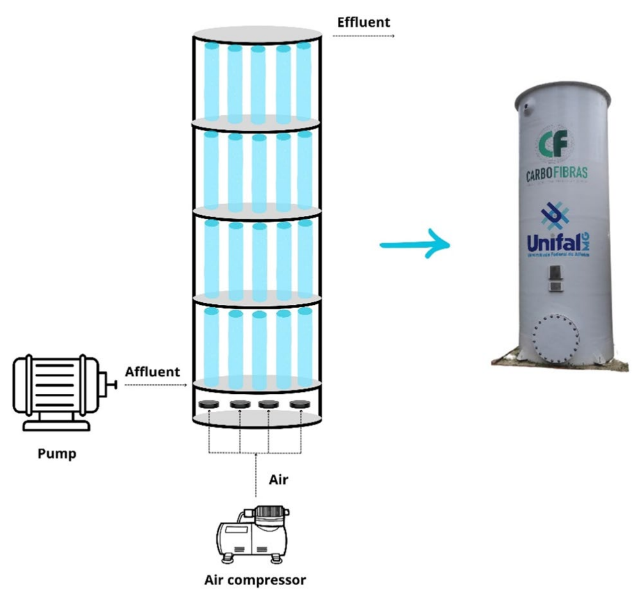

Fig. 1 Schematic representation of SBRIA

In order to simulate the COD post-sedimentation (COD_s), an effluent sample was allowed to settle for a duration of 3 min. Following this interval, the supernatant was collected and subjected to COD analysis.

Efficiency calculations

Nitrogen removal, nitrification (NH_4^+-N removal) and denitrification efficiencies were calculated in accordance with Eqs. (1), (2), (3):

$$Nitrogen\ removal\ (\%) = \frac{\left[TKN + NO_2^- + NO_3^-\right]_{influent} - \left[TKN + NO_2^- + NO_3^-\right]_{effluent}}{\left[TKN + NO_2^- + NO_3^-\right]_{influent}} \quad (1)$$

$$Nitrification\ (\%) = \frac{\left[\left[NH_4^+\right]_{influent} - \left[NH_4^+\right]_{effluent}\right.}{\left[NH_4^+\right]_{influent}} \quad (2)$$

$$Denitrification\ (\%) = \frac{\left[NH_4^+ + NO_2^- + NO_3^-\right]_{influent} - \left[NH_4^+ + NO_2^- + NO_3^-\right]_{effluent}}{\left[NH_4^+ + NO_2^- + NO_3^-\right]_{influent} - \left[NH_4^+\right]_{effluent}} \quad (3)$$

COD_T, COD_F, and BOD_5 removal efficiencies were obtained from Eq. (4) below:

$$Removal\ efficiency\ (\%) = \frac{[Influent] - [Effluent]}{[Influent]} \quad (4)$$

The estimation of nitrogen removal efficiency obtained by using a decanting unit after the SBRIA were calculated, considering the molecular formula of particulate biomass as $C_5H_7NO_2$ (molecular weight = 113 g/mol). By stoichiometric calculations, the equivalent COD of 1 g of volatile suspended solids (*VSS*) was determined, resulting in a value of 1.42 gO_2/gVSS. Furthermore, based on the composition of the biomass, where only 14 g out of 113 g of the molecular weight corresponds to nitrogen (N), a ratio of 0.124 gN/gVSS was obtained.

To ascertain the mass of nitrogen equivalent to 1 g of COD, it was divided by the equivalent COD of the biomass, yielding 0.087 gN/gO_2. Thus, when calculating the particulate COD (COD_p), it is known that 1 g of COD will contain 0.087 g of nitrogen. The COD_p was computed using Eq. (5).

$$COD_p = COD_T - COD_S \quad (5)$$

Results and discussion

Inoculation and adaptation of pilot scale SBRIA

The SBRIA technology quick performance and start-up depend on proper reactor design, operational parameters, and aeration. Under ideal conditions, total nitrification can occur rapidly, typically within 3–5 days (Yamaguchi et al. 1996; Le et al. 2019), due to existing natural nitrifying and denitrifying bacteria in sewage. After 5 days, the reactor achieved full NH_4^+-N oxidation in sewage, proving SND-based treatment feasibility with intermittent aeration. Alkalinity consumption confirmed total nitrification (477 mg $CaCO_3 \cdot L^{-1}$). Stable pH (7.5 ± 0.3) negated external alkalinity need.

Aeration's importance in achieving SND makes pre-operation assessment vital. The system efficacy was verified by organic degradation during adaptation, yielding 78.6 ± 5% COD_F removal, indicating total nitrification. This implies nitrifiers were not outcompeted by aerobic heterotrophs. With these outcomes, SBRIA operation began, enabling performance evaluation.

Performance of SBRIA

Nitrogen and organic matter removal

The study's examination of domestic sewage (Table 2) illustrates the SBRIA system's effectiveness in removing nitrogen and carbon, showcasing its robustness. This underscores its potential for broader exploration and application in wastewater treatment.

The TN removal efficiency reached a mean value of 57 ± 27% without the need for an external carbon source, consistent with findings from previous studies in the field (Barana et al. 2013; Santos et al. 2016). In typical conventional nitrogen removal systems, the setup involves separate units for nitrification and denitrification. The initial unit before nitrification aims to eliminate organic matter and toxic compounds (Metcalf and Eddy 2003). This configuration helps establish nitrifying microorganisms, which are sensitive to environmental conditions and can be adversely affected by high concentrations of COD, leading to their potential washout during standard treatment processes (Correa et al. 2018). Then, the conventional approach necessitates the addition of organic matter to support the denitrification process (Metcalf and Eddy 2003). In contrast, the SBRIA technique simplifies both processes within a single unit, operating at higher C/N ratios. In our recent study, actual domestic sewage demonstrated a COD_T/N ratio of 16. Despite this ratio, efficient nitrification is observed, as illustrated in Fig. 2. Interestingly, this technique enabled effective denitrification without the need for external carbon sources for nitrogen removal.

The efficiency demonstrated in this study is lower than the results reported by Moura et al. (2018), who examined the bench-scale implementation of the SBRIA system for sanitary sewage treatment, achieving an 80% removal of total nitrogen. Hence, the upscaling has induced modifications

Table 2 Operational parameters control for SBRIA

Operational parameters	Affluent ($mg{\cdot}L^{-1}$)	Effluent ($mg{\cdot}L^{-1}$)	Efficiency (%)
Total carbon oxygen demand (COD_T)	637.8 ± 250.3	297.2 ± 283.4	56 ± 31
Filtered carbon oxygen demand (COD_F)	333.4 ± 172.7	56.6 ± 31.6	81 ± 10
Sedimented carbon oxygen demand (COD_s)[a]	503.0 ±108.3	108.3 ± 65.6	77 ± 10
Biochemical oxygen demand (BOD_5)	486.0 ± 214.6	74.9 ± 57.8	82 ± 14
Alkalinity	435.2 ± 201.2	166.8 ± 79.8	-
pH	8.03 ± 0.8	7.71 ± 0.70	-
TKN	40.0 ± 16.5	13.9 ± 13.8	65
Ammoniacal nitrogen (NH_4^+-N)	24.2 ± 9.4	3.6 ± 3.6	85 ± 13
Nitrite (NO_2^--N)	0.15 ± 0.19	0.42 ± 0.32	-
Nitrate (NO_3^--N)	2.42 ± 2.80	4.11 ± 4.20	-
Total nitrogen (TN)	42.6 ± 16.7	17.1 ± 14.9	57 ± 27
Total solids (TS)	607.8 ± 187.4	627.0 ± 265.1	-
Total volatile solids (TVS)	388.6 ± 92.6	377.6 ± 130.4	-
Total fixed solids (TFS)	221.2 ± 140.0	229.4 ± 143.5	-

[a]COD_s was determined by measuring de COD_T after waiting 3 min for the sample to sedimented simulating a decanting unit

in the quality of the final effluent, which will be discussed in "Total solid in the effluent."

The removal of NH_4^+-N demonstrated medium values of 84 ± 13%, which closely align with findings from other bench-scale studies utilizing the SBRIA reactor (Santos et al. 2016; Moura et al. 2018; Oliveira et al. 2022), indicating a high nitrification rate. Similar observations were made for denitrification rates, which reached values of 78 ± 22% (Table 2), with no detectable accumulation of NO_2^--N and NO_3^--N. The successful occurrence of both nitrification and denitrification processes within the same treatment unit highlights the significance of intermittent aeration and presents technological advantages for achieving SND in the SBRIA system. Previous studies have also

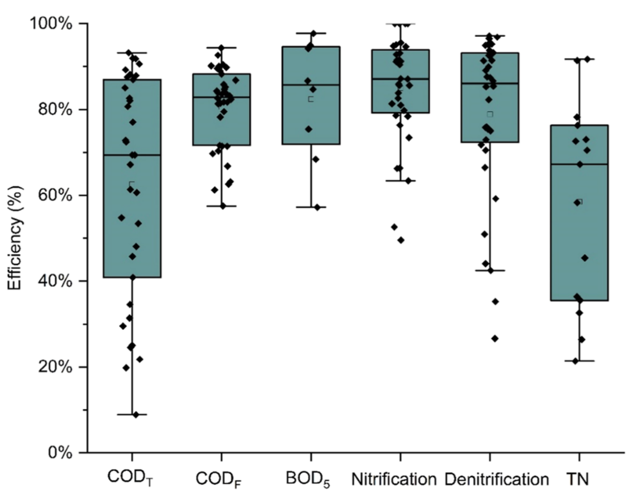

Fig. 2 Monitoring results of SBRIA performance in COD_T, COD_F, BOD_5, nitrification, denitrification, and TN efficiencies

indicated that the employed aeration cycle (2 h of aeration followed by 1 h of no aeration) creates favorable conditions for both processes, resulting in high rates of nitrogen removal. (Santos et al. 2016; Moura et al. 2018; Oliveira et al. 2022).

The SBRIA reactor configuration demonstrated substantial removal efficiencies for COD_F (81 ± 10%) and BOD_5 (82 ± 14%), affirming its robustness and technological potential in treating domestic sewage. However, the COD_T removal efficiency declined to 56 ± 31%, indicating notable variability during operation (Fig. 2). Previous studies examining the SBRIA reactor for domestic sewage treatment (Correa et al. 2018; Moura et al. 2012; Moura et al. 2018; Oliveira et al. 2022) did not include analyses of filtered (COD_F) and settled (COD_S) chemical oxygen demand. This omission was due to minimal solids carryover to the effluent at the bench-scale level, resulting in reduced effluent Total solid (TS) concentration and subsequently, effluent COD_T concentration. However, during the scale-up process, alterations in air diffusers and air blower flow rates could potentially increase biomass detachment from the supporting material. Consequently, considering post-treatment measures for total solid (TS) removal, as detailed in "Total solid in the effluent," might become necessary."

Despite that, it is crucial to note the compositional variability in the affluent observed during operation period, as indicated in Table 2 and Fig. 2. This variability may arise from the irregular discharge of industrial wastewater into the sewers. This variance highlights the SBRIA's potential as cost-effective co-treatment of both domestic sewage and occasional industrial contributions, showcasing comparable efficiency to conventional methods.

Total solid in the effluent

Effluent total solids (TS) averaged 627.0 ± 265.1 mg·L^{-1}. Of this, 377.6 ± 130.4 mg·L^{-1} were total volatile solids (TVS), indicating biomass, while 229.4 ± 143.5 mg·L^{-1} comprised other solid forms. TS and TVS were notably higher than cited SBRIA literature values (Moura et al. 2018; Oliveira et al. 2023; Cicekalan et al. 2023), signaling a need for a clarification unit. This ensures compliance with discharge standards into water bodies. Final clarification units are commonly used to remove suspended particles and enable carbon, nitrogen, and phosphorus removal (Ferdowsi et al. 2022; Cicekalan et al. 2023)

To study the impact of sedimentation on effluent COD, SBRIA reactor effluent samples underwent sedimentation for COD analysis. Post-sedimentation COD concentration (COD_s) averaged 108.3 ± 65.6 mg·L^{-1} (Table 2). This indicates a mean difference of 189 mg·L^{-1} between COD_T and COD_s. This difference could elevate COD_T removal efficiency to 83%, resembling results from literature for this reactor model (Moura et al. 2012, 2018; Santos et al. 2016; Oliveira et al. 2023).

The total nitrogen in the effluent after retaining solids in the clarifier was also estimated. As explained in "Efficiency calculations," every milligram of particulate COD contains 0.087 mg of nitrogen. As COD_p that could be retained in clarifier is 189 mg·L^{-1} (Eq. (5)), we derive an estimate of 16.4 mg·L^{-1} of retained total nitrogen. This would lead to a notable increase in the nitrogen removal efficiency within the system, given that the effluent TN concentration was 17.1 mg·L^{-1}. Due to stoichiometric estimation, confirmation of the improvement needs future nitrogen analyses.

The TS achieved via SBRIA is lower than aeration tanks in activated sludge systems (Metcalf and Eddy 2003). This enables a smaller clarifier, reducing operational costs and emphasizing these innovation benefits. Previous work (Santos et al. 2016; Moura et al. 2018; Oliveira et al. 2023) displayed clarifier-free success in simulating domestic sewage treatment at bench scale.

pH and alkalinity

The influent exhibited a moderately high pH (8.9 ± 0.8), surpassing the optimal range for bacterial growth (~7.0). Nevertheless, the reactor exhibited a favorable response, yielding promising results for SND. The elevated alkaline pH in domestic sewage, uncommon in typical scenarios, suggests the presence of industrial wastewater in the influent and affirms the system resilience in remediating polluted wastewaters. However, since these industrial discharge contributions are sporadic, the effluent maintains its predominance as typical domestic sewage.

Despite the alkalinity consumption of 268.4 ± 216 mg $CaCO_3$·L^{-1} exceeding the expected stoichiometric value (89.2 ± 8.4 mg $CaCO_3$·L^{-1}), the reactor demonstrated no signs of acidification and operated efficiently without the need for alkalizing agents. This finding highlights the cost reduction potential and technological prowess of the system. The minimal requirement for pH control provided by the SND process (Rout et al. 2021) was successfully fulfilled within the present system as well.

Application and future research

SBRIA bench-scale success in domestic sewage treatment is expanded here in a pilot-scale study. Positive results in nitrogen and carbon removal are observed. Cost reduction due to intermittent aeration, plus elimination of alkaline additives and carbon supplementation was notable. SBRIA handles industrial effluents well, needing a smaller clarifier than traditional methods. However, elevated total solids (TS) in effluent pose a challenge, warranting further investigation.

The pilot-scale SBRIA reactor effectively enhances simultaneous nitrification and denitrification (SND), making it feasible for practical use. Its benefits for nitrogen removal from domestic wastewater, noted by Rout et al. (2021), are confirmed here, highlighting SBRIA potential. Optimizing operational parameters like aeration flow can aid its development. Addressing substantial influent variability, which hindered system stability, requires further study. Still, these initial results underscore SBRIA potential for effective treatment of both domestic and industrial wastewater.

The significance of this study becomes apparent in light of the scarcity of pilot-scale studies on SBRIA, providing substantial information that could significantly contribute to the future implementation of this technology. It highlights the innovative results obtained in this research, underscoring its potential impact and importance.

Conclusions

The SBRIA demonstrated efficient simultaneous removal of nitrogen and carbon, offering cost reduction through intermittent aeration and eliminating the need for alkaline additives and external carbon supplementation. The system's robustness was evident in its ability to withstand alkaline pH and the presence of toxic compounds in the influent. The preliminary results obtained in this study represent significant progress in domestic wastewater treatment and present a promising alternative technology for nutrient removal. The pilot-scale operation of the SBRIA represents a significant stride towards optimizing this treatment for real-world wastewater applications.

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Author contribution Talita Aleixo Barbosa: formal analysis, conceptualization, and investigation; Alessandra Giordani: data curation, investigation, and writing—original draft; Rafael Brito de Moura: conceptualization, resources, supervision, and writing—review and editing.

Declarations

Ethics approval Not applicable

Consent to participate All the authors gave their consent to participate in the work.

Consent for publication All the authors gave explicit consent to submit the work to Environmental Science and Pollution Research.

Competing interests The authors declare no competing interests.

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