

Performance evaluation of anaerobic baffled biodigester for treatment of black water

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In this study, the performance of anaerobic baffled biodigester installed in different regions of South India was evaluated for black water treatment. The evaluation was based on the vendors, establishment, impact of different sampling methods (grab and composite sampling) and the application of post-treatment unit. The treatment efficiency of the digester was assessed in terms of removal of organics (biological oxygen demand (BOD), chemical oxygen demand (COD)), total suspended solids (TSS) and pathogens (faecal coliform). The maximum removal rate of COD, BOD and TSS was found to be in the range of 70–75%, 68–80% and 55–75% respectively. Variations were observed between the grab and composite samplings with respect to the removal efficiency of organics, solids and pathogens. There was no significant difference in the performances of anaerobic biodigesters installed by different vendors in South India. The application of post-treatment unit such as gravel bed/reed bed after biodigester facilitated the removal of residual organic pollutants and provided better quality outlet water. The results indicated that the performance of anaerobic baffled biodigesters varies based on the number of users, location, usage pattern and the post-treatment unit installed.

Keywords: Anaerobic digestion, biodigester, black water, community toilet, onsite treatment, sanitation.

FAECAL contamination of water resources remains a major concern, especially in developing countries. Almost 99.8% of deaths in developing countries is due to sanitation, water and hygiene-related problems¹. Dense black water consists of organic materials, nutrients and pathogens, which constitute high concentrations of chemical oxygen demand (COD), nitrogen and phosphorus. Treatment of black-water through the use of appropriate sanitation systems acts as the primary barrier to prevent the spread of pathogens in the environment. On-site/decentralized wastewater treatment is used to dispose/reuse small volumes of wastewater at the same location where it is generated. Such systems are desirable in rural and peri-urban areas which could be single households or groups of dwelling situated in close proximity². Usage of

on-site treatment system has several advantages compared to centralized wastewater treatment system, which includes functional simplicity, economic affordability, no need for large-scale pipe network and easy energy recovery³. Anaerobic treatment is considered as a promising core technology for recovering resource and energy from source-separated bio-waste such as concentrated black water and brown water⁴.

Septic tank is extensively used as an on-site treatment system for black water because of its low energy consumption, small space requirement and relatively simple reactor design². Septic tanks are capable of removing 20–50% of pollutant load in wastewater⁵; their low treatment efficiency is a major concern. Various options practised for on-site treatment of black water are dry pits, twin-pit (leach pit), septic tanks, biodigesters/biotanks, biotank with reed bed treatment, constructed wet lands⁶, packaged treatment units^{7,8}, etc. However, it has been reported that the treatment efficiency of these systems is not very high due to the presence of high pollutant concentration. Moreover, most of the existing on-site treatment systems do not have any post-treatment facility to remove residual pollutants or pathogens⁹. Several advanced reactors such as the anaerobic filter reactor (AF)^{10,11}, up-flow anaerobic sludge blanket reactor (UASB)¹², expanded granular sludge bed reactor, anaerobic baffled reactor¹³, membrane bioreactor (MBR) and moving-bed biological reactors (MBBR) have been developed to tackle the challenges of efficient domestic wastewater treatment. However, they are not popular as on-site treatment systems due to the complexity, cost and requirement of skilled personnel for operation and maintenance. Most of the earlier studies, had not justified whether the treatment systems were sustainable or not in terms of energy and economics^{7,14}. The conventional on-site system has been widely used for black water treatment in developing countries.

India is lagging behind other countries with respect to environmental sanitation, and it requires newer strategies and targeted inventions with follow-up evaluation¹⁵. In order to achieve sustainable and less expensive on-site treatment of black water, the Defense Research and Development Organisation (DRDO), India has developed an anaerobic baffled biodigester specifically inoculated with an enriched and bio-augmented microbial consortium. This eco-friendly biodegradation technology was initially designed for human waste disposal for the armed

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forces posted at high altitudes and glaciers. The consortium designed for organic matter degradation was prepared by acclimatization, enrichment and bio-augmentation with psychrophilic microbes collected from Antarctica and low-temperature areas. These microbial consortia break down biodegradable organic matter into methane and carbon dioxide in the absence of oxygen¹⁶. According to the developers, the microbial consortium was able to work in varying temperatures, i.e. 5°–50°C, and could resist freezing, thawing and temperature fluctuations. DRDO has also reported that these biodigesters have the capability to treat faecal waste to the extent of more than 90% and inactivate the pathogens during fermentation, rendering the effluent almost free of them. The consortium is being prepared and marketed by various approved vendors. These biodigesters have been installed in large numbers at various regions and facilities in India and elsewhere¹⁷. However, there are limited studies available on the performance of these anaerobic bioreactors for the treatment of black water^{14,18}. Also, anaerobic biodigesters inoculated with specific microbial consortia for the treatment of black water in a long run have not been studied. The field data pertaining to continuous monitoring of biodigesters, the effect of inocula over different regions, and the efficiency of inocula available in the market are also not well reported, though a large number of such units are deployed at various regions in India. Hence, it is essential to carry out performance evaluation of the anaerobic baffled biodigester for the treatment of black water.

The present study evaluated the performance of existing anaerobic baffled biodigesters installed by DRDO licensee vendors (field installations) in different parts of South India. Studies were also carried out to (i) examine the impact of sampling method on evaluating the digester performance, (ii) assess the vendors-based variations on digester performance, (iii) evaluate establishment-based variation on digester performance and (iv) examine the role of post-treatment systems like gravel/reed bed on effluent quality.

Materials and methods

Site details and analysis

The anaerobic baffled biodigesters were installed at different locations in India for the treatment of black water. The technology behind this treatment mechanism was developed and promoted by DRDO; various vendors are available in the market for these types of digesters all over India. The basic criterion used for the selection of sites was that the installed biodigesters should have completed one year of operation. In the present study, three different vendors were chosen based on accessibility and institutional pattern. A questionnaire survey was con-

ducted to assess the socio-economic aspects and to understand the type of institutions where the units are installed and the number of people using them. Based on accessibility, 13 sites were selected and in-depth composite samplings were carried out once a month to evaluate the performance of the system. In addition to composite sampling, grab sampling was also carried out in five sites, to understand how the sampling methods influence performance evaluation. In some locations, post-treatment units were connected to the biodigesters. Table 1 shows the list of 13 sites and Figure 1 presents their distribution. Table 2 shows the characteristics of the inocula. A detailed description of the biodigester is given in the [Supplementary Material \(Section 1\)](#).

Sampling details and analysis

Grab sampling was carried out once a month during November 2015 to March 2016. For this, samples were taken from the first compartment of the biodigester. Due to fluctuations observed in the inlet organics and solids concentration every month, composite sampling was planned. Civil modifications were carried out to perform composite sampling, which was carried out once a month from October 2016 to July 2018. Composite samples were taken at regular intervals of 24 h. For flow measurement during composite sampling, offline pipe connections were provided in all the reactors in such a way that the flow directly entered the digester on all days, except the sampling day. On the day of sampling the flow passed through the sampling chamber provided in the inlet and outlet. This was controlled with the help of a valve. Details are provided in the [Supplementary Figure 1](#). The sampling chambers of all units were cleaned thoroughly 24 h before composite sampling. The flow rate to the digester was calculated based on the volume of raw water collected in the inlet tank at the stipulated time (24 h).

Samples of raw water, treated water after biodigester, treated water after post-treatment unit and tap water (control) were collected once a month from all the 13 sites. After sampling, the samples were transported to the laboratory and stored at a temperature below 4°C. The analyses were carried out within 24–48 h of sample collection. The samples were collected, transported and preserved according to standard methods¹⁹. The collected samples were analysed for various physico-chemical and bacteriological parameters (pH, total biological oxygen demand (BOD), COD, solids, and faecal coliforms (FC)). All the physico-chemical parameters of influent and effluent samples were analysed according to standard methods¹⁹. To maintain quality control, the samples were processed in triplicate for wastewater analysis, and standards were run at regular intervals. Hydraulic retention time (HRT) was calculated for all the sites. One-way

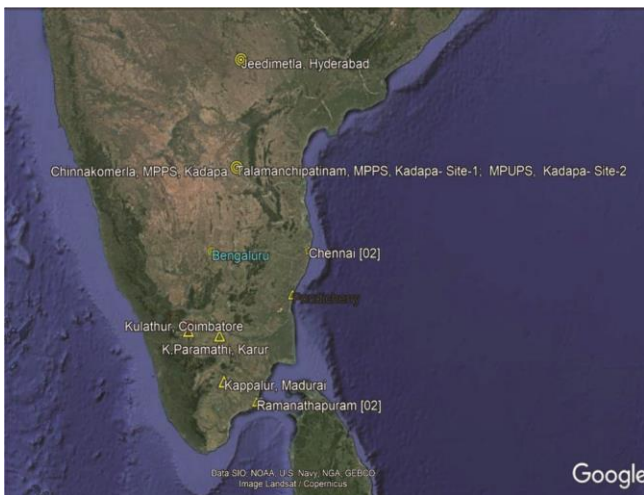
Table 1. Details of anaerobic baffled biodigester in different regions of South India

| Vendor | Plant | Treatment type | No. of users/day | Reactor capacity (m ³) | Inflow rate (l/d) | Outflow rate (l/d) | Hydraulic retention time (d) |
|--------|--|----------------------------|------------------|------------------------------------|-------------------|--------------------|------------------------------|
| A | Tirumalai Nagar Park, Chennai | Bio-digester | 25–30 | 2 | 340 | 280 | 5.88 |
| | Rajiv Nagar Park, Chennai | Bio-digester | 25–30 | 2 | 289 | 220 | 6.92 |
| B | Company in Jeedimetla, Hyderabad | Bio-digester | 300 | 10 | 4000 | 3260 | 2.5 |
| | Company in Bengaluru | Bio-digester | 15–20 | 0.8 | 220 | 184 | 3.63 |
| | School in Kadapa (site 1) | Bio-digester | 30–35 | 1 | 190 | 120 | 5.3 |
| | School in Chinnakomerla village, Kadapa (site 2) | Bio-digester | 100–120 | 1 | 257 | 170 | 3.9 |
| | School in Talamanchipatnam, Kadapa (site 3) | Bio-digester | 40–45 | 1 | 160 | 95 | 6.3 |
| | Sedarapet, Puducherry | Bio-digester | 120–150 | 8 | 1100 | 900 | 7.27 |
| C | Pambanbusstand, Ramanathapuram | Bio-digester + gravel bed | 100 | 8 | 2100 | 1450 | 3.8 |
| | Ramanathapuram (Collectorate Office) | Bio-digester + gravel bed | 50–60 | 8 | 1750 | 1560 | 4.6 |
| | Kappalore community toilet block, Madurai | Bio-digester + sand filter | 100–150 | 8 | 750 | 680 | 10.6 |
| | Paramathy, Karur | Bio-digester + reed bed | 70–100 | 8 | 1750 | 1234 | 4.57 |
| | Kulathur village, Coimbatore | Bio-digester + gravel bed | 80–100 | 8 | 1860 | 1150 | 4.3 |

Table 2. Characteristics of vendor A inoculum, vendor B inoculum and control anaerobic sludge

| Parameters | Vendor A inoculum | | Vendor B inoculum | | Control anaerobic sludge | |
|---|-------------------|------|-------------------|------|--------------------------|------|
| | Mean | SD | Mean | SD | Mean | SD |
| pH | 7.31 | 0.30 | 4.03 | 0.01 | 6.95 | 0.53 |
| Temperature (°C) | 30.35 | 1.06 | 33.05 | 0.07 | 29.40 | 0.14 |
| Total chemical oxygen demand (COD) (mg/l) | 7065 | 804 | 11557 | 628 | 2230 | 325 |
| sCOD (mg/l) | 443 | 45 | 3556 | 419 | 217 | 52 |
| MLSS (mg/l) | 28,942 | 604 | 74,360 | 700 | 40,290 | 961 |
| MLVSS (mg/l) | 19,325 | 200 | 60,100 | 280 | 17,540 | 368 |
| SMA (g CH ₄ -COD/g VSS/d) | 0.140 | – | 0.132 | – | 0.193 | – |

sCOD, soluble COD; MLSS, mixed liquor suspended solids; MLVSS, mixed liquor volatile suspended solids

**Figure 1.** Distribution of 13 anaerobic baffled biodigesters in South India.

analysis was performed to determine whether the biodigesters procured from different vendors showed any variation in treatment efficiency. Detailed description of the methodology adopted for each parameter is given in the [Supplementary Material \(Section 2\)](#).

Results and discussion

Black water characteristics

The performance of anaerobic baffled biodigester installed in 13 different locations was assessed. In order to understand whether the sampling strategy causes any variation in influent and effluent quality, five sites were selected (i.e. Karur, Madurai, Ramanathapuram, Thirumalai Nagar and Rajiv Nagar) based on accessibility to carry out grab and composite sampling. Tables 3 and 4 show the average raw water and treated water concentrations of organics, solids, faecal coliforms and nutrients for grab and composite sampling. The average treated water pH was observed to be in the range 6.5–7.8, which falls within the recommended values for anaerobic digestion²⁰, signifying no excessive accretion of organic acids in the biodigester. The average BOD to COD ratio of raw water was around 0.69, indicating that biological treatment of raw water is possible²¹. During grab sampling, the average raw water concentration of BOD, COD and TSS was found to be in the range 127–778, 72–781 and 155–561 mg/l respectively. In the case of composite sampling, the average concentration of raw water BOD, COD and TSS was 158–595, 283–812 and 41–920 mg/l

Table 3. The physico-chemical characteristics of both influent and effluent during grab sampling

| Field units | Concentration | | | | | | | |
|---------------------|---------------------------------------|-----------|-------------------------------------|-----------|-------------------------------------|-----------|-----------------------------------|----------|
| | Biological oxygen demand (BOD) (mg/l) | | Chemical oxygen demand (COD) (mg/l) | | Total suspended solids (TSS) (mg/l) | | Faecal coliform (FC) (MPN/100 ml) | |
| | Inlet | Outlet | Inlet | Outlet | Inlet | Outlet | Inlet | Outlet |
| Karur | 330 ± 246 | 73 ± 42 | 899 ± 383 | 358 ± 199 | 635 ± 448 | 208 ± 149 | 3.43E+8 | 7.6E+4 |
| Madurai | 303 ± 164 | 90 ± 49 | 933 ± 889 | 264 ± 194 | 613 ± 514 | 305 ± 392 | 3.98E+08 | 2.6E+5 |
| Tirumalai Nagar | 654 ± 284 | 130 ± 114 | 528 ± 236 | 230 ± 122 | 536 ± 493 | 188 ± 194 | 8.1E+7 | 6.5E+4 |
| Rajiv Nagar | 380 ± 209 | 141 ± 96 | 668 ± 252 | 309 ± 106 | 513 ± 508 | 162 ± 106 | 4.1E+8 | 2.8E+4 |
| Kadapa 1 | 296 ± 85 | 85 ± 27 | 819 ± 327 | 313 ± 150 | 279 ± 255 | 100 ± 69 | 8.7E+7 | 7.5E+4 |
| Kadapa 2 | 275 ± 165 | 82 ± 44 | 526 ± 388 | 220 ± 154 | 283 ± 158 | 136 ± 69 | 2.74E+8 | 8.1E+4 |
| Kadapa 3 | 357 ± 197 | 97 ± 39 | 1047 ± 614 | 486 ± 360 | 396 ± 297 | 176 ± 80 | 3.2E+7 | 1.6E+4 |
| Bengaluru | 466 ± 185 | 213 ± 84 | 1064 ± 727 | 419 ± 288 | 374 ± 228 | 209 ± 102 | 4.3E7 | 1.5E+4 |
| Hyderabad | 540 ± 216 | 146 ± 53 | 1801 ± 933 | 589 ± 389 | 655 ± 240 | 424 ± 179 | 6.1E+8 | 2.12E+4 |
| Ramanthapuram (PBS) | 549 ± 191 | 152 ± 49 | 1164 ± 298 | 394 ± 101 | 985 ± 279 | 211 ± 130 | 1.19E+8 | 2.2E+5 |
| Ramanathapuram (CO) | 549 ± 191 | 152 ± 49 | 1572 ± 749 | 450 ± 174 | 1077 ± 331 | 218 ± 191 | 3.62E+8 | 5.7E+5 |
| Puducherry | 466 ± 185 | 213 ± 84 | 1764 ± 917 | 770 ± 353 | 1101 ± 5 | 532 ± 18 | 2.57E+8 | 2.11E+05 |
| Coimbatore | 662 ± 279 | 198 ± 89 | 2158 ± 192 | 790 ± 215 | 762 ± 22 | 233 ± 55 | 1.07E+8 | 1.01E+5 |

Table 4. Physico-chemical characteristics of influent and effluent during composite sampling

| Field units | Concentration | | | | | | | |
|------------------|---------------|-----------|------------|-----------|------------|----------|-----------------|----------|
| | BOD (mg/l) | | COD (mg/l) | | TSS (mg/l) | | FC (MPN/100 ml) | |
| | Inlet | Outlet | Inlet | Outlet | Inlet | Outlet | Inlet | Outlet |
| Karur | 273 ± 171 | 143 ± 104 | 524 ± 284 | 331 ± 307 | 487 ± 190 | 143 ± 81 | 1.99E+8 | 1.9E+5 |
| Madurai | 143 ± 99 | 67 ± 24 | 217 ± 128 | 110 ± 21 | 207 ± 40 | 161 ± 97 | 2.88E+7 | 2.46E+4 |
| Thirumalai Nagar | 153 ± 121 | 102 ± 92 | 215 ± 174 | 143 ± 122 | 155 ± 48 | 74 ± 23 | 4.4E+6 | 4.48E+3 |
| Rajiv Nagar | 140 ± 72 | 72 ± 39 | 236 ± 79 | 139 ± 51 | 194 ± 114 | 98 ± 65 | 3.24E+8 | 3.474E+5 |
| Ramanathapuram | 1182 ± 967 | 140 ± 84 | 1666 ± 686 | 256 ± 164 | 1308 ± 505 | 114 ± 42 | 1.1E+7 | 3.245E+4 |

respectively. The higher concentration of organics and solids while carrying out grab sampling clearly indicates that grab sampling from the first compartment is not a representative method for sample collection for the anaerobic biodigester. However, in composite sampling, the wastewater was held for about 24 h in a collection chamber, and thorough mixing was also done prior to sample collection. The black water characteristics of composite sampling in this study were similar to those obtained by Sharma and Kazmi¹¹. On the contrary, it was much lower than those obtained by Kujawa-Roeleveld and Zeeman²² and Hocaoglu *et al.*²³. This is because the reactors (UASB septic tanks) used in their studies were connected to two vacuum toilets, using approximately 1 litre water to flush the waste. This volume is comparatively lower than the usage of flush water (5–6 litre) in the present study. As a result, the strength of wastewater in the above studies was high. Kujawa-Roeleveld and Zeeman²² reported that the influent COD concentration for lower flush water consumption was 9503 ± 6460 mg/l (one time faeces and five times urine as produced by one individual per day), which is nine times higher than the value obtained in the present study. Hence, flush water usage in toilets has a significant influence on black water characteristics. The concentration range of FC in all sites was 10E+6–10E+

7MPN/100 ml. Similar range of FC (6.6E+7 – 3.3E+7 MPN/100 ml) was observed by Sharma and Kazmi⁸ in black water generated at a residential school in Uttarakhand, India and 1.7E+6 ± 1.1E+6 MPN/100 ml in raw black water treated in a laboratory scale treatment system.

Performance of anaerobic baffled biodigester based on grab and composite sampling

Table 4 presents the average effluent quality of the biodigester during composite sampling. The pollutant (organic) load was reflected in terms of BOD, COD and TSS. The average effluent COD concentration in the biodigesters with regular users was in the range 220–400 mg/l, which is significantly less than the influent concentration. Figure 2a shows the overall removal efficiency of the biological treatment. The biodigester with regular number of users showed higher COD, BOD and TSS removal efficiency in the range 70–75%, 68–80% and 60–80% respectively. COD and BOD removal was mostly governed by anaerobic microbial activity in which four different groups of microbes (fermentative, syntrophic, acetogenic and methanogenic bacteria) degraded organic matter into CO₂ and methane through

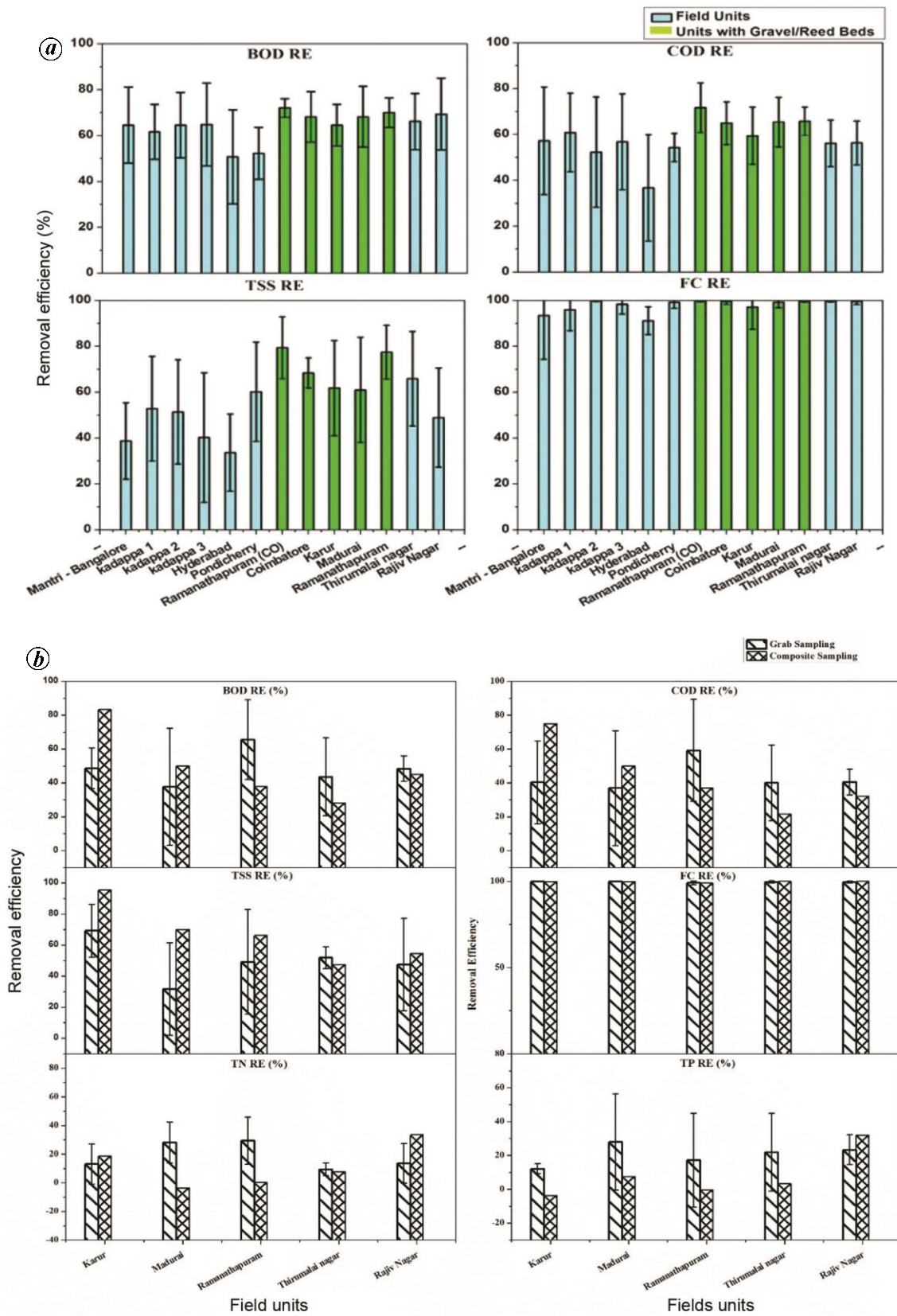


Figure 2. Average removal efficiency of biological oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS) and faecal coliform (FC) of anaerobic baffled biodigesters. *a*, At different locations in South India; *b*, During grab and composite sampling.

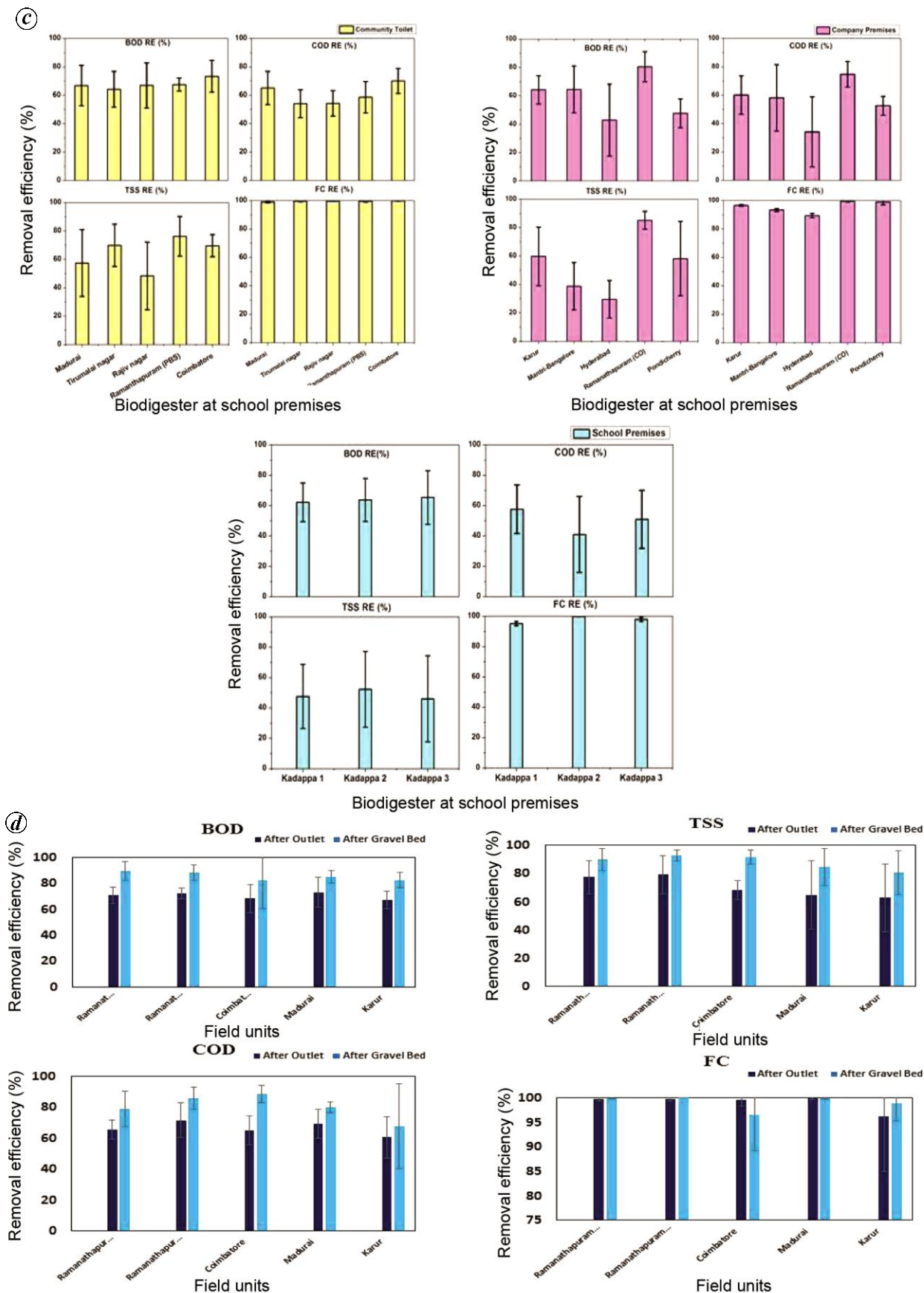


Figure 2(Continued). c, Depending on the type of establishment. d, Sampling after biodigester and after the post treatment unit.

complex biochemical pathway. TSS was a visual indicator of suspended organic and inorganic pollutant load and its removal showed the settleability of solids in the digester. Even though there was large fluctuation in influent concentration, the treated water characteristics did not vary significantly throughout the study. The average HRT found in the field units was in the range 3–10 d. However, this variation did not show significant impact on COD removal efficiency. After the treatment, 3log reduction of FC was obtained. According to Colon *et al.*²⁴, the substantial reduction of FC in anaerobic treatment was due to the combined mechanism of physical (adsorption into the suspended solids) and biological processes (natural die-off of microbes). The removal efficiency observed in this study was comparable with other studies using anaerobic packaged systems, UASB reactors and baffled septic tanks with anaerobic filter. Sharma and Khazmi¹¹ used a filter-based packaged system for treating source-separated black water and achieved a removal efficiency of 72.6% in terms of COD and 83.2% in terms of BOD. De graff *et al.*²⁵ reported that the UASB reactor treating black water at an HRT of 7d and at a temperature of 25°C achieved removal efficiency of 73%. Grab and composite sampling results (BOD, COD and TSS removal efficiencies) were compared (Figure 2b). Variations between grab and composite samples were observed in all the sites. The sites with regular number of users showed higher difference in BOD, COD and TSS removal, in the range 11–34%, 11–18% and 18–44% respectively (Figure 2b). FC removal difference was observed to be less than 1% for all the sites while performing grab and composite sampling. The composite sampling showed an estimated average value over a 24 h period, whereas grab sampling showed the value of samples at a particular point and time. Due to higher fluctuation in influent organics and solids concentration, grab sampling from the first compartment was not considered as a representative method for sample collection for the anaerobic baffled biodigester whereas, it was suitable for the treatment systems where waste water was well mixed, and had consistent influent flow rate and characteristics. Moreover, composite sampling reduces data uncertainty considerably when compared to grab sampling²⁶. Thus the present study recommends the use of composite sampling for characterizing the nature and magnitude of the discharge pattern. In addition, performance of the biodigesters installed by different vendors was studied. It was observed that there was no significant difference in the performance of these anaerobic biodigesters. Detailed information is presented in the [Supplementary Material \(Section 3\)](#).

Performance based on type of establishment

The black water characteristics based on the type of establishment is discussed below. Figure 3 shows the

average influent BOD and COD concentrations of the digesters installed in community toilets, company toilets and school toilets. The organic loading rate of digesters in the community, company and school toilets was in the range 0.6–2.19, 0.8–1.6 and 0.4–1.1 kg COD/d respectively. The higher variation is due to variability in the number of users, amount of faeces coming in and water usage by the people. The influent solids concentration at the community, company and school toilets was in the range 493–945, 370–1183 and 259–423 mg/l respectively. Fluctuation in organics loading and solids concentration in different localities was due to the lifestyle of the users. It was observed that biodigesters installed in the school toilets showed lower organics concentration than those in the community and company toilets (Figure 3), since toilets in the schools are generally used as urinals. The influent organics concentrations in the community toilets and biodigesters in the company premises are in good agreement with the values reported by Hocaoglu, and Henze and Ledin, whereas biodigesters in the school premises showed slightly lower values than those reported. The average FC concentration of inlet water was in the range $3.5E+7$ – $3.7E+8$, $4.3E+7$ – $3.5E+8$, 2.5 – $3E+7$ MPN/100 ml for the community, company and school toilets respectively. During the entire study period, FC concentration range in influent was consistent for all the localities. Figure 2c shows the removal efficiency of organics, solids and pathogens for the biodigesters at different localities. The biodigesters at the school premises achieved removal efficiencies of BOD, COD and TSS in the range of 60–65%, 50–58% and 45–50% respectively. Biodigesters connected with community toilets achieved BOD, COD and TSS removal in the range 65–70%, 55–60% and 60–70% respectively. The removal efficiency of BOD, COD and TSS was in the range 60–65%, 50–55% and 60–70% respectively, for biodigesters at the company premises. The presence of sludge particle was observed in treated water from the digester at the school premises, which indicates sludge wash-out in these biodigesters. This in turn increased the COD and TSS concentration of treated water. As a result, removal rate was comparatively lower than the biodigesters at the community and company premises. It was also observed that the sludge wash-out was mainly due to higher influent flow rate, which lead to shorter HRT. This resulted in less stabilized sludge due to lower percentage of hydrolysis²⁷. According to an earlier study by Munoz *et al.*²⁸, an increase in HRT may improve COD and nitrogen removal. However, the present study, HRT of 5, 7 and 10 d showed similar treatment efficiency in terms of organics and solids removal. The higher reactor capacity with less influent flow rate and lower organics loading resulted in higher HRT. Also, it had been observed that the flow rate of influent varied in the field sites based on the number of users. Though FC removal efficiency was observed to be 95% in all the sites, the treated effluents did not meet the

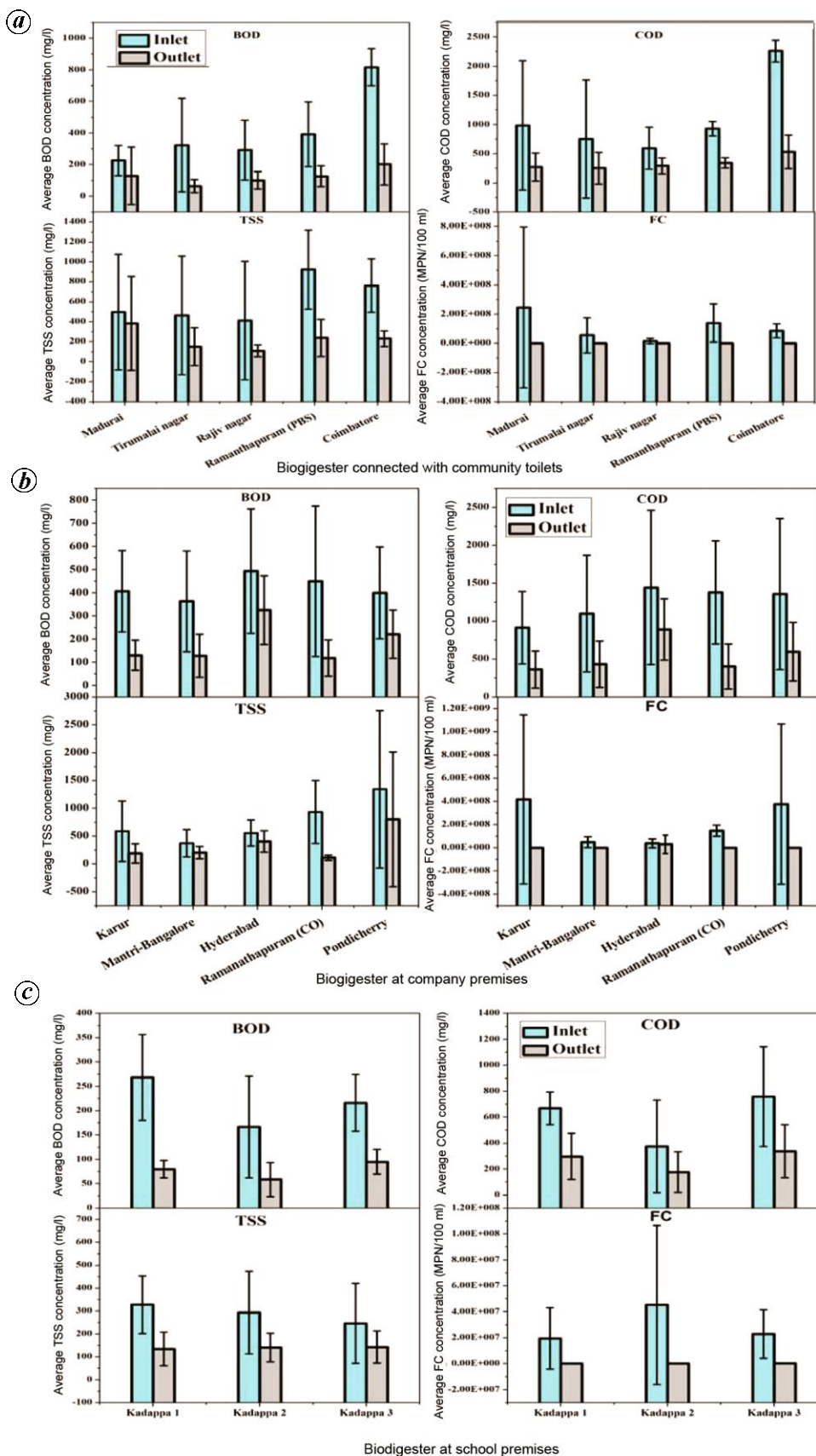


Figure 3. Average concentration of BOD, COD, TSS and FC of anaerobic baffled biodigester at different establishments. (a) community toilets, (b) company toilets and (c) school toilets.

effluent discharge standards prescribed by Central Pollution Control Board (CPCB)²⁹.

Contribution of post treatment units in effluent quality

The removal efficiencies of biodigester and biodigester with post-treatment units were compared (Figure 2 d) to evaluate the effectiveness of post-treatment units in the removal of residual organics, solids and pathogens. The results indicated that the biodigester followed by post-treatment unit (gravel bed) could further increase the removal efficiency by 15–20% for COD (Figure 2 d), 10–15% for BOD and 10% for solids. Thus, biodigesters with post-treatment units showed better performance in terms of organics and solids removal when compared with the units that had only biodigesters for treating black water. Thus, the combination of anaerobic baffled biodigester with post-treatment unit will be able to achieve better treatment efficiency in case of black water. The findings were in agreement with previous studies. Nguyen *et al.*³⁰ examined baffled septic tank with and without anaerobic filter for black water treatment in Vietnam. They reported that the treatment system without post-treatment effectively achieved 74.85% COD and 71.47% BOD removal. However, this treatment system was not able to meet the wastewater discharge standards in Vietnam. Therefore, the authors studied the post-treatment performance of BASTAF effluent with a vertical flow constructed wetland and achieved 10% improvement in organics and solids removal, which is comparable to the results obtained in the present study. Other studies reported higher removal efficiencies for treatment systems such as anaerobic packaged systems³¹ and UASB-septic tanks¹² compared to conventional septic tank. However, these systems also could not fulfil the prescribed disposal standards for wastewater. Hence, the present authors emphasize the need for post-treatment after anaerobic treatment system. Moreover, the post-treatment (reed bed and gravel bed) unit after bio-digester removed residual organics and solids effectively. Hence, proper maintenance of such units is recommended to achieve efficient treatment in such on-site treatment systems. To achieve the desired effluent quality for reuse, constructed wetlands or reed beds are recommended as an option for post-treatment. Any submerged attached growth aerobic biological system followed by dual media filtration process also can produce the desired quality of effluent, for various reuse purposes.

In the case of FC removal performance, the gravel/reed bed was inefficient in achieving significant improvement. If the treated water is to be reused, chlorination or some alternative disinfection system is indeed for pathogen removal. The samples collected before and post-treatment showed a consistent 3log reduction of FC. Though it showed 99% removal, it did not comply with the Indian

disposal standards for treated wastewater. Hence, additional disinfection systems are needed for the removal of FC. Moreover, improvement in the removal of organic matter and nutrients by the post-treatment units was mainly because of filtration and cleaning processes due to biological activity in the biofilm attached on the gravel/sand. Thus, the results of the present study show that the performance of anaerobic baffled biodigesters varies based on the number of toilets users these were attached to, the frequency of usage, location of the toilets, purpose of use, sample-collection points and post-treatment units installed after the biodigesters.

Conclusion

The performance of existing anaerobic baffled biodigesters installed in different regions of south India was evaluated in terms of organics, solids and pathogens removal. There was no significant difference observed between performances of anaerobic biodigesters installed by different DRDO licensee vendors in South India. The study results confirmed that grab and composite sampling method showed percentage variation of organics and solids in influent. Units with regular usage performed better, i.e. among the 13 sites studied, those with regular number of users showed higher COD removal efficiency in the range of 70–75% and BOD removal efficiency at about 50–60%. Even though FC removal efficiency was around 95% in all the sites, the treated effluents did not meet the CPCB standards. Presence of reed bed/gravel bed enabled better outlet quality compared to systems employing only the biodigesters. The results of the present study indicate that the characteristics of the treated water depend upon the usage of toilets, amount of faeces coming in, the number of users, location and post-treatment units installed after biodigesters.

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