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Technical and economic viability of a compact, partially submersed black water treatment system for floating residences

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Abstract

Riverine populations in the Amazon lack appropriate sanitation technologies due to the challenges imposed by the várzea (floodplain) environment. This compromises their health and the quality of the environment in which they live. This study aims to verify the technical and economic viability of a black water treatment using a septic tank + anaerobic filter (bamboo rings, crushed stone, brick fragments) with locally available components, of small volume and which is partially submersed. The system's pollutant removal efficiency was considered using analyses of pH, temperature, biochemical oxygen demand (BOD), chemical oxygen demand (COD), nitrogen, ammonium and phosphorus. Economic viability was calculated using the costs of the systems, compared with the value of a standard residence and family income of residents of the Mamirauá and Amanã Reserves. BOD removal efficiency was similar for the media filter tested (average 77%). COD load removal was between 67 and 83%. Nitrogen and phosphorus concentrations remained high in relation to legal standards, with 59 and 96 mg L^{-1} of phosphorus for the brick fragment filters, and 230 and 379 mg L^{-1} of nitrogen for the crushed stone and bamboo ring filters, respectively. The cost for the system was US$ 1,000, about 5% of the cost of a standard residence. The three filter configurations were similar in terms of organic material removal. The technology proved viable in terms of efficiency and cost as it is an accessible option for the várzea environment.

Key words: black water, septic tank, sewage treatment, *várzea*, viability

INTRODUCTION

The sanitation in riverine communities on the Amazonian floodplain (*várzea*) has been neglected. Official data from the Brazilian government (IBGE 2011) show that sanitation in rural areas of the northern region present the worst ratio of access to a sanitation system, with coverage of only 8.4% of homes in 2010. Information about the reality of sanitation in *várzea* areas is scarce.

Studies of sanitation efficiency are common. Little is known about the use of these technologies in *várzea* areas of the Amazon, where the natural environment is challenging and limiting in terms of conventional systems for treating black waters (Borges Pedro *et al.* 2011). Problems include highly variable water levels (up to 12 metres), the absence of collective sewer networks, and shortage of electricity for more advanced technologies. Open defecation is a common practice.

It is clear that sanitation technologies should be tested and applied in these regions so that natural waters are not contaminated by domestic sewage and maintain at least the minimum quality required for the various uses.

The key proposal of this article is to verify the technical and economic viability of a black water treatment technology comprising a septic tank and anaerobic filter of reduced volume, partially-submerged, with components that are available locally.

METHODOLOGY

In this study, three compact black water treatment systems were evaluated (flush toilet), comprising two treatment units each (Figure 1): a septic tank (useful volume = 170 litres) and an anaerobic filter (useful volume = 141 litres). The media filters were the differential between the systems. The media filters tested were crushed stone no. 5 (experiments A and B), bamboo rings (A), and brick fragments (A and B), i.e., 5 filters were analysed.

The systems were installed in a floating lodge that treats black waters generated by tourists and employees. The units are partially submerged (approximately 60% of the reactor vessel volume was below water level).

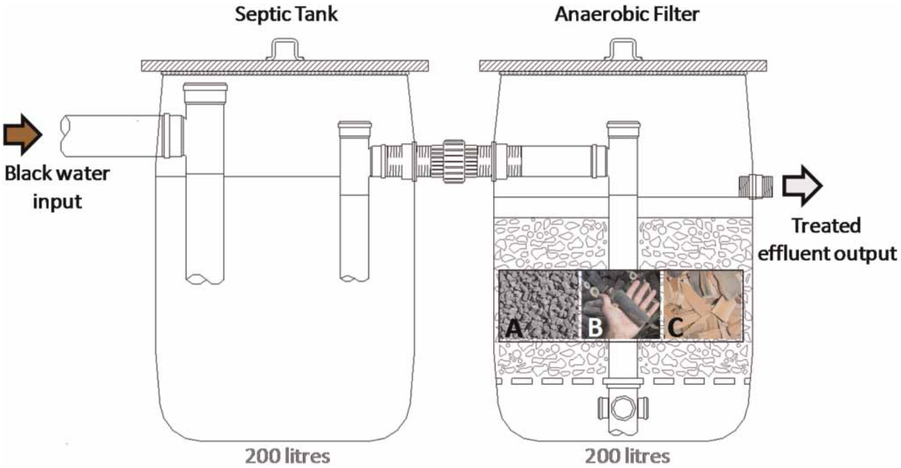

Figure 1 | Schematic drawing of the compact black water treatment system, highlighting the three media tested in the filter: A–crushed stone no. 5; B–bamboo rings; C–brick fragments.

The Uakari Lodge, the location of the study, is a community-based ecotourism enterprise in the Mamirauá Sustainable Development Reserve, a protected area in northern Brazil that is almost entirely in *várzea* (Figure 2). This region is a World Heritage Site and a Wetland of International Importance (Ramsar Convention 2013).

To evaluate effluent quality over time, monthly samples were taken between 2010 and 2013. The samples were collected at the entrance to the septic tank and exit of the anaerobic filters, to characterize the raw water. Determinations were made of: ammonium, biochemical oxygen demand (BOD), chemical oxygen demand (COD), total phosphorus, total nitrogen, pH, temperature and turbidity. All of the analyses followed American Public Health Association recommendations (APHA 2005).

Calculation of load removal efficiency took into account the average number of guests per day.

To test the homogeneity of the BOD removal data, the *Levene* test was conducted, to verify normality, the *Kolmogorov–Sminov* test, and to evaluate the similarity between the average efficiencies of BOD removal, the *Kruskal*–Wallis test.

Factors considered in evaluating the technical viability of the systems included both pollutant removal efficiency and technical aspects.

Methods for the analysis of economic viability

To determine the financial viability of the project, we carried out a cost analysis, assessing the impact of the treatment system structure cost on the total cost of constructing a floating home, as well as the impact of annual maintenance of the home with a black water treatment system on the disposable income of families resident in the Mamirauá and Amanã Reserves.

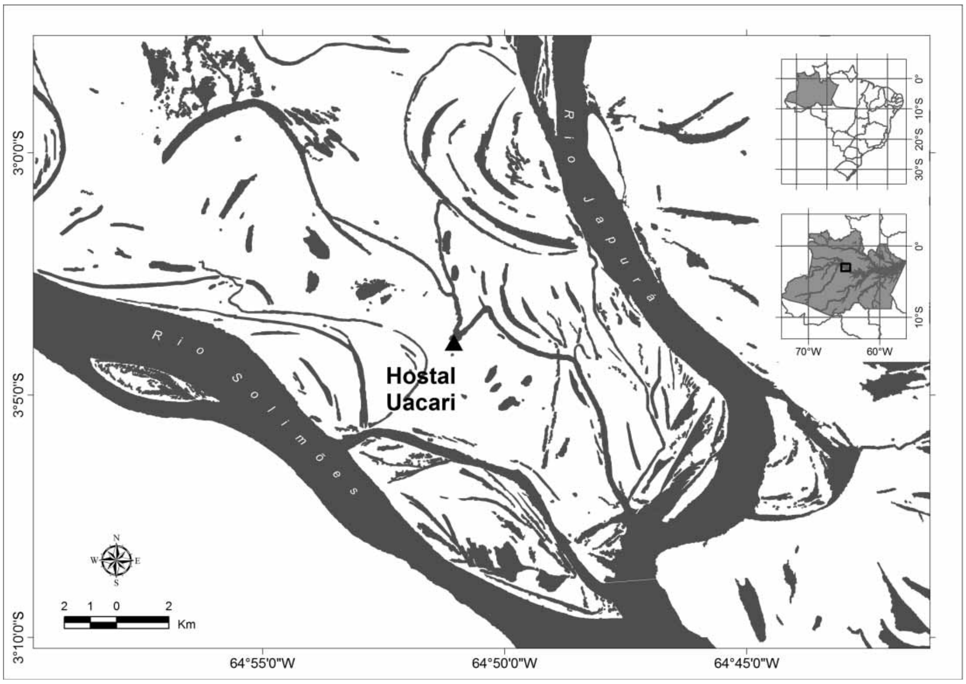

Figure 2 | Location of the study in the Mamirauá Sustainable Development Reserve, Brazil. Source: SIG-IDSM.

Costs are related to the size of the residential structure, so parameters were established to estimate the total costs of materials used in construction. The residence considered was large enough to house six people, a typical average in the Mamirauá and Amanã Reserves (Peralta & Lima 2013).

To determine construction costs, a builder was interviewed and the quantities of material estimated. The data for construction of the system came from this experimental study. All prices were collected in Tefé in 2014, the closest urban centre to the Mamirauá Reserve, and converted to US Dollar. We thus considered the following cases:

- Case 1. A floating home with no compact black water treatment system – (i) cost of construction materials; (ii) cost of labour.
- Case 2. A floating home with a compact black water treatment system – (i) cost of construction materials for residence; (ii) cost of labour for residence; (iii) cost of construction materials for treatment system; (iv) cost of labour for treatment system construction.

Case 1 differs from case 2 in the costs of materials and labour for the treatment system. The annual costs in each case were calculated on the basis of depreciation and preventive maintenance.

The lifespan of floating homes is 25 years, according to the builder, and that of the treatment system 40 years, since its key components are made of PVC (Baitz *et al.* 2004). Since structures are used until they no longer serve their purpose the depreciation calculation was made by dividing the total value of the materials for its life span (Humphries *et al.* 2012) and preventive maintenance costs were fixed at 60% of annual depreciation.

RESULTS AND DISCUSSION

Pollutant removal capacity

The analytical results are presented in Table 1. The organic material concentration (BOD and COD) is higher than reported elsewhere for raw sewage, but is reduced significantly in all of the filters, demonstrating the system's removal potential for this pollutant. With respect to COD concentration, raw

Table 1 | Physical and chemical parameters of anaerobic filter effluent for different filter media

Parameters	Raw black water	Crushed stone A	Crushed stone B	Bamboo rings	Brick fragments A	Brick fragments B
pH	8.1	8.2	8.4	8.2	8.5	7.5
sd	0.6	0.5	0.5	0.5	0.6	0.5
n	15	15	21	23	22	21
Temperature (°C)	27.1	28.1	27.5	27.8	27.9	28.0
sd	1.7	1.9	1.7	1.7	1.9	1.7
n	12	12	17	19	18	17
Turbidity (NTU)	4,432.8	140.0	134.2	189.1	76.7	370.7
sd	6,594.3	87.1	81.7	113.5	56.8	165.0
n	14	14	20	22	21	20
Ammonium (mg L^{-1})	482.5	297.2	197.8	354.1	293.5	296.8
sd	552.1	111.9	105.6	129.7	116.0	192.2
n	14	11	21	20	21	19
BOD (mg L^{-1})	10,402.1	167.2	283.4	421.1	236.0	569.0
sd	13,762.1	76.7	172.0	174.2	174.9	322.1
n	12	12	19	21	18	19
COD (mg L^{-1})	19,582.1	899.9	802.8	923.3	770.2	1,362.9
sd	28,780.9	1,205.0	1,016.8	1,001.9	1,279.1	1,212.2
n	15	12	16	20	18	18
Phosphorus (mg L^{-1})	315.4	78.5	75.1	71.5	59.3	95.9
sd	275.8	64.9	75.3	44.5	34.0	37.1
n	14	12	20	20	20	18
Nitrogen (mg L^{-1})	581.9	314.5	229.5	379.4	323.3	316.7
sd	272.3	95.9	127.3	107.1	112.9	77.2
n	13	12	21	21	21	19

Legend: sd. = standard deviation; *n* = number of samples/determinations; BOD = biochemical oxygen demand; COD = chemical oxygen demand.

sewage has a high standard deviation, indicating that the parameter varies with time, which is explained by the sewage contribution to the system. Since the treatment units are installed in a guest lodge, effluent generation is directly related to the number of tourists, varying over the year. The estimated flow for each system is approximately 60.5 L/day^{-1}, with 2.5 tourists using each system daily, on average. The hydraulic retention time is 3 (± 2) days, possibly due to the relatively small reactor volumes.

In this study, temperature was not a limiting factor since the overall average for all of the filters was above 27 °C, the same as that of the water body in which the units are installed, as they are partially submerged.

The minimum viable temperature range for anaerobic systems is between 20 and 25 °C (Kalogo & Verstraete 2001; Bergamo *et al.* 2009), although Luostarinen *et al.* (2007) concluded that temperature has no significant effect on COD removal.

The average pH values found were not within the optimal range. Sperling & Chernicharo (2005) indicate that the ideal for methanogenesis is between 6.6 and 7.4, with a tolerance of 0.6 between the extremes. All of the filters exhibited an average pH above the optimum, although very close to it. These values can affect system efficiency as they inhibit methanogenic micro-organisms.

The total phosphorus values for the filters were between 59.3 and 95.9 mg L^{-1} for the treated effluents, slightly below those presented by Van Voorthuizen *et al.* (2008), treating black water anaerobically (112 mg L^{-1}). The total phosphorus concentration in the effluents studied was similar for all the filters, apart from 'brick fragments A', which achieved an average concentration of 59.3 mg L^{-1}.

The significant differences between the removal efficiencies of the brick fragments A and B filters are thought to relate to the influent feed. System B is used more frequently, as the lavatory is used by lodge employees. This increases daily use, with a greater concentration of nutrients in relation to the lavatories used only by tourists.

In general, phosphorus concentrations are elevated in black waters without treatment. In this study, the mean phosphorus concentration in the influent was 315 mg L^{-1}. Van Voorthuizen *et al.* (2008) report an average concentration for total phosphorus of 121 mg L^{-1} in black waters, while Zeeman *et al.* (2008) show a concentration range of 110–280 mg L^{-1}.

The majority of nitrogen – some 82% – in raw black water was present as ammonium. This is the same as presented by Van Voorthuizen *et al.* (2008), while Henze & Ledin (2001) showed total nitrogen and phosphorus concentrations in ranges of 100–300 and 40–90 mg L^{-1}, respectively. The values from this study averaged 581.9 to 315.4 mg L^{-1} for raw black waters. The average total nitrogen concentration reported by Gallagher & Sharvelle (2011) is 145 mg L^{-1}.

The BOD was used to verify treatment efficiency (Figure 3). The average removal efficiency for septic tanks followed by anaerobic filters is up to 85% (Von Sperling & Chernicharo 2005). The five evaluated filters behaved similarly up to December 2013, after which their efficiencies fell and, later, became dispersed. Removal efficiencies decreased in January and February 2013 as the raw effluent had low BOD concentrations, possibly due to cleaning activities.

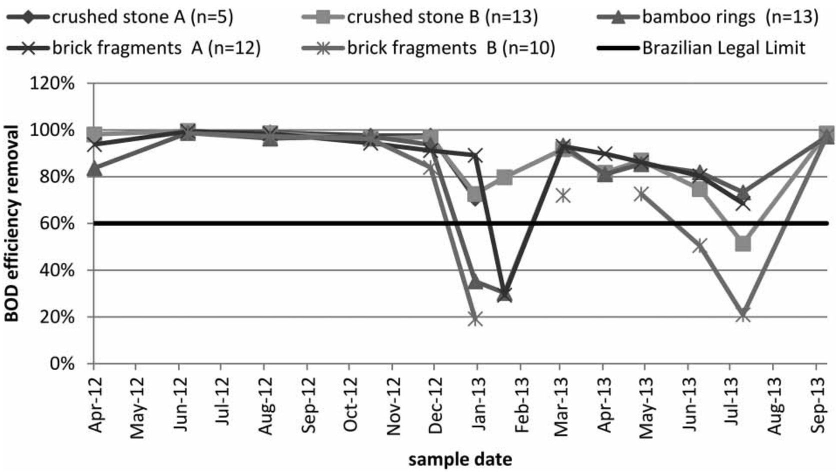

Figure 3 | Efficiency of BOD removal for three different types of filtration media.

The statistical aspects of BOD removal efficiency (Table 3) were used to verify the homogeneity of the variances between the filters ($p = 0.139$ in the *Levene* test), although the data do not show normal distribution ($p = 0.000$ in the Kolmogorov–Smirnov test). The results of the *Kruskal–Wallis* test ($p = 0.301$) indicate that the filter removal averages are similar, in other words, the filters performed similarly.

Verifying the removal of organic load (Table 2), measured via COD, the brick fragments A filter had the highest removal capacity, removing on average 83% of the input load. The high black water load inhibits removal to some extent, and the system must be improved to increase efficiency.

Table 2 | COD organic load and removal efficiency with anaerobic filters

	Raw black water	Crushed stone A	Crushed stone B	Bamboo rings	Brick fragments A	Brick fragments B
COD Load (g/day)	1,185.6	26.5	51.8	56.1	42.7	79.8
Removal efficiency (%)	–	81% (± 27.5)	77% (± 38.7)	77% (± 27.1)	83% (± 13)	67% (± 51.3)

The determination of technical viability is related to adherence to legal standards for effluent emissions. Brazilian legislation stipulates that sewage treatment units must have BOD removal efficiencies exceeding 60%. In this study, only 7 out of 53 samples did not reach this minimum.

Average effluent nitrogen concentrations are all above the legal limits permitted. Nitrogen concentrations in the effluents were all in the range 229.5–379.4 mg L^{-1}, against the legal maximum of 20 mg L^{-1}. However, it does not seem that these concentrations had any impact on the receiving waters as the system outflow is low, approximately 60.5 L/day.

The removal efficiencies for other pollutants are shown in Table 3.

The most efficient filter for COD removal was brick fragments A, with 83%, indicating that the system's ability to remove organic material is good. The brick fragments B filter achieved a lower removal rate (51%). It is possible that this relates more to discontinuous use of the system due to tourism's high seasonality, affecting the input. Leitão *et al.* (2006) report that hydraulic and effluent load fluctuations affect anaerobic reactor performance. Silva *et al.* (2013) obtained an average of 41% COD removal by septic tank systems incorporating full-scale anaerobic filters, corroborating with this study.

Nutrient removal by the systems was variable. The crushed stone A filter reached a removal efficiency of 84% for phosphorus, while the bamboo ring filter achieved 39% nitrogen removal.

Table 3 | Efficiency of removal of different parameters treated with crushed stone, bamboo rings or brick fragments in anaerobic filters

Filter media	Crushed stones A	Crushed stones B	Bamboo rings	Brick fragments A	Brick fragments B
BOD R.E.	71%	87%	81%	84%	64%
sd	54%	14%	23%	19%	37%
n	6	13	13	12	11
COD R.E.	67%	77%	77%	83%	51%
sd	49%	27%	28%	19%	50%
n	8	11	15	13	13
Phosphorus R.E.	84%	81%	78%	82%	65%
sd	11%	26%	20%	16%	31%
n	5	9	10	10	9
Nitrogen R.E.	55%	63%	39%	47%	57%
sd	18%	19%	23%	25%	13%
n	5	9	10	10	9
Total Solids R.E.	84%	77%	80%	86%	79%
sd	26%	26%	25%	11%	21%
n	9	9	11	12	13

Legend: R.E. = removal efficiency; sd. = standard deviation; *n* = number of samples/determinations; BOD = biochemical oxygen demand; COD = chemical oxygen demand.

Technical aspects

The technical aspects of the technology are discussed here, taking into account the key factors influencing sanitation selection (Brikke & Bredero 2003), as well as the specific characteristics of this case study.

- Local conditions: the number of residences, their locations and the demographic profile affect the sanitation adopted. Originally, the system was developed for floating homes, but it can also be used for land-based homes subject to seasonal flooding.
- Current situation: This technology was designed for floating residences in rural wetlands that are flooded periodically or permanently, and where access to sanitation is difficult. Because of this, it

is also applicable to urban areas where there is no sewerage network serving floating residences. This situation enables people to cease the common practice of open defecation.

- Reuse of sub-products: various sanitation technologies enable reuse of their sub-products (urine and feces), as do many dry sanitation models. The technology in this study does not enable sub-product reuse as the effluent is lost in the receiving water.
- Water availability: this system depends on water for flushing. The ideal situation is when the residence has piped water in sufficient quantity to facilitate flushing. In the absence of a network, buckets can be used, which is easy as the home is on the water.
- Degree of complexity: this determines the technology's acceptance and adoption by users; it involves aspects such as (a) ease of construction, (b) potential for local/home repair, (c) use and operation, (d) maintenance, (e) availability of components. All of these are positive for the proposed technology, since construction is simple and can be done locally (residents can build their own system following assembly instructions). Maintenance consists of emptying the system annually, preferably with a manual pump, and one of the treatment units and discharges the waste (sludge) to previously prepared drains. The technology is easy to operate, and functions well if best-use practices are followed. All components are available in the local market, which facilitates both construction and repair. None of the items/materials are complex, such as pumps or electrical devices.
- Number of users: the technology, at reduced volume, is designed for family units, thus the number of users for any system is restricted. Ideally, a maximum of 4 people uses one installation, although it can operate with up to 6.
- Area required: the area occupied is quite small. The entire system measures around 2.5 m^2 (1×2.5 m), and does not take space inside the house as it is fixed to the outside.
- Potential impact of effluents: the potential for the treated effluents to cause pollution is reduced because the organic material is treated with high efficiency (average BOD removal efficiency = 77%). However, phosphorus and nitrogen nutrients continue to be present at high concentrations. Nevertheless, the input concentrations of these nutrients are higher and they are removed to some extent. Furthermore, the enormous volume of water in the river reduces the effluent potential because of its dilution.

Economic viability of the black water treatment system

For case 1, the total cost was US$ 19,000 (Table 4), In case 2, additional costs related to the treatment system were included: US$ 860 for materials and US$ 120 for labour, totalling US$ 19,980; with an annual cost of US$ 800.

Table 4 | Total costs for cases 1 and 2

	Item	Price in US$
Case 1 – cost for one family residence	Total for construction	19,000
Case 2 – cost for one residence including a black water treatment system	Tanks, tubes and connections	180
	Consumable materials	20
	Components for lid	50
	Components for external wood structure	330
	Toilet	120
	Manual cleaning pump	170
	Total for materials	870
	Labour	130
	Total for treatment system	1,000
	Total case 2 (case 1 + treatment system)	19,980 (95% of house construction and 5% of treatment system)

The difference between the two cases – the cost of the sanitation unit – is around US$ 1,000, which represents only 5% of the building total. The small additional contribution seen in case 2 indicates that installation of the treatment system in floating residences is financially feasible.

Another aspect analysed was the annual costs of the treatment system after installation. The costs were determined for each case – see Table 5.

Table 5 | Annual costs for a floating residence and for the black water treatment system

	Total cost (US$)	Cost of materials (US$)	Lifespan (years)	Annual depreciation	Preventive maintenance cost (US$)	Annual cost of structure (US$)
Annual cost of floating residence (case 1)	19,200	11,900	25	500	300	760
Annual cost of treatment system	1,000	870	40	25	15	40
Annual cost for case 2 (case 1 + annual cost of treatment system structure)	800					

Case 1 shows an annual cost of US$ 760, while in case 2 this increased to US$ 800 because of the annual costs of the treatment system. Floating residences are used frequently by the Mamirauá reserve populations, thus depreciation and maintenance costs would already be absorbed in family budgets. So, the relevant value is the annual cost of the treatment system.

The treatment system adds US$ 40 to the annual expenses. According to Peralta & Lima (2013), average household income in the reserves in 2010 was around US$ 4,000. In other words, the annual costs of the treatment system would be 1% of family income, so its impact would be small. This is a key indicator for user accessibility to the technology.

To acquire the system, total outlay for construction of a treatment system structure would take up 24% of the annual family budget. While acquisition of a system requires a large portion of family income, the processes determining consumption in such households should be considered. These comprise a logic in which 'production and consumption are (…) mutually exclusive' (Peralta e Lima 2013). Consumption decisions are linked to subjective evaluation by the household group, and production is determined by its needs, desires and projects. Thus, the acquisition of goods is planned in advance, with a view to future expenditure.

CONCLUSIONS

The following conclusions can be drawn

- The three filter tested (crushed stone, bamboo rings and brick fragments) exhibited similar treatment efficiencies, primarily in relation to organic material. In this context, the materials used should be those with the easiest accessibility.
- The proposed technology is technically viable in relation to the characteristics of the *várzea* environment, where access to sanitation is practically non-existent. However, new studies should be undertaken, prioritizing modifications to the system whereby the concentrations of total phosphorus and nitrogen in the effluent are reduced and legal standards met.
- The viability of the technology depends on its financial accessibility in the target market, and this study's results confirm that it is financially viable. It is for the family group to decide whether to adopt the technology, since their income is the result of their own productive work.

- Floating residences are very common in the protected area analysed. In general, community members build their own homes, using available natural resources in traditional ways –the wood used to construct floating homes is taken from the communities. Access to these resources can reduce the total costs incurred, facilitating access.

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