Research Paper

Performance of black ceramic water filters and their implementation in rural Ecuador

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ABSTRACT

In rural Ecuador, microbial water contamination is associated with child morbidity mainly due to gastroenteritis. Black ceramic water filters (BCWF) are a new household water treatment recently developed to improve microbial removal from the classical model implemented worldwide. This study has assessed BCWF microbial performance at laboratory level by continuous filtering of spiked water with microbial surrogates (*Escherichia coli* and MS2 bacteriophage) and highly contaminated surface water to evaluate physicochemical pollutants' removal. At field level, baseline studies in Nanegal and Gualea districts have been performed to evaluate water quality and hygiene practices among communities and a six-month BCWF field implementation study in the Santa Marianita community. Results revealed poor drinking water quality in communities studied. Water treatment practices at household level were reported in low percentages. Conversely, results in BCWF filter assays at laboratory level for 600 litres of usage have shown 5.36 logarithms of bacterial removal and 3.83 logarithms for viral removal and significant reductions of physicochemical pollutants considering international standards. BCWF implementation in the Santa Marianita community reveals promising results on microbial water quality in households using this new technology. However, it is important to reinforce correct BCWF maintenance for better performance at field level.

Key words | ceramic water filters, Ecuador water access, waterborne virus, water quality

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INTRODUCTION

Regarding recent updates on water access in 2015, there are 2.1 billion people still lacking access to improved drinking water sources, many of those living in rural areas (WHO 2017). However, several authors have discussed that the 'improved source' indicator used by the Join Monitoring Program (JMP) of the World Health Organization (WHO) does not give a real picture of safe water access because it does not consider water quality (Shaheed *et al.* 2014). Microbial water quality is essential to define drinking water as safe and is, therefore, a key factor for reducing child morbidity and mortality.

Almost 40% of the population in rural areas of Ecuador do not have access to improved water sources (MSP and INEC 2013), but these numbers might be underestimated when regarding water quality. Guidelines regarding drinking water quality define a safe drinking water source when less than 60% of monitored samples are faecally contaminated (Bain *et al.* 2014). Studies in rural Ecuador reveal

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that source water and household water, even after local treatments have been applied, have poor quality with high percentages of polluted samples (Carlton *et al.* 2014).

Conversely, epidemiological data from the Ecuador Health Ministry in 2015 indicate that the top seven causes of morbidity are infectious diseases, with 10% of total disease incidence associated with gastrointestinal infections (MSP 2017). Child mortality caused by diarrhoea among children under five years is still the leading cause worldwide, while in Ecuador, recent data reference high mortality rates within Latin America with 14 per 10,000 children in 2015, only surpassed by Bolivia and Venezuela (GBD 2017).

Another aggravating consequence for health, caused by poor water quality, is the burden of child malnutrition associated with chronic gastrointestinal infections as reported in areas with low sanitation access worldwide (Dangour *et al.* 2013). In the case of Ecuador, a 25.3% child malnutrition level has been reported across the entire country (<5 years), but those numbers are almost double in rural areas.

Among the most prevalent aetiologies causing gastroenteritis in children in areas with poor sanitation, viruses are the most prevalent agent worldwide (Kotloff *et al.* 2012). Among Ecuador's children, it has been reported that *Shigella* spp., rotavirus and *Giardia lamblia* are the top causes of diarrhea (Vasco *et al.* 2014). Although multivariable causes are associated with diarrhoea, drinking contaminated water plays an important role that can be easily improved with appropriate treatments.

In order to reach the most affected populations lacking safe drinking water, a decade ago the WHO, in partnership with UNICEF, proposed household water treatment (HWT) strategies to increase access in remote areas with a low density of inhabitants (Clasen 2010). The HWTs are designed to provide drinking water for a whole family at the point of use, and most of them have a system to store the treated water safely to avoid recontamination. Tens of HWTs have been designed in the last decade to provide efficient solutions for international organizations with the objective to increase equal access to safe drinking water worldwide.

Recently, a new prototype has been developed with promising results: the black ceramic water filter (BCWF) (Guerrero-Latorre *et al.* 2015). This new technology is the product of research that aimed to improve the effectiveness of the existing ceramic water filters for the removal of enteric viruses.

BCWFs fired in a reductive atmosphere are a simple variation, in relation to the classical ceramic water filter (CWF), that keeps the product inexpensive and improves viral removal efficiencies up to 3 logarithms, accomplishing the WHO requirements for HWTS technologies (WHO 2011a). Moreover, long-term assays with BCWF show consistent removal values after 1,000 L filtered. This new improved prototype can be easily implemented in existing CWF factories, as firing in a reductive atmosphere will just require a specific kiln that can be built with local materials (traditional bricks, sand and concrete), or current kiln models can even be accommodated to fire in reductive conditions.

The aim of this study is to implement this new HWT technology in Ecuador, to evaluate its performance after specific local production and to evaluate its potential implementation in a rural scenario by a baseline analysis. To properly design any programme to improve drinking water quality, baseline studies are needed to evaluate the levels of water contamination, the knowledge, practices and aptitudes from the community prior to intervention.

METHODS

Baseline study area

Communities included in the study were selected by an inclusion criterion defined as: Nanegal and Gualea communities of at least ten families permanently living where water supply was not managed by the *Empresa Pública Metropolitana de Agua Potable y Saneamiento de Quito* (EMAPS, Quito). Community chiefs included in the study were asked to participate prior to intervention.

Hygiene practices and water quality assessment

Ten households were interviewed in each community to address important issues about drinking water knowledge, aptitudes and practices (KAP questionnaires). To our knowledge, this is the first questionnaire developed to assess the level of KAP towards drinking water among families with children in the region. Thirty questions were asked in four separate parts: (i) sociodemographic status of the interviewed person; (ii) water access; (iii) water treatments; (iv) hygiene practices.

Water samples at the point of use were collected in ten households randomly selected from all communities included in the study during February–June 2017. Analysis of total coliforms and *E. coli* per 100 mL where done by filtration with commercial nitrocellulose membranes with pores of 0.45 μm and incubated in a chromogenic agar at 37 °C for 18 h (Chromocult Agar, Merck) (ISO 2014). Filtration was done with a pump and no pressure was applied. Moreover, water sources from all communities included in the study were evaluated for specific human faecal contamination, using human adenovirus as a viral indicator in 10 L water samples by qPCR and using nested PCR as a confirmatory test (Rodriguez-Manzano *et al.* 2012).

HWTS production and evaluation

The new prototype of CWF, called BCWF, was produced for the first time in the Horeb factory located in San Carlos, Pichincha, Ecuador. This factory has been producing CWF since 2010 at a rate of 500 filters/year. In March 2017, a black ceramic kiln was built in the Horeb facility and the first reductive ceramic filters were cooked. The first BCWF produced in Ecuador (San Carlos, Pichincha) were cooked in a firewood kiln up to 905 °C applying a reductive atmosphere at the end of the process (see Figure 1). After cooking, a filtration test was applied to select filters with a 1.5–2.5 L/h ratio. Following the filtration test, colloidal silver was applied with 250 mL of a solution at 375 mg/L. Ready-to-use filters were sent to UDLA laboratories for microbiological testing.

Filtration tests were done with spiked water using two microbiological surrogates: *E. coli* (CECT 25922) as a model bacteria and MS2 bacteriophage as a model virus, following adapted protocols based on international standard procedures (ISO 2004). Dechlorinated tap water was spiked with surrogates to a final concentration of 1.5×10^6 cfu/mL for *E. coli* and 8.24×10^4 pfu/mL for MS2 phage. Then, 5 L of spiked water was applied to each filter (three replicates) and after 2 hours of filtering, effluents were collected under sterile conditions. Input and output waters were quantified for *E. coli* and MS2 surrogates in order to calculate log reduction values (LRV) for each test. A permanent filtration system was implemented to evaluate filters throughout simulated use up to 600 L. Moreover, the removal of several physicochemical parameters was evaluated by filtering three samples of highly polluted river water: colour, turbidity, nitrite, nitrate, biochemical oxygen demand (BOD) and chemical oxygen demand (COD), ammonia, phosphate, chloride, sulfate, oil and alkalinity.

BCWF pilot implementation study

The Santa Marianita community was selected to implement the BCWF technology and to follow up during six months. After ethical approval (Research Ethics Committee with Human Beings (CEISH) UDLA, reference number 2017-0902), the households with at least one child of <10 years old that agreed to participate ($n = 32$) were randomly

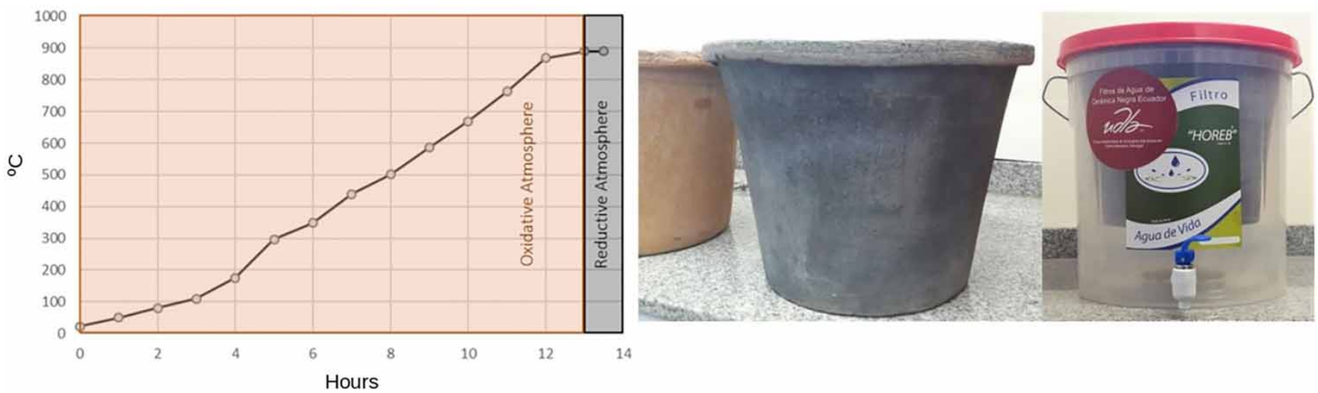

Figure 1 | Ceramic reductive firing of BCWF. Left = temperature curve; right = BCWF appearance.

distributed in two groups: control and experimental. The control group had no BCWF provided and the families used their conventional strategies for drinking water. The experimental group received the BCWF and a short training on usage. All participants were visited every 3 weeks (9 visits in total) for water quality testing before and after treatment.

RESULTS

Baseline study

Following inclusion criteria, five communities were selected to participate in the study. Two from Nanegal District: Santa Marianita and Palmito Pampa and three from Gualea District: Vista Hermosa, Guanabana and Las Tolas (Figure 2).

Water quality and hygiene practices

KAP questionnaires and drinking water analysis conducted in the five communities studied are summarized in Table 1. Results show that the profile interviewed was female, adult and with primary education. Pipeline was the main water source in households interviewed as all communities had distribution systems implemented from a unique source from surface water. The number of litres collected per day was variable, except for Palmito Pamba where restrictions were applied as it had the only treated system managed by the community using chlorination. The same behaviour was observed for the number of litres used for drinking purposes, giving the lower numbers for Palmito Pamba. Regarding household water treatments used, the main treatment reported was boiling in all communities. However, Santa Marianita had a majority of households reporting direct consumption of tap water. Closed and clean containers were also observed in most of the households visited. Washing hands at critical points was highly variable in each community but, overall, there was a significant lack of this hygienic behaviour.

Drinking water quality in the communities studied reveals that water treatments are mandatory almost everywhere. Palmito Pamba was the only community chlorinating its water within a central system, and faecal indicators showed its excellent quality of water with no *E. coli* detected in any sample. The worst microbial quality rated by faecal indicator bacteria was Guanábana, followed by Vista Hermosa, Santa Marianita and Las Tolas.

Santa Marianita was the only community with human viral contamination detected in their drinking source with 84.6 GC/100 mL. Nested PCR was performed to amplify adenovirus and results confirmed the presence of viral contamination. PCR product was sequenced (ABI3130 genetic analyser Applied Biosystems), obtaining a 70-bp sequence with 94% coverage and 99% identity with human adenovirus 40, recently isolated in children from Brazil (Portes *et al.* 2017). This type of human adenovirus is associated with acute gastroenteritis (Lion 2014). These results indicate the urgent need to take measures in this community to treat their water prior to consumption, especially among children.

Figure 2 | Map of Gualea and Nanegal districts. Communities studied are marked with the approximate population in superscript.

Black ceramic water filter efficacy at laboratory level

Eight assays of microbiological efficiency showed reduction values of 5.36 logarithms for *E. coli* (standard error ±0.38) and 3.83 logarithms for MS2 bacteriophage (standard error ±1.47) (Figure 3). Bacteria removal shows similar results to those previously reported by classical CWF studied (van der Laan *et al.* 2014). The viral removal has higher variability but mean reduction values up to 600 L filtered have increased 2 logarithms compared with the classic

Table 1 | KAP questionnaires results in communities from Gualea (Vista Hermosa, Guanabana and Las Tolas) and Nanegal (Santa Marianita and Palmito Pamba) districts

	Vista Hermosa	**Guanabana**	**Las Tolas**	**Santa Marianita**	**Palmito Pamba**
Gender (% interviewed people)					
Female	**70**	**60**	**60**	**70**	**60**
Male	30	40	40	30	40
Age (% interviewed people)					
<20 years	0	0	20	0	0
20–40 years	36.4	**50**	10	**70**	44.4
>40 years	**63.6**	**50**	**70**	30	**55.6**
Education (% interviewed people)					
Primary	**54.5**	**60**	30	**70**	**70**
Secondary	9.1	30	**70**	30	20
No education	36.4	10	0	0	10
Water source (% of houses)					
Pipeline	**66.7**	**63.7**	**63.7**	**90**	**100**
Private well	0	0	0	10	0
Rain	16.7	0	0	0	0
Surface water	16.6	36.3	36.3	0	0
Liters collected per day (% of houses)					
<20	9	**55.5**	**66.6**	45	**100**
20–50	45.2	22.2	22.2	**55**	0
>50	**45.8**	22.3	11.2	0	0
Liters of drinking water person/day (% of houses)					
1–3	36.4	20	0	**50**	**100**
3–5	0	0	0	0	0
5–10	9	20	**100**	25	0
>10	**54.6**	**60**	0	25	0
Household treatments used (% of houses)					
Boiling	**70**	**60**	**60**	40	**60**
Chlorination	20	10	20	0	0
Filtration (cloth filter)	10	20	0	0	10
Nothing	0	10	20	**60**	30
Closed and clean containers (% of houses)					
Yes	**90**	**60**	**80**	**70**	**50**
No	10	40	20	30	**50**
Washing hands critical points (% of houses)					
2 or less times	10	20	**50**	20	0
3 times	10	**40**	30	**50**	30
4 times	30	10	0	30	**50**
5 or more times	**50**	30	20	0	20
Microbial contamination (*E. coli* cfu/100 mL)					
<10 *E. coli*/100 mL	30	10	0	0	**100**
10–100 *E. coli*/100 mL	10	20	**100**	**100**	0
>100 *E. coli*/100 mL	**60**	**70**	0	0	0
Mean (*E. coli*/100 mL)	100.36	135.89	26.6	36.82	0
Viral contamination (HAdV GC/100 mL)					
	ND	ND	ND	**84,6**	ND

Bold numbers indicate the highest values for each category.

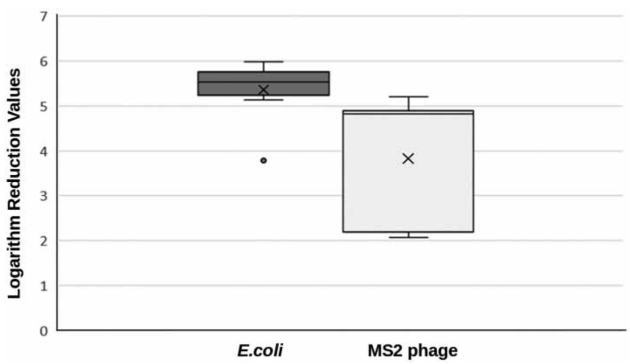

Figure 3 | BCWF microbial efficiency after 600 L filtered using bacterial and viral surrogates.

model of ceramic filter previously described with 1.4 LRV for MS2 phage (Brown & Sobsey 2010).

In order to analyse physical and chemical parameters, highly contaminated surface water was sampled in Guayllabamba river to analyse effluent in three filter replicates. Results shown in Table 2 highlight the reduction percentages for each parameter analysed, compared with standard limits established in drinking water guidelines. Bacteria removal was complete with non-detected colonies in effluents analysed. Colour and turbidity values were re-established after filtration to drinking water standards. The other parameters with non-health concern reported were evaluated giving significant reductions ranging between 100% reduction (BOD) to 13% reduction (COD).

Field BCWF implementation

Six month follow-up revealed the effectiveness of BCWF usage (Table 3). The control group was composed of 17 households with several families drinking water directly from the tap source ($n = 9$), others were boiling water ($n = 8$) with different frequencies and one family reported always drinking bottled commercial water. The experimental group was 18 families using the BCWF during the studied period. The water samples were collected before and after treatment to evaluate the efficiency for each treatment strategy. The control group households that were drinking tap water without any treatment applied were drinking moderate ($n = 8$) or high ($n = 1$) risk microbiological water quality. Control households boiling water with variable frequency had moderate ($n = 6$) or low ($n = 1$) risk level drinking water. Conversely, BCWF showed better water quality after treatment with four households with safe microbial quality levels, 11 households with low risk drinking water and only three households with moderate risk water quality. During the follow-up, poor BCWF

Table 2 | BCWF removal assay with natural waters testing microbial and physicochemical removal in filtered waters considering drinking water guidelines (WHO 2011b)

Parameter	Raw water		Effluent ($n = 3$)	SD		Reduction (%) level	Limits drinking water guidelines
E. coli (cfu/100 mL)	3,450.0	✗	0	0	✓	**100.0*****	0
Color	46.0	✗	6.83	0.67	✓	**85.14****	15
Turbidity	44.00	✗	0.67	0.58	✓	**98.48*****	5
Nitrite (mg/L)	0.60	✓	0.41	0.06	✓	32.09*	3
Nitrate (mg/L)	2.88	✓	2.19	0.19	✓	23.96*	50
BOD	6.00		0.00	0.00		**100.00*****	NHC
COD	21.00		18.25	0.68		13.07*	NHC
Ammonia (mg/L)	0.23		0.17	0.06		23.43*	NHC
Phosphate (mg/L)	0.77		0.12	0.01		**84.59****	NHC
Chloride (mg/L)	18.71		12.97	0.75		30.70*	NHC
Sulfate (mg/L)	29.57		21.98	1.73		25.66*	NHC
Oil (mg/L)	0.01		0.01	0.00		46.15*	NHC
Alkalinity (mg/L)	121.65		102.93	16.21		15.38*	NHC

Reduction levels: *10–50%; **50–90%; ***>90%; NHC: non-health concern. Bold numbers highlight significant reduction levels.

Table 3 | Microbiological quality of drinking water in the Santa Marianita community

Group (Control 'A'/Experimental 'B')	HWTS used	Use reported	*E. coli* tap water cfu/100 mL Mean value (min–max) $n = 9$	*E. coli* drinking water cfu/100 mL Mean value (min–max) $n = 9$
A	No treatment	–––	57 (4–127)***	57 (4–127)***
	No treatment	–––	20 (3–32)***	20 (3–32)***
	No treatment	–––	52 (4–94)***	52 (4–94)***
	No treatment	–––	72 (29–184)***	72 (29–184)***
	No treatment	–––	60 (18–200)***	60 (18–200)***
	No treatment	–––	113 (52–214)****	113 (52–214)****
	No treatment	–––	29 (3–100)***	29 (3–100)***
	No treatment	–––	60 (24–127)***	60 (24–127)***
	No treatment	–––	84 (12–300)***	84 (12–300)***
	Boiling	Always	74 (13–293)***	0 (0–2)***
	Boiling	Always	80 (13–254)***	32 (0–104)***
	Boiling	Always	55 (43–67)***	1 (0–3)**
	Boiling	Frequent	54 (26–90)***	20 (0–77)***
	Boiling	Frequent	45 (14–73)***	25 (0–73)***
	Boiling	Always	80 (13–254)***	16 (2–58)***
	Boiling	Rare	94 (13–327)***	86 (0–246)***
	Boiling	Always	80 (17–277)***	15 (0–41)***
	Bottled water	Always	–––	3 (0–11)**
B	BCWF	Always	45 (20–82)***	2 (0–7)**
	BCWF	Always	29 (12–48)***	4 (0–24)**
	BCWF	Always	129 (15–450)****	1 (0–1)**
	BCWF	Always	112 (21–228)****	8 (0–25)**
	BCWF	Always	87 (14–216)***	6 (0–34)**
	BCWF	Always	109 (16–213)****	0 (0–0)*
	BCWF	Always	55 (2–209)***	7 (0–5)**
	BCWF	Always	216 (23–648)****	15 (0–61)***
	BCWF	Always	110 (35–290)****	7 (0–41)**
	BCWF	Always	98 (42–280)***	6 (0–23)**
	BCWF	Always	138 (74–228)****	28 (0–91)***
	BCWF	Always	107 (9–379)****	9 (0–26)**
	BCWF	Always	122 (41–309)****	24 (0–115)***
	BCWF	Always	49 (27–95)***	0 (0–1)*
	BCWF	Always	54 (1–284)***	0 (0–1)*
	BCWF	Always	48 (13–101)***	2 (0–12)**
	BCWF	Always	50 (16–158)***	0 (0–0)*
	BCWF	Always	35 (8–116)***	7 (0–25)**

Water quality is represented in categories considering the *E. coli* concentration (cfu/100 mL) and safety level: 0, safe (*); 0–10, low risk (**); 10–100, moderate risk (***); 100–1,000, high risk (****).

maintenance was observed in some households regarding washing of containers and taps from the filter.

DISCUSSION

The present study has evaluated the water quality in rural communities near Quito, showing that their drinking water source is highly impacted by microbial pollution in those areas. Moreover, a pilot BCWF implementation study has shown the field efficacy of this new HWTS in a real scenario. Following the JMP basis, those communities had improved water sources as they had distribution systems connected to their households, but water quality did not meet with WHO standards. The results from this study point out that the term 'improved water source' does not always correlate with 'microbial water quality' and increased evidence that new parameters are needed to monitor safe water access worldwide. Nevertheless, Palmito Pampa is an example showing water committees can solve water quality problems, by simple central treatments managed with low resources. In the communities where no central treatments are applied, the water pollution levels indicate that treatments are required to avoid health issues related to faecal–oral transmission. Especially, Santa Marianita had the most alarming values as human faecal viral contamination was detected, and an aetiological agent of gastroenteritis was sequenced from the main water source. Regarding the KAP questionnaire, it is important to highlight the low percentage of Santa Marianita community (40%) practising measures to improve drinking water for their families. Those scenarios need new strategies to improve water quality at home. BCWFs are a HWT that have as great potential as the classical version of CWF, which has previously reported high and long-term adherence to this water treatment (Ojomo *et al.* 2015). Moreover, microbial reduction performance shown by the BCWF at laboratory level using spiked and natural water is enough to provide safe water in the communities studied. The values obtained for bacteria removal are analogous to the classical model of CWF. BCWF viral removal reaches 3.83 logarithms of reduction with an important variability that might be due to the heterogeneity distribution of viruses in water matrices. However, the mean reduction is almost 2 logarithms higher than the classical filter reported by studies after 600 L filtering using the same viral surrogate MS2, as viral removal by CWF has been quantified as 0.6 and 1.4 LRV. The viral removal for communities where viral pollution was detected advances a promising application to avoid viral gastroenteritis among populations, especially children.

The pilot implementation of BCWF in Santa Marianita reveals the field effectiveness of this new HWT, showing good results of disinfection and improving the water quality in a real scenario compared with control group households. However, the BCWF removal efficencies demonstrated at laboratory level (*E. coli* LRV 5.36) are not reproduced in the field scenario as hygiene practices might alter the microbial output.

CONCLUSION

This study provides new evidence of the need to implement new indicators for safe drinking water access when monitoring Sustainable Development Goals that include microbial water quality. Additionally, the results obtained indicate that viral indicator of faecal contamination complements important information on drinking water microbial risks. BCWFs produced for the first time in Ecuador show great laboratory performance in reducing microbial and chemical parameters with natural and artificial waters. The first BCWF implementation in a rural community showed promising results in improving microbiological water quality, but hygiene practices and maintenance need to be reinforced among communities for better performance.

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