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RESEARCH ARTICLE

Evaluation of a participatory citizen approach to monitor microbial water quality of self-supply in urban Indonesia

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ABSTRACT

A participatory citizen approach was established to monitor microbial water quality in household self-supply in Bekasi, Indonesia, and evaluated using a conceptual framework for context analysis, process evaluation and impact assessment (CPI). Households tested their self-supplied water for *Escherichia coli* presence every two weeks for six months, accompanied by pre- and post-monitoring surveys. The approach provided reliable water quality results, and increased awareness of water quality; however, nearly half of the households dropped out of the monitoring and increased awareness did not translate into actions that improved water quality within the study period. Contamination rates ranged from 11% to 70% at source and from 15% to 44% at point-of-use. Household-led testing could fulfil an important monitoring role in self-supply contexts, however it may have little impact on the drinking water safety unless accompanied by support to improve source protection and strengthen household water treatment and storage practices.

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Self-supply; water quality monitoring; microbial water quality; participatory monitoring; citizen science

Introduction

More than 1 billion people worldwide secure their household water supply through self-supply (Chávez García Silva et al. 2020; Foster et al. 2022, 2021). Self-supply refers to an on-premises water source, usually groundwater or rainwater, that is privately owned, financed and managed by an individual household (Grönwall, Mulenga, and McGranahan 2010). Self-supply has developed in low- and middle-income countries (LMICs) in a variety of different contexts such as densely populated urban areas as well as remote rural settings (Foster et al. 2021; Genter, Willetts, and Foster 2021). It has become essential for people who need to supplement inadequate public water supplies, and for those outside the reach of water utilities or community-managed water supplies (Grönwall, Mulenga, and McGranahan 2010). Although heavily relied upon by households in many LMICs, self-supply is generally unregulated, unmonitored and overlooked by policy and practice.

Monitoring water service delivery is essential for government's regulation and to track progress towards the Sustainable Development Goal of universal access to safe drinking water by 2030 (SDG 6). The relevant indicator is the proportion of the population using safely managed drinking water services, where safely managed refers to drinking water from an improved water source that is located on-premises, available when needed, and free from faecal and priority chemical contamination (WHO, & UNICEF 2017). Self-supply is often not explicitly recognised as a formal service delivery model and, by default, water safety is the responsibility of households (Genter et al. 2023). Although poor water quality is a major problem (Genter et al. 2022; Genter, Willetts, and Foster 2021), self-supply has the potential to fulfil the criteria of a safely managed water service as it is located on the premises of a user household. Self-supply is not adequately captured in SDG monitoring, as water quality is currently monitored using routine water quality data from utilities or regulators or Multiple Indicator Cluster Surveys (MICS) conducted only in certain countries every few years (Foster et al. 2021) To achieve SDG 6 on safely managed drinking water for all, it is crucial to understand service delivery outcomes of self-supply and water quality monitoring options.

Studies have shown drinking water from groundwater self-supply sources is commonly contaminated, pointing to the need for regular monitoring of water quality (Genter et al. 2022). Monitoring of faecal contamination of drinking water is usually based on faecal indicator bacteria *Escherichia coli (E. coli)* in a 100 mL water sample, which is the recommended measure by the (WHO 2022). The guideline value is that no *E. coli* should be detected in any 100 mL sample (WHO 2022). SDG Target 6.1 calls for regular reporting on the bacteriological quality of drinking water at the national level, conducted at the local or regional level (WHO 2017). Methods for the quantification of *E. coli* include direct quantification of colony forming units via membrane filtration techniques and estimates of the Most Probable Number (MPN) of bacteria via broth-culture-based assays (Bain et al. 2012). Presence/absence tests have shown to offer a cost-effective alternative to quantitative methods, as they are quicker to perform and require less laboratory equipment (MacLeod et al. 2019). Nevertheless, methods for the detection and monitoring of microbial contamination in LMICs may be hampered by limited resources, and inadequate

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or inaccessible laboratory infrastructure (Genter et al. 2019; Khatibi and Yamakanamardi 2010; Schertenleib et al. 2019). To our knowledge, the literature currently lacks documentation on the methods of monitoring and reporting microbial quality in self-supply services. To support the provision of safe drinking water for self-supply, monitoring is necessary to inform self-supply water quality management.

There is little guidance and evidence on best monitoring practices for self-supply services in low resource settings. The WHO guidelines for drinking water quality and the water safety plan manual recommend that operational monitoring and independent surveillance should occur for common drinking water quality monitoring programs (Bartram et al. 2009; WHO 2022). Operational monitoring serves to inform decision-making and corrective actions on control measures such as source protection and water treatment, while surveillance of drinking water quality engages an independent third party in oversight of the water supply, with the specific mandate for protection of public health (Crocker and Bartram 2014). Operational monitoring of piped water supplies using dedicated or shared laboratories and surveillance is a common monitoring scenario, however, operational monitoring of non-piped, or point-source water supplies, such as boreholes, is rare (Crocker and Bartram 2014).

Participatory citizen monitoring has become increasingly popular in natural science research but is still scarce in the field of drinking water monitoring. Citizen science is the participation of the general public in the generation of scientific knowledge (Buytaert et al. 2014). In the water sector, citizen science is most prominent in the field of surface water quality monitoring programs measuring chemical parameters and biological indicators (Brouwer et al. 2018; Conrad and Hilchey 2011). Citizen science water projects are predominantly in the Global North, however, there is growth in citizen science water projects in the Global South (Walker, Smigaj, and Tani 2021). While participatory monitoring projects in the Global North have been dominated by water quality assessments and focused largely on education and raising awareness, Global South projects have focused more on improving livelihoods (Walker, Smigaj, and Tani 2021). Citizen science in the field of drinking water monitoring is scarce, and is often limited to the data collection of physical-chemical parameters in water samples and excludes microbial parameters (Brouwer et al. 2018; Buytaert et al. 2014; Peckenham, Thornton, and Peckenham 2012). The first citizen science project on drinking water that was documented in the academic literature was conducted by (Brouwer et al. 2018) in the Netherlands. In that study, citizens of Amsterdam participated in taking samples from their own kitchen tap and tested the microbiological stability of drinking water using test strips resulting in raised participant's awareness about microbial water quality. In other fields, citizen science has shown positive impacts on participants, including public engagement, raising awareness, social learning, knowledge gain or democratization of science (Walker, Smigaj, and Tani 2021). However, there may also be negative impacts of citizen science such as over-burdening the public (Walker, Smigaj, and Tani 2021).

Since self-supply is managed by households themselves, involving households to self-monitor their water quality could offer a promising approach. Therefore, this study sought to understand the extent to which participatory citizen monitoring using Aquagenx® presence/absence field test is an appropriate approach to monitor self-supply services in terms of microbial water quality. The study focused on the feasibility of the participatory monitoring approach, including motivation of participation, awareness and understanding of participants, as well as the water quality results.

Methods

Study area

The participatory monitoring was undertaken in the Indonesian city of Bekasi. Kota Bekasi was selected based on widespread use of self-supply and the lack of access to piped water. The city is located in West Java on the eastern border of Jakarta and is divided into 12 districts *(Kecamatan)*. With a population density of 12,085 people/km^2 (2020) and approximately three million inhabitants, it is one of the most populous cities in Indonesia (BPS Kota Bekasi 2021). More than 88% of households relied on groundwater as their water source in 2020 (BPS Kota Bekasi 2021). In Kota Bekasi, self-supply is not monitored or regulated and, by default, monitoring and management of water quality sits with households themselves. Based on the regulation of the Ministry of Health (MoH) no. 492/2010, drinking water operators are mandated to ensure water quality standards with support and monitoring from local government and public health agencies (Priadi et al. 2023). Central and local governments must conduct twice-yearly sanitary inspections of non-piped drinking water supplies, including dug wells and boreholes, while those at high and very high risk of contamination are requested to improve water and sanitation facilities (MoH regulation no. 736/2010). Those at low and medium risk should have their water tested at least monthly for microbial and physical parameters and biannually for compulsory and optional chemical parameters (Priadi et al. 2023). However, these regulations are unrealistic for the large number of privately owned self-supply systems in Indonesia and are largely disregarded (Priadi et al. 2023).

The study took part in three purposively selected sub-districts *(Kelurahan)*, namely Jatliluhur, Sumur Batu and Jatirangga, from three different districts (Jatiasih, Bantar Gebang and Jatisampurna). The hamlets *(RW Rukun Warga)* were selected in consultation with the heads of the selected sub-districts, and the neighborhoods *(RT Rukun Tetangga)* in consultation with the respective head of the selected hamlets. Prior to the data collection, informed consent was obtained in local language from heads of neighbourhoods and from all participants. Ethical approval to conduct the research was provided by the Human Research Ethics Committee of the University of Technology Sydney as well as the Community Engagement Ethical Committee of the Universitas Indonesia.

Household selection

All households of the selected neighbourhoods were listed and 300 households were randomly selected for the purposes of the previous studies (Genter et al. 2022, 2023).

Of these 300 randomly selected households, a target number of 30 households was chosen for budget reasons for this study. The selection criteria included a willingness to participate, using self-supply as a water source for drinking and domestic purposes, and the availability of WhatsApp on at least one family member's mobile phone for reporting water quality test results. After three rounds of phone calls, a total of 30 households were selected, ten in Jatiluhur, five in Jatirangga and 15 in Sumur Batu.

Conceptual framework

The context analysis, process evaluation and impact assessment (CPI) framework proposed by Gharesifard et al., (2019) was used to frame and analyse the participatory monitoring approach for self-supply water services and to evaluate its feasibility. The CPI framework, as described by Gharesifard et al., (2019), was introduced to analyse the dynamics underlying the establishment and functioning of community-based monitoring initiatives. The CPI framework emphasizes the importance of community involvement in monitoring, which is also a core principle of participatory monitoring. The CPI framework provides a useful basis for thinking about how to design and implement participatory monitoring approaches that involve community members in monitoring as its principles and components can be adapted to a range of monitoring and evaluation approaches with different scopes, scales, and levels of participation. The framework encompasses five distinct dimensions, which are categorized into context-related and initiative-related aspects, and are suitable for conducting context analysis, process evaluation and impact assessment of the monitoring approach. The five dimensions and corresponding 22 internal and context-related factors considered in the CPI framework are as follows (Figure 1):

- Goals and objectives: What are overarching objectives and actor-specific goals of the initiative and to what extent does the design of the initiative help achieve those goals/objectives?
- Power dynamics: Who controls and influences the initiative and how?
- Participation: Who participates in the initiative and how?
- Technology: How effective and appropriate are the choices and delivery of the selected technologies?
- Results: What are the outputs, outcomes and impacts of the initiative?

This study applies the framework in a novel context, specifically utilizing a household-based rather than a community-based approach. This approach has enabled the identification of new insights and potential areas for improvement within the framework. The 'results' dimension, positioned at the top of the diagram, is influenced by the dimensions of 'power dynamics', 'participation', and 'technology'. In this study, the CPI framework was adapted to place the dimension of 'participation' at the centre of the framework, reflecting the use of a household-based approach where participants play a central role in conducting the water quality testing. Additionally, flows between the dimensions were introduced in the diagram. The 'goals and objectives' dimension located at the bottom of the framework is influenced by the dimensions of 'power dynamics', 'participation', and 'technology'.

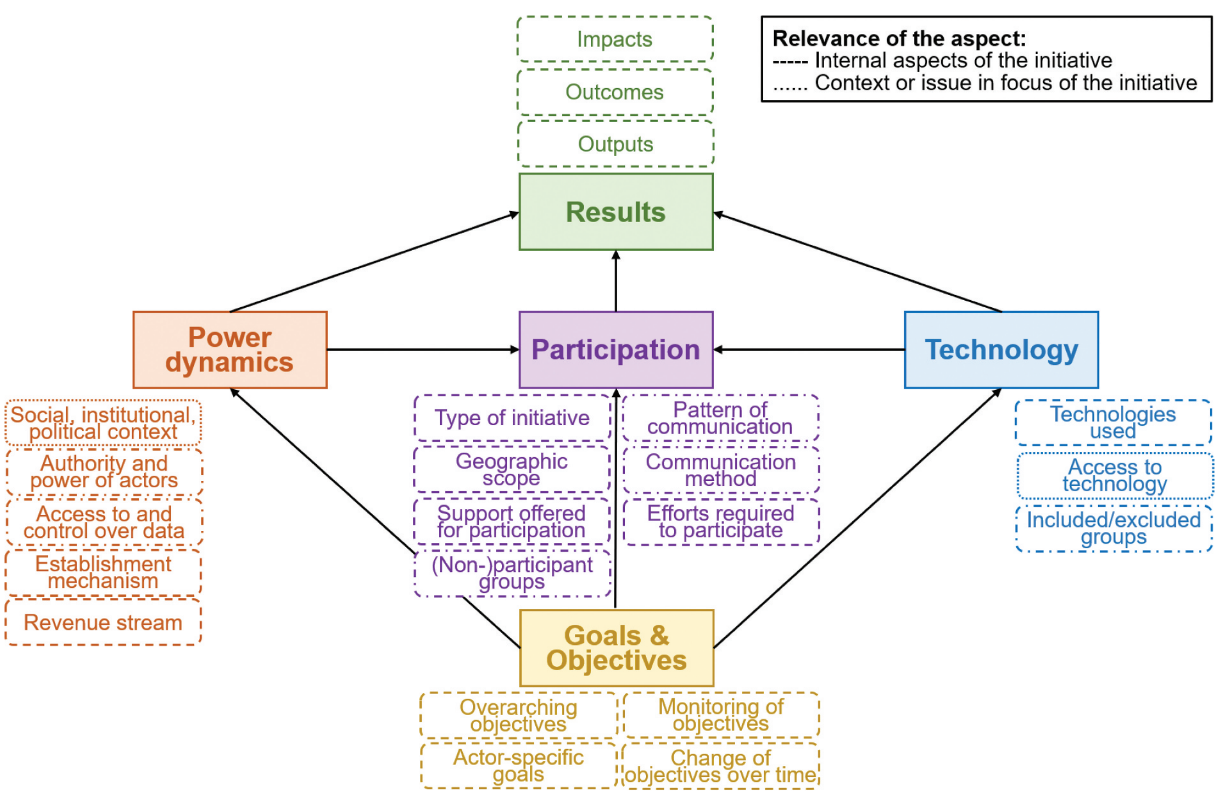

Figure 1. Adapted CPI framework of Gharesifard et al., (2019) including the five dimensions and 22 context and/or internal aspects of the initiative.

The analysis of this study primarily focuses on the 'results' of the framework, including outputs and outcomes, and how these are affected by the 'participation' and 'technology' dimensions. However, the study also sheds light on the other aspects of the framework, as it applies the framework in a novel household-based context. In the participatory monitoring approach, 18 of the 22 proposed internal and context-related aspects of the framework are considered (Supplementary S4 Table A1). It is important to note that the scope of this study was limited to the short term. As such, certain aspects, such as actor-specific goals, change of objectives over time, and monitoring of objectives and impacts, were not taken into account. However, these aspects are covered in the context of long-term implementation in the discussion section.

Participatory citizen approach

Prior to the start of the project, a contextual baseline analysis was conducted as part of the study design, which analysed and defined the contextual factors such as the social, institutional, and political context as well as the authority and power of different actors, access to and control over data and access to the technology. Furthermore, overarching objectives were defined, and the technologies used to achieve the goals. The process evaluation is used to help enhance the understanding of the process that led to the outcomes and outputs by considering the dimensions 'participation' and 'power dynamics'. The internal aspects of the 'participation' dimension, such as efforts required to participate and support offered were defined and evaluated, as well as who controls and influences the initiative and how. The impact assessment focused on the short-term outcomes (i.e. short-term changes) and outputs (i.e. direct outputs), and how these were influenced by the 'participation' and 'technology' dimension. The outputs included the motivation of participation, as well as water quality results. These outputs were obtained through a participatory water quality testing using field test kits, along with pre- and post-monitoring surveys. Short-term outcomes included participants awareness and understanding on water quality. The pre-monitoring survey was used to assess participants' initial awareness and understanding of water quality, while the post-monitoring survey was used to evaluate any changes in these factors following participation in the project. For a comprehensive application of the CPI framework used in this study, see Table A1 in Supplementary S4.

After establishing the study design, including defining relevant contextual and internal aspects, households were advised to test their self-supply water for the presence of *E. coli* every two weeks at both the source and point of use. Households were provided Aquagenx® test kits covering a six-month period between April and November 2022 (total of 12 sampling rounds). Access to this technology was made possible by the import of the test kits to Indonesia. The messaging app WhatsApp was defined as the communication method between the research team and the participants, as such, households without a mobile phone with functioning WhatsApp were not selected for participation. Water quality outputs obtained by participants were shared with the research team by mobile phone using WhatsApp. Support was offered to participate, with a reward of 15,000 Rupiah (approximately US$ 1.00) of mobile phone balance provided to each participant after each sampling round. Furthermore, participants were trained by two local enumerators at the start of the campaign. Participating households were able to discontinue their participation in the monitoring at any time. After one month and at the end of the campaign, a pre- and post-monitoring survey was conducted by the enumerators during field visit to evaluate the outcomes. Three quality control samples were collected by the enumerators during the field visit at the start of the campaign (sampling round 1, $n = 30$), after one month (sampling round 3, $n = 26$) and at the end of the campaign (sampling round 12, $n = 17$) at the same time as household members. Analysed water quality results were shared with participants using WhatsApp.

Microbial water quality testing

Water quality was tested for the presence of *E. coli* using Aquagenx® presence/absence test kits according to the manufacturer's instructions (Aquagenx 2013). The Aquagenx® test kit uses a powdered growth medium containing a glucose substrate known as X-Gluc. When *E. coli* bacteria metabolize this substrate, the water changes colour to blue, serving as an indicator of *E. coli* presence. The Aquagenx® test kit has been evaluated by UNICEF and WHO as part of the Rapid Water Quality Testing Project, aiming to catalyse the continuous improvement of existing and new portable water quality testing products to allow more efficient, accurate, or low-cost testing of drinking water quality in the field (WHO, & UNICEF 2022). The test kit correctly identified the presence or absence of *E. coli* in more than 90% of cases when incubated at a temperature of 25°C for 48 hours, or at a temperature of 35°C for 20 hours (WHO, & UNICEF 2022). This test was chosen as the preferred method for the participatory monitoring approach due to its simplicity and design for on-site field testing in low resource areas. While alternatives such as hydrogen sulphide detecting tests are suitable for low resource settings due to their low-cost nature and ease of local manufacture, these tests are not approved by the U.S. EPA or recommended by the WHO guidelines for drinking water (Bain et al. 2012; Matwewe, Hyland, and Thomas 2018; Wright et al. 2012). Approved methods such as IDEXX Colilert were not considered appropriate for participatory on-site testing in low resource areas due to the extensive equipment and cost (Bain et al. 2012). The primary aim of the participatory monitoring approach was not to evaluate testing methods per se, but rather to assess how households respond to the opportunity to test their own water quality.

Microbial water quality was tested by participants from the main self-supply source and main drinking water source at the point-of-use. The 100 mL Whirl-Pak Thio-bags were labelled using a permanent marker with the participants' initials, the source or point-of-use type code and the date. Hands were disinfected with hand sanitizer immediately before collecting the 100 mL water samples from the groundwater self-supply source or point-of-use source using the Whirl-Pak Thio-Bag. The water samples from self-supply sources were collected in a way participants usually would obtain water. Point-of-use samples were collected in a way participants usually would when drinking from a storage container, as for example pouring water into a glass or cup, or directly from a storage container. Water samples were filled to the upper black fill mark line and the Aquagenx® growth medium was added to the water sample in the Whirl-Pak Thio-Bag. Whirl-Pak Thio-Bags were closed and growth medium in the sample was dissolved by swirling the bag gently. The sample was incubated for 48 hours at ambient temperature, ideally more than 30°C. Instructions of Aquagenx® recommend an incubation period of 40–48 hours at an ambient temperature of 25–30°C, 24–30 hours at 31–34°C and 20 hours at 35–37°C. Ambient temperature was recorded during the study period using temperature loggers (Elitech RC-5 USB temperature data logger) in a total of three households, one in each district. The temperature was also recorded by the enumerators during the quality control field visits. Incubation time was recorded by participants. After 48 hours, a picture of the labelled water sample was taken and shared with the research team using WhatsApp. If the water sample was blue/blue green it was positive for *E. coli*, if it was yellow/yellow brown it was negative for *E. coli*. The microbial water quality testing is part of the CPI framework 'technology' dimension and was used to obtain the outputs on water quality.

Pre- and post-monitoring survey

A structured pre-monitoring survey and a structured post-monitoring survey was conducted in local language by the enumerators using Qualtrics software (Qualtrics, Provo, UT, USA). The pre-monitoring survey was conducted one month after the start of the campaign (May 21st – 25th, 2022, sampling round 3) while the post-monitoring survey was conducted at the end of the campaign (October 29th - November 8th, 2022, sampling round 12). The surveys covered themes on participants' socio-economic and demographic characteristics, feasibility, and motivation to use the test, awareness and understanding as well as perception of water quality. The pre- and post-monitoring survey was used to evaluate how different aspects of the 'participation' and 'technology' dimensions lead to the outputs and outcomes in terms of motivation of participation, as well as awareness and understanding of participants.

Rainfall and groundwater measurements

Rainfall and groundwater levels were measured to provide insight into the temporal variability and as potential factors influencing water quality. Rainfall was measured using a Davis® (0.2 mm) Rain Gauge Smart Sensor at a household in Jatirangga during five months from June 2nd to November 4th, 2022, according to the manufacturer's instructions. Groundwater levels were measured using HOBO® MX Bluetooth Water Level Loggers (MX2001) in two private protected dug wells in Jatirangga during five months from June 2nd to November 4th, 2022, and in one private protected dug well in Jatiluhur from June 3rd to November 6th, 2022, according to the manufacturer's instruction (Supplementary S2 Database). Rainfall and groundwater output data over time were plotted using Microsoft Office Excel 2016.

Data analysis

Statistical analysis software R (version 1.2.5001, R Foundation for Statistical Computing, Vienna, Austria) and Microsoft Office Excel 2016 were used for analysis. R package 'DescTools' was used to calculate proportions and corresponding confidence intervals (CI), as well as statistical significant tests. CIs for binominal proportions were calculated using the 'BinomCI' function based on the Clopper-Pearson method, while CIs for multinominal proportions were calculated using the 'MultinomCI' function based on the Sisonglaz method. Fisher's exact test was calculated to examine the relationship between the socio-economic and demographic characteristics of participants who dropped out and those who completed the full testing. Stuart-Maxwell test was used to compare marginal homogeneity for pre- and post-survey responses of single-select questions for participants who completed monitoring and did not drop out.

For the purposes of previous studies, the wealth index was constructed for households in Bekasi using the same approach as the 2017 Indonesian Demographic and Health Survey (DHS) based on the relevant indicators and corresponding values (National Population and Family Planning Board BKKBN et al. 2018). See (Genter et al. 2022) for more information on the wealth index and wealth quintiles calculations.

To examine whether self-testing water quality resulted in improved water quality over time, a generalized estimating equations (GEE) analysis was conducted that accounted for rainfall variability. Cumulative rainfall was calculated for periods of three days, one week and two weeks prior to each microbial water quality sampling date using Microsoft Office Excel 2016. Microbial water quality data measured before the first rainwater measurement until sampling round four were excluded for this analysis. GEE (R package 'gee') were used to model the longitudinal repeated measures to specify the correlation between cumulative rainfall (three days, one week and two weeks) and the presence of *E. coli* at source and point-of-use over time. The specific households were considered as a grouping factor (id variable). Households that only participated in one sampling round were excluded from analysis, resulting in a cluster size of $n = 22$ households for the analysis of three days cumulative rainfall prior to water sampling, and $n = 21$ households for the analysis of one- and two-weeks cumulative rainfall prior to water sampling (Supplementary S3 Database). An autoregressive correlation structure was used to adjust for the correlation between measurements within each household. Odds ratios, 95% CIs and *p*-values were calculated for the sampling round and rainfall predictors in the GEE model fit. Robust standard errors were used to calculate the 95% CIs. The *p*-values were calculated based on the z-values obtained from the coefficient estimates and standard errors of the model, using the 'pnorm' function in R. The resulting *p*-values were used to determine whether each predictor variable was statistically significant at the 0.05 significance level. Quasi-Likelihood Information Criterion (QIC) was used as a measure of goodness-of-fit for the GEE models. The QIC is a measure of model fit that adjusts the traditional Akaike Information Criterion to account for the quasi-likelihood estimation used in GEEs

(Pan 2001). A lower QIC value indicates a better fit to the data.

Results

Context – participants' socio-economic, demographic and water supply characteristics

Participants' socio-economic and demographic characteristics are presented in Table 1. Of the 30 final selected participants, ten were from Jatiluhur, five from Jatirangga and 15 from Sumur Batu. Households were evenly distributed amongst the wealth quintiles. The selected participants were mostly female with about three quarters ($n = 23$) of the respondents being female and about one quarter being male ($n = 7$). The socio-economic and demographic characteristics were comparable to the full sample of households included in the previous studies (Supplementary S1 Table A1, Genter et al. 2022, 2023). Of the 30 selected households that agreed to participate in participatory monitoring, about half ($n = 16$) fully completed all tasks, including fortnightly water quality testing for six months and responding to the pre- and post-monitoring survey; the other half ($n = 14$) dropped out from testing during the six months period. The pre- and post-monitoring survey were conducted by 87% ($n = 26$) and 57% ($n = 17$) of the selected participants. Sixteen participants completed the pre- and post-monitoring survey, ten participants completed only the pre-monitoring, one participant completed only the post-monitoring survey, and three participants did not participate in either the pre- or post-monitoring survey.

Self-supply sources were used for drinking, cooking, showering, washing cars and watering plants (Supplementary S1 Table A2). Pre-survey results indicate that private boreholes were the most frequently used source of drinking water (n = 24, 92%), followed by refill water (n = 10, 39%). If used for drinking, water from self-supply sources was boiled every time before consumption by most participants (Supplementary S1 Table A2). Refill water and bottled water were never or only sometimes boiled before consumption. Diarrhoea was experienced within 15% of households in the past month prior to the start of the monitoring. Five participants experienced problems with accessing the self-supply water sources due to drought (n = 4), flood (n = 2) and pump failure (n = 2), in the past month prior to the start of the monitoring. Water from self-supply sources was available 24 hours per day for most participants (n = 21, 81%), however, five participants reported an availability of less than 24 hours per day (19%).

Outputs – motivation of participation and dropout from testing

The study found a high dropout rate among participants, with nearly half of the selected households dropping out by the end of the monitoring period. The dropout rate was 53%, with 14 participants dropping out from testing. Out of those participants, five dropped out by the end of the fourth round and eleven by the end of the eighth round (Figure 2). One participant who dropped out after the first sampling round took a sample at the final twelfth sampling round and participated in the post-monitoring survey. When asking participants about the reason for the dropout, five were too busy, one got sick, one was bothered by the smell of the test and one didn't trust that the reward would be transferred. The reasons were unknown for six participants who dropped out. Fisher's exact test showed a significant relationship between participants' place of living and the dropout from monitoring (Table 1). Participants were significantly more likely to complete the monitoring in Jatirangga ($p = 0.045$) as compared with other sub-districts (Sumur Batu and Jatiluhur). No significant associations were observed for wealth status, participant gender, reason for participation, preferred frequency of testing, difficulties of testing, and understanding of the training and usage of the test (Tables 1 and 2). Sampling interruption was observed from three participants. One sample was excluded because of the result was falsified, with a household -resubmitting a photograph of an older sample. In sampling round five, nine results were taken by the participants, but the results could not be recorded due to an enumerator error.

The participants who completed the monitoring were motivated and willing to continue monitoring, with their primary

Table 1. Socio-economic and demographic characteristics of (i) participants from all selected households; (ii) those who participated in the full duration of the water quality testing and completed pre- and post-monitoring survey; (iii) those who dropped out from water quality testing; (iv) those who conducted the pre-monitoring survey; and (v) those who conducted the post-monitoring survey. Percentages refer to the total number of selected participants (n = 30).

Participants	Final selection			Full participation			Dropout			Pre-survey			Post-survey		
Variables	n	[%]	95% CI [%]	n	[%]	95% CI [%]	n	[%]	95% CI [%]	n	[%]	95% CI [%]	n	[%]	95% CI [%]
Total	30	100	-	16	53.3	34.3–71.7	14	46.7	28.3–65.7	26	86.7	69.3–96.2	17	56.7	37.4–74.5
Village															
Jatiluhur (p = 0.709)	10	33.3	16.6–52.2	6	37.5	18.8–67.0	4	28.6	14.5–55.6	9	34.6	19.2–57.2	7	41.2	23.5–69.9
Jatirangga (p = 0.045)*	5	16.7	0.0–35.6	5	31.3	12.5–60.8	0	0.0	0.0–27.0	5	19.2	3.8–41.9	5	29.4	11.8–58.1
Sumur Batu (p = 0.066)	15	50.0	0.3–68.9	5	31.3	12.5–60.8	10	71.4	57.1–98.5	12	46.2	30.8–68.8	5	29.4	11.8–58.1
Wealth[a]															
Q1 (poorest)	5	16.7	0.0–33.9	1	6.3	0.0–33.9	4	28.6	7.1–56.9	4	15.4	0.0–36.8	1	5.9	0.0–33.3
Q2	5	16.7	0.0–33.9	2	12.5	0.0–40.1	3	21.4	0.0–49.8	4	15.4	0.0–36.8	2	11.8	0.0–39.2
Q3	8	26.7	10.0–43.9	7	43.8	25.0–71.4	1	7.1	0.0–35.5	8	30.8	15.4–52.2	7	41.2	23.5–68.6
Q4	5	16.7	0.0–33.9	3	18.8	0.0–46.4	2	14.3	0.0–42.6	5	19.2	3.8–40.6	3	17.6	0.0–45.1
Q5 (wealthiest)	7	23.3	6.7–40.6	3	18.8	0.0–46.6	4	28.6	7.1–56.9	5	19.2	3.8–40.6	4	23.5	5.9–51.0
Sex															
Female (p = 1.000)	23	76.7	57.7–90.1	12	75.0	47.6–92.7	11	78.6	49.2–95.3	21	80.8	60.6–93.4	12	70.6	44.0–89.7
Male (p = 1.000)	7	23.3	9.9–42.3	4	25.0	7.3–52.4	3	21.4	4.7–50.8	5	19.2	6.6–39.4	5	29.4	10.3–56.0

*Significant category $p < 0.05$, full participation versus dropout.
[a]Fisher's exact p-value $p = 0.568$ for poorer households (Q1 and Q2) versus wealthier households (Q3, Q4 and Q5).

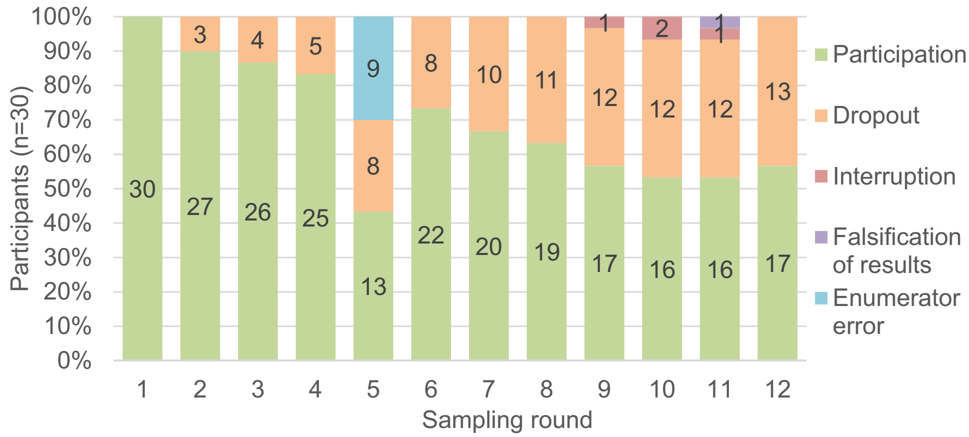

Figure 2. Participation of the selected households in fortnightly water quality testing (12 rounds) during the six months period.

Table 2. Understanding motivation for participation and drop-out from testing based on pre-survey results of participants who completed the monitoring and those who dropped out.

	Pre-survey Full Participation			Pre-survey Dropout		
Variables	n	[%]	95% CI [%]	n	[%]	95% CI [%]
Total	16	100	-	10	100	-
Who in the household has the main responsibility for doing the testing?						
Woman (p = 0.617)	12	75.0	62.5–99.2	9	90.0	80.0–100.0
Man (p = 0.617)	4	25.0	12.5–49.2	1	10.0	0.0–26.5
Child	0	0.0	0.0–24.2	0	0.0	0.0–16.5
More than one person	0	0.0	0.0–24.2	0	0.0	0.0–16.5
Why are you interested to participate in the water quality testing?						
Learning about drinking water quality (p = 1.000)	16	100.0	79.4–100.0	9	90.0	55.5–99.7
Caring about personal and family's health (p = 1.000)	16	100.0	79.4–100.0	9	90.0	55.5–99.7
Recognition or respect from others (p = 1.000)	3	18.8	4.0–45.6	1	10.0	0.3–44.5
Felt compelled to participate	0	0.0	0.0–20.6	1	10.0	0.3–44.5
Because of the remuneration	0	0.0	0.0–20.6	0	0.0	0.0–30.8
Other reason	1	6.3	0.2–30.2	1	10.0	0.3–44.5
What's your preferred frequency of testing the water?						
Once per week (p = 0.508)	2	12.5	0.0–39.7	0	0.0	0.0–28.7
Once all two weeks (p = 0.399)	9	56.3	37.5–83.4	8	80.0	70.0–100.0
Once each month (p = 0.668)	5	31.3	12.5–58.4	2	20.0	10.0–48.7
No time	0	0.0	0.0–27.2	0	0.0	0.0–28.7
Other	0	0.0	0.0–27.2	0	0.0	0.0–28.7
In which steps do you have difficulties in testing the water quality with Aquagenx®?						
No difficulties (p = 0.677)	5	31.3	11.0–58.7	2	50.0	18.7–81.3
Collecting the water sample (p = 1.000)	2	12.5	1.6–38.3	1	20.0	2.5–55.6
Adding the growth medium (p = 0.060)	6	37.5	15.2–64.6	8	60.0	26.2–87.8
Incubating the sample	0	0.0	0.0–20.6	0	0.0	0.0–30.8
Score and send the results	0	0.0	0.0–20.6	0	0.0	0.0–30.8
Other	5	31.3	11.0–58.7	0	50.0	18.7–81.3
How difficult was the training to understand how to test the water quality?[a]						
Very easy (p = 1.000)	1	6.3	0.0–34.2	1	10.0	0.0–47.4
Easy (p = 1.000)	6	37.5	18.8–65.4	4	40.0	20.0–77.4
Neutral (p = 0.702)	8	50.0	31.3–77.9	4	40.0	20.0–77.4
Difficult (p = 1.000)	1	6.3	0.0–34.2	1	10.0	0.0–47.4
Very difficult (p = 1.000)	0	0.0	0.0–27.9	0	0.0	0.0–37.4
How difficult is the test to use?[b]						
Very easy (p = 1.000)	1	6.3	0.0–34.2	1	1.0	0.0–44.7
Easy (p = 1.000)	6	37.5	18.8–65.4	3	30.0	10.0–64.7
Neutral (p = 0.702)	8	50.0	31.3–77.9	6	60.0	40.0–94.7
Difficult (p = 1.000)	1	6.3	0.0–34.2	0	0.0	0.0–34.7
Very difficult (p = 1.000)	0	0.0	0.0–27.9	0	0.0	0.0–34.7

[a]Fisher's exact p-value p = 1.000 for no difficulties (very easy, easy, neutral) versus difficulties (difficult, very difficult) in understanding the training.
[b]Fisher's exact p-value p = 1.000 for no difficulties (very easy, easy, neutral) versus difficulties (difficult, very difficult) in using the test.

reason being to learn about drinking water quality and prioritize their family's health. The post-survey showed that most participants who didn't drop out were willing to continue monitoring the water quality given the opportunity (94%, Supplementary S1 Table A3). Also, willingness to pay an amount for continued water quality monitoring was likely; 38% expressed a willingness to pay for continued water quality testing as likely, 56% as neutral, and 6% as unlikely. The majority of participants that completed the monitoring were women with responsibility for doing the tests being changed by two participants (12%) during the monitoring period (Table 2 and Supplementary S1 Table A3). Learning about drinking water quality and caring about personal and family's health were the most important reasons for participation. Recognition or respect from others was an important reason for three participants who completed the monitoring. Other reasons mentioned were the support of students who were involved in the project. The majority of participants were satisfied with the frequency of testing, which was once every two weeks. However, about 30% preferred less frequent testing of once a month. Adding the growth medium was the most difficult part of testing the water quality with Aquagenx®. The water quality testing training was easy to neutral for most households to understand, with two participants rating it as difficult and two as very easy. Similarly, the use of the water quality tests was easy to neutral for most households, with one participant rating it as difficult and two as very easy in the pre-survey (Table 2).

Outputs – water quality results

Self-supply samples at source and point-of-use were frequently contaminated with *E. coli* with the proportions of contaminated samples varying during the study period. The proportion of contaminated source samples each month ranged between 10.5% and 70.0% while the proportion of contaminated point-of-use samples ranged between 15.0% and 43.8% (Figure 3). Quality control samples showed 90.0% ($n = 27$), 84.6% ($n = 22$) and 94.1% ($n = 16$) accuracy after the first, third, and twelfth sampling rounds, respectively. The measured ambient temperature ranged between 27.5°C and 31.2°C in Jatiluhur, 27.5°C and 32.1°C in Jatirangga and 29.2°C and 31.6°C in Sumur Batu, which is within the recommended incubation temperature range without the need for an incubator. Most participants tested the water from boreholes ($n = 26$, round 1), while one household tested the water from an unprotected dug well and three tested water from a protected well (Supplementary S1 Table A5). During the study period, the number of source types changed due to the dropout of participants or the use of alternative drinking water sources such as refill water at household level (Supplementary S1 Table A6). The range of contaminated self-supply samples was similar for participants that did not drop out from testing and completed the monitoring (Supplementary S1 Figure A1). Considering only participants that did not drop out from testing, the proportion of contaminated source samples ranged between 12.5% and 68.8% while the proportion of contaminated point-of-use samples ranged between 12.5% and 37.5% (Supplementary S1 Figure A1). Over the entire study period, *E. coli* was detected in 42.5% of the 214 samples from 26 boreholes, in 36.4% of the eleven samples from one unprotected dug well and in 26.1% of the 23 samples from three protected wells (Supplementary S1 Table A5). At point-of-use, *E. coli* was present in 29.3% of the 184 borehole samples, in 25.0% of the twelve samples from protected wells and in 27.5% of the 51 refill water samples (Supplementary S1 Table A6).

Outcomes – awareness and understanding of water quality

Participatory monitoring might have improved participants' understanding of self-supply water quality. When asked about the perceived source water and drinking water safety, the water quality was less frequently rated as good at the endline compared with the baseline (Table 3). Stuart-Maxwell test showed a statistically significant change in perception of self-supply safety at source ($p = 0.046$) when ratings were collapsed into two categories of good (excellent, very good, good) and poor (fair, poor). No significant change was observed in perception of drinking water safety at point-of-use ($p = 0.317$). Before and after the monitoring, all participants selected taste as an important water safety indicator. However, water storage method was the least frequently selected, with around one-third of respondents selecting it before and after the monitoring. In the post-monitoring survey, statements to test understanding of water quality were more frequently selected correctly, with more frequent selection of the correct statement 'microbial

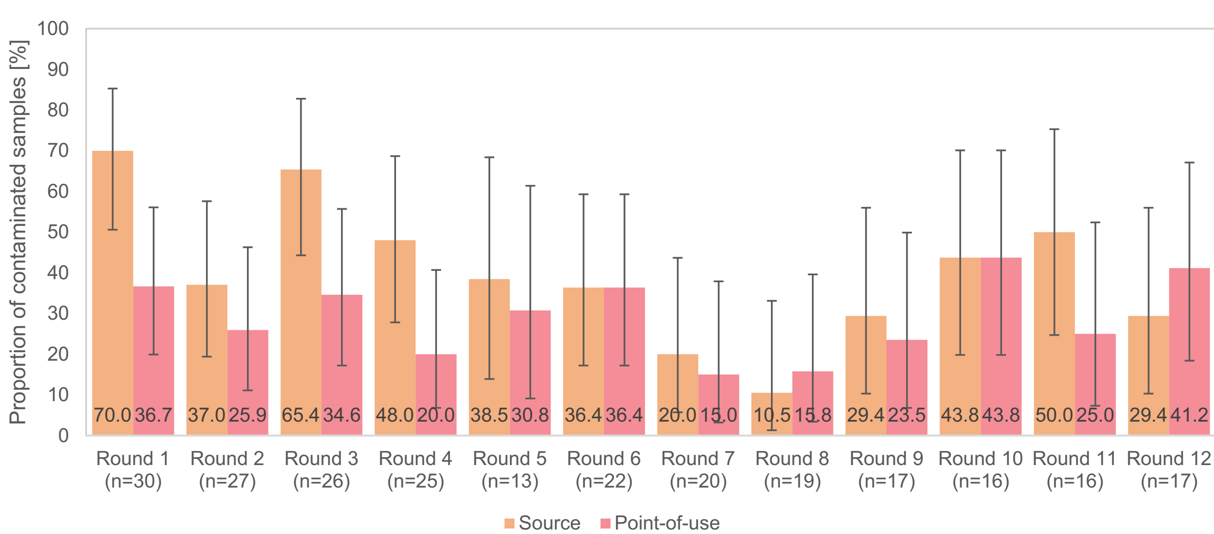

Figure 3. Proportion of source and point-of-use samples with positive *E. coli* detection in each sampling round during the six months monitoring period.

Table 3. Change in awareness and understanding on water quality before and after the monitoring of participants who completed the monitoring.

	Pre-survey			Post-survey		
Variables	n	[%]	95% CI [%]	n	[%]	95% CI [%]
Total	16	100.0	-	16	100.0	-
Which of the following factors do you think are important indicators of whether water is safe to drink?						
Taste	16	100.0	79.4–100.0	16	100.0	79.4–100.0
Appearance – Particles	10	62.5	35.4–84.8	7	43.8	19.8–70.1
Appearance – Colour	15	93.8	69.8–99.8	14	87.5	61.7–98.4
Odour	14	87.5	61.7–98.4	15	93.8	69.8–99.8
Recent flooding/rain	11	68.8	41.3–89.0	14	87.5	61.7–98.4
Proximity of sanitation facilities	9	56.3	29.9–80.2	12	75.0	47.6–92.7
Previous experience (have/have not previously been sick)	5	31.3	11.0–58.7	12	75.0	47.6–92.7
Whether water has been treated	12	75.0	47.6–92.7	10	62.5	35.4–84.8
How water is stored	6	37.5	15.2–64.6	6	37.5	15.2–64.6
Please select the following statements which you think are true.						
Microbial contamination in drinking water can cause diarrheal diseases	15	93.8	69.8–99.8	16	100.0	79.4–100.0
Boiling water is an effective method of removing pathogens in drinking water	16	100.0	79.4–100.0	16	100.0	79.4–100.0
Groundwater is always safe to drink	3	18.8	4.0–45.6	1	6.3	0.2–30.2
How would you rate the safety of your tested self-supply at the source before treatment?						
Excellent	0	0.0	0.0–10.5	0	0.0	0.0–28.4
Very good	0	0.0	0.0–10.5	3	18.8	0.0–47.2
Good	15	93.8	87.5–100.0	8	50.0	31.3–78.4
Fair	1	6.3	0.0–16.7	5	31.3	12.5–59.7
Poor	0	0.0	0.0–10.5	0	0.0	0.0–28.4
How would you rate the safety of your tested drinking water at home after treatment?						
Excellent	0	0.0	0.0–18.3	0	0.0	0.0–27.1
Very good	1	6.3	0.0–24.6	4	25.0	6.3–52.1
Good	14	87.5	81.3–100.0	9	56.3	37.5–83.4
Fair	1	6.3	0.0–24.6	3	18.8	0.0–45.9
Poor	0	0.0	0.0–18.3	0	0.0	0.0–27.1
What will/did you do in response to a contaminated water test result?						
Do nothing	2	12.5	1.6–38.3	2	12.5	1.6–38.3
Choose an alternative water source for drinking	8	50.0	24.7–75.3	13	81.3	54.4–96.0
Boil the water before consumption	13	81.3	54.4–96.0	13	81.3	54.4–96.0
Clean the storage containers	10	62.5	35.4–84.8	12	75.0	47.6–92.7
Running my tap water before using it each day	1	6.3	0.2–30.2	10	62.5	35.4–84.8
How likely are you to talk the following groups of people about drinking water quality? [Family]						
Never	3	18.8	0.0–47.4	4	25.0	6.3–52.7
Rarely	1	6.3	0.0–34.9	2	12.5	0.0–40.2
Sometimes	7	43.8	25.0–72.4	8	50.0	31.3–77.7
Often	5	31.3	12.5–59.9	2	12.5	0.0–40.2
Every time	0	0.0	0.0–28.6	0	0.0	0.0–27.7
Not relevant	0	0.0	0.0–28.6	0	0.0	0.0–27.7
How likely are you to talk the following groups of people about drinking water quality? [Friends]						
Never	5	31.3	12.5–60.1	6	37.5	18.8–66.4
Rarely	4	25.0	6.3–53.8	6	37.5	18.8–66.4
Sometimes	5	31.3	12.5–60.1	3	18.8	0.0–47.7
Often	2	12.5	0.0–41.3	1	6.3	0.0–35.2
Every time	0	0.0	0.0–28.8	0	0.0	0.0–28.9
Not relevant	0	0.0	0.0–28.8	0	0.0	0.0–28.9
How likely are you to talk the following groups of people about drinking water quality? [Neighbours]						
Never	6	37.5	18.8–66.4	7	43.8	25.0–72.3
Rarely	3	18.8	0.0–47.7	4	25.0	6.3–53.6
Sometimes	6	37.5	18.8–66.4	4	25.0	6.3–53.6
Often	1	6.3	0.0–35.2	1	6.3	0.0–34.8
Every time	0	0.0	0.0–28.9	0	0.0	0.0–28.6
Not relevant	0	0.0	0.0–28.9	0	0.0	0.0–28.6
How likely are you to talk the following groups of people about drinking water quality? [Colleagues]						
Never	7	43.8	25.0–72.3	15	93.8	87.5–100.0
Rarely	1	6.3	0.0–34.8	1	6.3	0.0–16.7
Sometimes	2	12.5	0.0–41.1	0	0.0	0.0–10.5
Often	0	0.0	0.0–28.6	0	0.0	0.0–10.5
Every time	0	0.0	0.0–28.6	0	0.0	0.0–10.5
Not relevant	6	37.5	18.8–66.1	0	0.0	0.0–10.5

contamination in drinking water can cause diarrheal diseases', and less frequent selection of the incorrect statement that groundwater is always safe to drink. All respondents selected the statement 'Boiling water is an effective method of removing pathogens in drinking water' as correct, before and after the monitoring. All participants except one responded that participating in the monitoring improved understanding about the quality of drinking water (Supplementary S1 Table A4). In addition, all participants responded that the tested water quality was as expected. Boiling the water before consumption was the most frequent response to a test result showing contamination at both baseline and endline (81%).

Table 4. GEE analysis shows that testing water over time did not have a significant effect on water quality at source or point-of-use. *E. coli* presence in self-supply sources was significantly influenced by rainfall. No significant effect of rainfall on water quality was observed in drinking water at point-of-use. Cumulative rainfall was considered as three days (Model I), one week (Model II) and two weeks (Model III) prior to the water quality testing date. Model III has the smallest QIC value indicating that it provides the best fit to the data among the three models.

	Model I: Three days			Model II: One week			Model III: Two weeks		
Predictor	OR	95% CI	*p*-value	OR	95% CI	*p*-value	OR	95% CI	*p*-value
Source[a]									
Cumulative rainfall [cm]	1.09	1.03–1.16	0.005*	1.07	1.01–1.13	0.029*	1.07	1.02–1.13	0.008*
Sampling round	0.94	0.80–1.11	0.467	1.01	0.85–1.19	0.940	0.97	0.79–1.19	0.769
Point-of-use[b]									
Cumulative rainfall [cm]	1.03	0.95–1.13	0.466	1.02	0.97–1.08	0.438	1.05	1.00–1.11	0.062
Sampling round	0.98	0.82–1.18	0.837	0.97	0.80–1.17	0.729	0.89	0.75–1.06	0.205

*Significant predictor $p < 0.05$.
[a]Model I: QIC = 31.306, Model II: QIC = 29.585, Model III: QIC = 27.458.
[b]Model I: QIC = 29.728, Model II: QIC = 28.884, Model III: QIC = 27.401.

After the monitoring, choosing an alternative water source for drinking was more frequently selected as a response to a contaminated water test (81%), as well as cleaning the storage container (75%). In response to a test for contaminated water, the practice of running tap water before daily use had become common after the monitoring (63%). After monitoring, participants commonly reported a change in treatment, as well as water storage practice. A change in hygiene practice and water source choice was reported by almost half of respondents. All respondents of the post-monitoring survey saw benefits from testing the water quality in better understanding of drinking water quality and more trust in water quality. Other benefits such as different perception of water quality, support in water source choice and improvement of health were also commonly selected.

Even if participatory monitoring might have improved the understanding on water quality, testing water over time did not have a significant effect on the presence of *E. coli* in self-supply sources or drinking water at point-of-use. This suggests corrective actions were either not taken or not effective. GEE analysis showed that, after adjusting for rainfall, testing water over time was not a significant predictor of *E. coli* presence at source and point-of-use (Table 4). *E. coli* in self-supply sources was, however, found to be significantly associated with rainfall, regardless of whether the models considered cumulative rainfall over a period of three days, one week, or two weeks prior to the water quality testing date. However, no significant effect of rainfall on water quality was observed in drinking water at point-of-use. Effects of rainfall were also observed on groundwater levels of private unprotected dug wells, with lower groundwater water levels observed during dry season months (Supplementary S1 Figure A2).

Discussion

This study of household-led water quality monitoring in urban Indonesia demonstrated a number of positive outcomes, including increased awareness, knowledge gain and behaviour change. Participants who fully engaged in the environmental monitoring were motivated to continue the testing, with driving factors including an interest to learn about drinking water quality and caring about personal and family's health. The participatory monitoring led citizens to develop a more realistic perception of water quality, a better understanding of drinking water quality, and to change their behaviour regarding water treatment and storage. However, as noted by Walker et al., (2021), citizens who volunteer for a project are typically targeted for participation, such as the participants of this study, and might be already aware of the issue, hence their interest. Despite this, the study of Walker et al., (2021) suggests that citizen science projects can still be effective in increasing awareness and knowledge when engagement leads to learning, as observed in our study. Given that self-supply services are the responsibility of individual households, it is important that self-supplying households have an understanding of water quality and risks for contamination, along with knowledge about household water treatment and safe storage options.

However, our study observed demotivation to engage in citizen science amongst a sub-set of participants, which is consistent with previous studies. Engagement of citizens, especially in the form of regular monitoring, may impose a non-trivial burden on participants (Walker, Smigaj, and Tani 2021). In our study, it was difficult to find 30 interested participants and almost half of them dropped out during the trial of six months, mostly due to time constraints. Demotivation among participants was also evidenced by instances where households falsified results. In other studies, excessive complexity, lengthy and overly detailed instructions in conducting participatory monitoring have been found to be off-putting participants (Forrest et al. 2019). However, in our study, most participants did not report any difficulties in understanding the instructions or the water quality test. Those who dropped out of the program mostly cited being too busy as their reason. To make participatory monitoring of self-supply attractive and minimize negative impacts for participants, it is important to make water quality testing as simple and time efficient as possible, and also to emphasize its importance in a way that resonates with households.

The results of this study suggest that Aquagenx® presence/absence tests may be suitable for participatory monitoring, albeit with some caveats. Selecting the appropriate technology is of importance in facilitating the monitoring of self-supply water services by citizens, at it requires simple, reliable, and low-cost water quality tests, as highlighted by (Bain et al. 2020). The Aquagenx® presence/absence test was relatively straightforward for participants to carry out, water quality results were reliable, and no incubator was required due to the study site's climate with an ambient temperature above 25°C. However, testing microbial water quality in more temperate climates with ambient temperatures below 25°C requires an incubator or heat source, complicating and increasing the costs of the participatory monitoring approach. Limitations of the testing method used included the difficulties that were reported with adding the growth medium, the qualitative nature of the results and unit costs which may be prohibitive for lower-income households. Cost per Aquagenx® presence/absence test was about US$ 5.70. The cost of fortnightly source and point-of-use testing (four tests per month) is estimated at 6.8% of the minimum monthly wage of Bekasi City (US$ 334), and 17.7% of the minimum monthly wage for West Java Province (US$ 129) in 2023 (WageIndicator 2023). Hence, while Aquagenx® presence/absence tests may be on the lower end of the cost spectrum for microbial drinking water tests, without subsidies they would be prohibitively expensive for lower-income households to use with a frequency that was trialled in this study. Reducing the frequency of testing would improve affordability. For example, the cost of testing at a single location (either source or point-of-use) on a monthly or annual basis would equate to 1.7% and 0.14% of the minimum wage in Bekasi City, respectively. Reducing the frequency of household-led testing may still provide valuable data for governments to track and oversee overall trends in self-supply water quality over time.

While less frequent testing would reduce the cost and time burden, the trade-off is a reduced capacity to capture temporal variation in water quality. If a participatory approach to monitoring self-supply water quality were to be rolled out at greater scale, balancing these opposing considerations would be critical. Another consideration is whether testing method might assess presence/absence of a faecal indicator (as it did in this study) or whether a quantitative method is needed. A limitation of the presence/absence method used in this study is that it could not fully capture the extent or variability of *E. coli* concentration during the monitoring period. However, the quantification of *E. coli* relies on more complex assays, such as MPN assays, which are more expensive and involve additional processes, which makes them more challenging to implement in resource – limited contexts (Bain et al. 2012; Brown, Bir, and Bain 2020, Genter et al. 2019; Schertenleib et al. 2019).

In order to ensure the long-term success of household-led monitoring, it is crucial to consider the relationship between the CPI dimensions 'power dynamics' and 'participation', which includes both intra-household dynamics among participants as well as dynamics between institutional actors and participants. While participatory monitoring can have a range of positive long-term impacts on participants, such as empowerment and improved livelihoods (Gharesifard, Wehn, and van der Zaag 2019; Walker, Smigaj, and Tani 2021), efforts required to participate should be kept to a minimum and adequate support should be provided, as citizens bear the burden of labour and responsibility for doing the testing. In this study, mostly women were responsible for doing the testing. It is unclear how the additional workload of the testing affects intra-household dynamics of households, as the labour associated with self-supply management is already tiring for some households (Genter et al. 2023). In this study, the regular communication with enumerators was a key factor in maintaining participation, and it is unlikely this could be sustained as part of a long-term monitoring programme. It is also important to consider who controls and influences the initiative in the long-term, as well as the funding needed to sustain it. In order to put water quality monitoring by households into practice, the question needs to be addressed of whether households can report their water quality results to the competent authority and whether the authority can actively follow up and respond. This study showed that some participants were willing to pay some amount to continue the testing, however, given the technology and testing costs, financial support would likely be needed for lower-income households. The involvement of more actors such as government and non-profit organizations would require monitoring of actor-specific goals and objectives, and changes in those objectives over time. Ultimately, the long-term success of household-led monitoring depends on careful consideration of power dynamics, participation and institutional arrangements to sustain the initiative over the long-term.

Although participatory monitoring increased awareness about water quality, this study shows that monitoring alone was insufficient to improve the safety of self-supply water services. The study found no significant improvement in water quality at the self-supply source or point-of-use after the participatory monitoring. The prevalence of *E. coli* contamination at point-of-use remained a frequent concern for self-supply drinking water in the area, despite the common practice of boiling water. This suggests that further improvements in source water quality and safe water treatment and storage practices at the household level are critical for improving the safety of self-supply services. The relationship between rainfall and *E. coli* concentration at the self-supply source also suggests targeted efforts to improve household water treatment are most important during wetter periods.

Based on the study's findings, it is suggested that an adaption of the CPI framework be considered to better account for the interrelation between its dimensions (Figure 4). The previously outlined framework in this study already includes some adaptions of Gharesifard et al., (2019) CPI framework, such as placing the dimension of 'participation' at the centre and indicating the relationships between the key dimensions (Figure 1). It is further suggested that bi-directional interrelations be established between the dimensions of 'goals and objectives' to the dimensions of 'power dynamics', 'participation' and 'technology' (Figure 4). For example, the overarching goal of evaluating the feasibility of a participatory monitoring approach for self-supply services was influenced by various aspects, including the current institutional context (monitoring is by default the responsibility of households themselves), the willingness of households to participate, and the access to relevant necessary technologies. Additionally, it is suggested that the adaptation of the CPI framework should allow for the interrelation of aspects between dimensions, rather than rigid categorization in a single dimension (Figure 4). To give some examples, the research showed that the results were highly influenced by the efforts required for participation and the pattern of communication between participants and enumerators. The choice of communication technology, such as WhatsApp, resulted in the exclusion of some groups. The geographic scope not only influenced the dimension of 'participation' but also affected the 'goals and objectives'. For instance, the study focused on urban

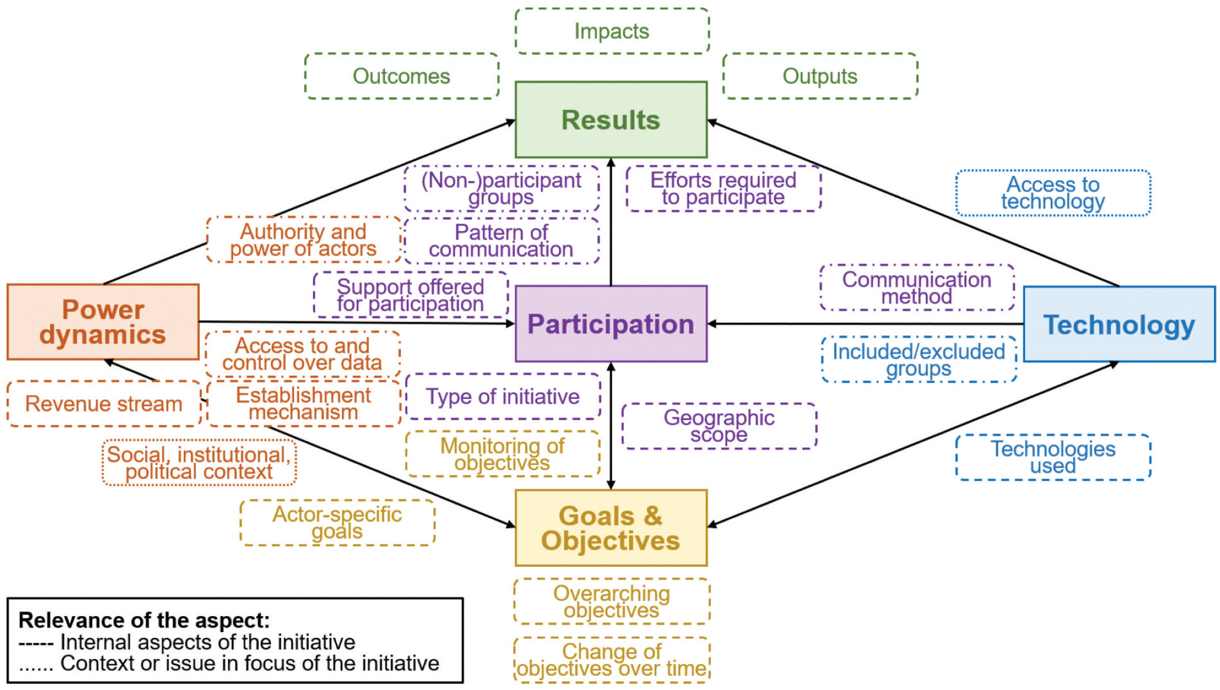

Figure 4. Adapted CPI framework of Gharesifard et al., (2019) accounting for interrelations between its dimensions and aspects.

groundwater self-supply, which may differ from other settings. Lastly, the support offered for participation highly influenced both 'participation' and 'power dynamics', as available resources were crucial factors. An adapted approach taking into account the interrelation between dimensions and the aspects that influence them prove a more comprehensive understanding of initiatives.

While the findings of this study contribute valuable insights into a participatory monitoring approach for microbial water quality in self-supply water services, it is important to acknowledge the limitations of this research. The relatively low number of participants limited the ability to fully explore the relationship between pre- and post-survey findings. Additionally, the participatory monitoring was conducted over a time period of six months, which limited the ability to assess long-term impacts beyond this timeframe. Therefore, future research should further investigate the effectiveness and sustainability of participatory monitoring approaches for self-supply services.

Conclusion

This study addresses a critical knowledge gap by establishing and evaluating a participatory monitoring approach for microbial water quality in self-supplied urban areas of Indonesia. The results have important implications for informing government decisions regarding self-supply in urban areas. This study highlights the potential benefits and limitations of participatory monitoring by citizens using field-based microbial water quality tests for self-supply services. While the approach can provide useful data for identifying the presence of microbial contamination in drinking water and raise awareness and understanding about water quality, participants can find it burdensome and lack motivation to test their water on a regular basis. As such, household-led testing conducted at reduced frequencies may be less demanding on households' workloads and still provide valuable data for governments to oversee trends in self-supply water quality over time. To make participatory monitoring attractive and feasible, water quality testing should be simple, inexpensive, and time-efficient, and needs complementary education or social marketing strategies for households. If participatory monitoring were to be scaled up or sustained, establishing an appropriate institutional architecture would be necessary. Finally, the study underscores the need for support strategies that prioritize safe water treatment and storage practices in urban areas where self-supply is common, as monitoring alone is unlikely to lead to water quality improvements.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials.

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