Environmental Science & Technology

Article

Cite This: Environ. Sci. Technol. XXXX, XXX, XXX−XXX

pubs.acs.org/est

Access to Household Water Quality Information Leads to Safer Water: A Cluster Randomized Controlled Trial in india

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Supporting Information

ABSTRACT: Household-specific feedback on the microbiological safety of drinking water may result in changes to water management practices that reduce exposure risks. We conducted a randomized, controlled trial in India to determine if information on household drinking water quality could change behavior and improve microbiological quality as indicated by *Escherichia coli* counts. We randomly assigned 589 participating households to one of three arms: (1) a *messaging-only arm* receiving messaging on safe water management (n = 237); (2) a *standard testing arm* receiving the same messaging plus laboratory *E. coli* testing results specific to that household's drinking water (n = 173); and (3) a *test kit arm* receiving messaging plus low-cost *E. coli* tests that could be used at the household's discretion (n = 179). Self-reported water treatment increased significantly in both the *standard testing arm* and the *test kit arm* between baseline and follow-up one month later. Mean $\log_{10}$ *E. coli* counts per 100 mL in household stored drinking water increased in the *messaging-only arm* from 1.42 to 1.87, while decreasing in the standard testing arm (1.38 to 0.89, 65% relative reduction) and the test kit arm (1.08 to 0.65, 76% relative reduction). Findings indicate that household-specific water quality information can improve both behaviors and drinking water quality.

■ INTRODUCTION

Diarrheal disease is a leading cause of childhood mortality, resulting in an estimated 1.3 million deaths in 2015.[1] The majority of diarrheal disease cases are attributable to fecal-oral transmission of pathogens via widespread environmental contamination, with exposures linked to lack of adequate sanitation at the household and community levels, poor hygiene, and unsafe food and water.[2,3] Although a substantial fraction of diarrheal deaths could potentially be averted by installing high-quality piped water supply systems where waterborne disease risks are greatest,[4,5] infrastructure expansion is costly and time-consuming.[6] Approximately 39% of the world's population still lacks access to a safely managed water supply[7] and microbiologically unsafe drinking water remains prevalent in low- and middle-income countries.[7−10]

Where safe water infrastructure is inadequate, communities and households can improve or maintain water quality through household water management practices, including treating drinking water and improving how household water is handled during transport and in the home. Point-of-use drinking water treatment can improve microbiological quality and may also reduce risk of enteric disease.[5,11] Storing drinking water in a

Received: January 3, 2018
Revised: April 6, 2018
Accepted: April 11, 2018
Published: April 11, 2018

DOI: 10.1021/acs.est.8b00035
Environ. Sci. Technol. XXXX, XXX, XXX−XXX

container with a narrow opening, lid, or spigot for dispensing reduces the risk of recontamination of water within the home.[5,11,12]

Despite the evidence that better household water management can improve or maintain water quality and may improve health outcomes, adoption of new behaviors is often low[13−16] and challenging to sustain.[17] In part, this is due to the complex range of behavioral determinants that inform water management practices, such as financial or time constraints, perceived convenience, or taste preferences.[18−20]

Lack of knowledge about water quality and disease risk can be a barrier to the adoption of improved household water management behaviors.[18,21−23] In low-income settings, water quality testing may be limited and typically occurs far from the community;[21] as a result, individuals rarely have access to timely and specific information on their own household or source water quality. Providing water quality information directly to individuals, or enabling them to obtain it themselves, may therefore help households overcome a key knowledge barrier. Such information might also facilitate households' decision-making with respect to changing or improving their own water quality.[23] Direct provision of information is simple and less dependent on testing by target beneficiaries, relative to provision of test kits. However, microbial water quality can be highly variable over time and space (Supporting Information (SI)), and so provision of test kits might better allow beneficiaries to determine how best to maintain drinking water safety by allowing for multiple points of testing as needed.

This paper presents the results of a cluster-randomized controlled trial (cRCT) of low-cost, field-deployable microbiological water test kits distributed at the household level in the rural Kanpur district of Uttar Pradesh, India. In India, where more than 100 000 children under 5 die of diarrhea each year,[24] the proportion of the population with access to piped drinking water may be as low as 24%;[2] piped water networks that are available are also at high risk of contamination due to intermittent service.[25,26] We developed a standard information and education intervention consisting of community meetings and household visits designed to improve knowledge and skill related to managing and maintaining household water quality. This information was implemented alone and in combination with interventions providing household-specific water quality information. Water quality information included standard laboratory testing or the provision of low-cost field-water quality test kits that could be used in the home.

We had three key objectives: (1) to determine whether provision of household-specific water quality information alongside education on how to improve water quality leads to changes in the microbiological contamination of stored household drinking water, as measured by *Escherichia coli* counts; (2) to determine whether household specific water quality information would lead to changes in key water management behaviors (storage, handling, and/or treatment); and (3) to determine whether household access to a novel low-cost and simple water quality test, distributed to households to use on their own, results in differential improvements in the microbiological quality of household-stored drinking water and key water management behaviors compared with controls receiving no specific water quality information.

■ MATERIALS ANDMETHODS

Study Design. The study design is based on standard approaches to cluster randomized controlled trials.[27] We registered this trial before beginning field work, including prespecification of hypotheses, methods, and outcome measures (trial registration: NCT03021434, clinicaltrials.gov). The predefined primary outcome variable was the arithmetic mean *E. coli* count[28] from samples of household drinking water collected at one unannounced visit 4 weeks postbaseline. Secondary outcomes included self-reported household water treatment frequency and method, self-reported primary drinking water source, self-reported water storage practices (e.g., keeping storage container covered, using a storage container with a narrow opening), and availability of soap for handwashing. Water storage practices and availability of soap were verified by direct observation. Additional outcomes included self-reported prevalence of diarrhea, abdominal pain, and vomiting (overall and among children under 5) in the 7 days prior to the survey.[29]

Overview and Sampling Frame. Our study took place in rural and peri-urban villages in the Kanpur district of Uttar Pradesh, India. We chose this area due to limited access to safe drinking water[30] and proximity to our laboratory at the Indian Institute of Technology Kanpur (IIT-K). We obtained a list of all villages in the Kanpur district from government census records.[30] We randomly selected 60 villages that had a population between 100 and 1000 households, did not receive chlorinated drinking water from public utilities, and could be reached within 2 h by car from IIT-K. Using simple randomization procedures, selected villages were allocated to one of two intervention arms or a comparison arm, with weighting to increase comparison arm allocation for multiple hypothesis testing. Because there was no available list of individuals or households within each village, we utilized participatory mapping by village leaders to identify households with children under five. We intentionally sampled households with children under five due to disproportionate diarrheal disease burden within this population.[1] Within each village catchment area, we randomly selected ten of these identified households.

After a given household was recruited, trained data collectors reviewed a participant information sheet with the respondent, which explained the project's overall objectives, duration of the study, and general study procedures. We obtained written informed consent from all participants prior to data collection activities, consistent with study approvals from institutional review boards at the London School of Hygiene and Tropical Medicine (ref. No.:11920) and IIT-K (IITK/IEC/2016−17 II/4).

Intervention. The intervention consisted of three components: (1) a community education session combined with information on household water management; (2) household education on household drinking water management; and (3) provision of information about household-specific water quality. Participants received household specific water quality data in one of two ways depending on study arm. The *messaging-only arm* received only the first two components and received no information on their household's stored water quality. For the purposes of this study, this *messaging-only* arm serves as the comparison (or control) arm for the study. In the *standard testing arm*, trained data collectors analyzed household water quality data in a laboratory by membrane filtration for *E.*

DOI: 10.1021/acs.est.8b00035
Environ. Sci. Technol. XXXX, XXX, XXX−XXX

coli. Data collectors then returned to households and informed them whether or not their water was contaminated. In the *test kit arm*, each household was provided with ten water testing kits yielding semiquantitative results for *E. coli*, which they were instructed to use at their discretion. All households received three visits during the intervention (two at baseline and one unannounced follow up visit 4 weeks later), as explained in additional detail below.

The *E. coli* test kit used by participants in this trial was developed in prior pilot testing in India (SI). The semiquantitative test uses the open-source Aquatest (AT) broth medium[31] with a resorufin methyl ester chromogen[32] (Biosynth AG, Switzerland) and ambient temperature incubation[33] for 48 h following sample collection. Briefly, water samples are measured to 10 and 100 mL volumes using single-use volumetric cylinders that also serve as packaging. These volumes are added to sealable bags containing premeasured AT medium. A color change from yellow-beige to pink-red indicates the presence of *E. coli*, and the combination of the two bags is used to interpret the final test result. Results can be interpreted as <1 *E. coli* per 100 mL (both bags negative, "safe"); 1−9 *E. coli* per 100 mL (large bag positive, small bag negative, "unsafe−low risk"); or ≥10 *E. coli* per 100 mL (small bag positive or both bags positive, "unsafe−medium to high risk"). Users were asked to interpret test results themselves at the end of the 48 h ambient temperature incubation period using a graphic interpretation card that was provided as part of the test. Illustrated step-by-step test instructions were also included with each kit (SI). All product labeling and documentation was in Hindi. Project enumerators spent approximately 5−10 min training each head of household (in Hindi) on use of the test by carefully reviewing each step in the process and explaining how to interpret the test results. Because *E. coli* counts in water can be highly variable (SI), even within the same household and on the same day, multiple tests are often recommended to estimate water quality. In this trial, participants were supplied with 10 test kits and encouraged to use them for multiple sources or at multiple time points, at the participant's discretion.

The intervention design was informed by the "extended parallel processing model (EPPM)",[34] a model which describes how behaviors are shaped by two broad determinants: efficacy beliefs and perceived threat. All participating villages received the community education and generalized household water management messaging. We designed household materials and information sessions (SI) to target efficacy beliefs by demonstrating methods that individuals can use to improve and maintain the microbiological quality of their water, including storing water to avoid contact with hands, boiling water, and hand washing with soap. Water quality test results and water quality test kits are assumed to target perceived susceptibility to water contamination by providing households with specific information about the quality of water in their own households. We tailored the information to be appropriate for local circumstances and resources; focusing education materials and information sessions on behaviors with low resource requirements for the household (e.g., boiling drinking water using readily available biomass, handwashing with soap, storing water in a covered container), rather than cost-intensive behaviors (e.g., switching to treated bottled water, purchasing commercial water filters, using bleach/chlorine tablets).

Project staff scheduled village information sessions in advance, and village leaders promoted the sessions among mothers and female heads of households, since they are typically responsible for management of household drinking water.[35] The session consisted of a short, 15−30 min presentation on waterborne disease, water management, and strategies for improving water quality in the home. Village information sessions were designed to be relatively informal, and study staff encouraged questions and discussion among participants. Although the information session was mainly targeted to adult women, children often attended since the presentations typically took place in school buildings.

Following the community information session, data collection staff met with village leaders to define the boundaries of the village via participatory mapping and to identify households having at least one child under the age of five. From this, we recruited a random sample of 10 households in the community to be part of the trial. To minimize bias, recruitment was not restricted to those that attended the community information session. Trained field staff visited the homes of all households recruited. While there, the enumerator spent 10−15 min reviewing water quality and management information with the head of household and other family members prior to completing the survey and water sample collection. All households were informed that data collectors would be returning after 72 h and again after approximately one month for a follow up visit. Households in the *test kit arm* were also given a test kit and instructed on how to use it. Project staff instructed them to use this test on their household drinking water within 24 h.

Following baseline data collection, all households were revisited within 72 h. For households in the *messaging-only arm*, enumerators reviewed the water quality and management information again but did not provide any water quality results. For households in the *standard testing arm*, the data collector reviewed with the head of household whether or not their water had been found to be contaminated and reviewed the water quality and management information. For households in the *test kit arm*, the enumerator reviewed the results of the test and provided an additional nine test kits, which they were instructed to use on their household drinking water at their discretion. They also reviewed the water quality and management information.

All households received an unannounced follow up visit approximately 4 weeks after the initial baseline visit. After completing data collection activities, data collection staff informed households in the *messaging-only* arm whether their drinking water sample from the baseline visit was contaminated.

Sample Size. We used standard formulas developed for statistical analysis of multi-intervention randomized controlled trials,[27,36−38] accounting for clustering in the comparison of means for continuous outcomes. A coefficient of variation (k) of 0.3 was used for sample size calculations based on previous microbial data collected during pilot work in Maharashtra (SI). We weighted arm allocation to minimize variance for multiple hypothesis testing,[38] resulting in a 4:3:3 control:intervention ratio in cluster allocation.

Sample size calculations assumed a mean baseline *E. coli* count of 85 cfu/100 mL with a standard deviation of 290 as a conservative estimate based on previous systematic sampling of small, rural water supplies and stored drinking water in Maharashtra (SI). To allow a minimum detectable effect size (MDES) of 0.5 $\log_{10}$ on the continuous outcome of *E. coli* cfu/100 mL at 80% power, we calculated that the sample would require 10 households per cluster, spread among 20 control

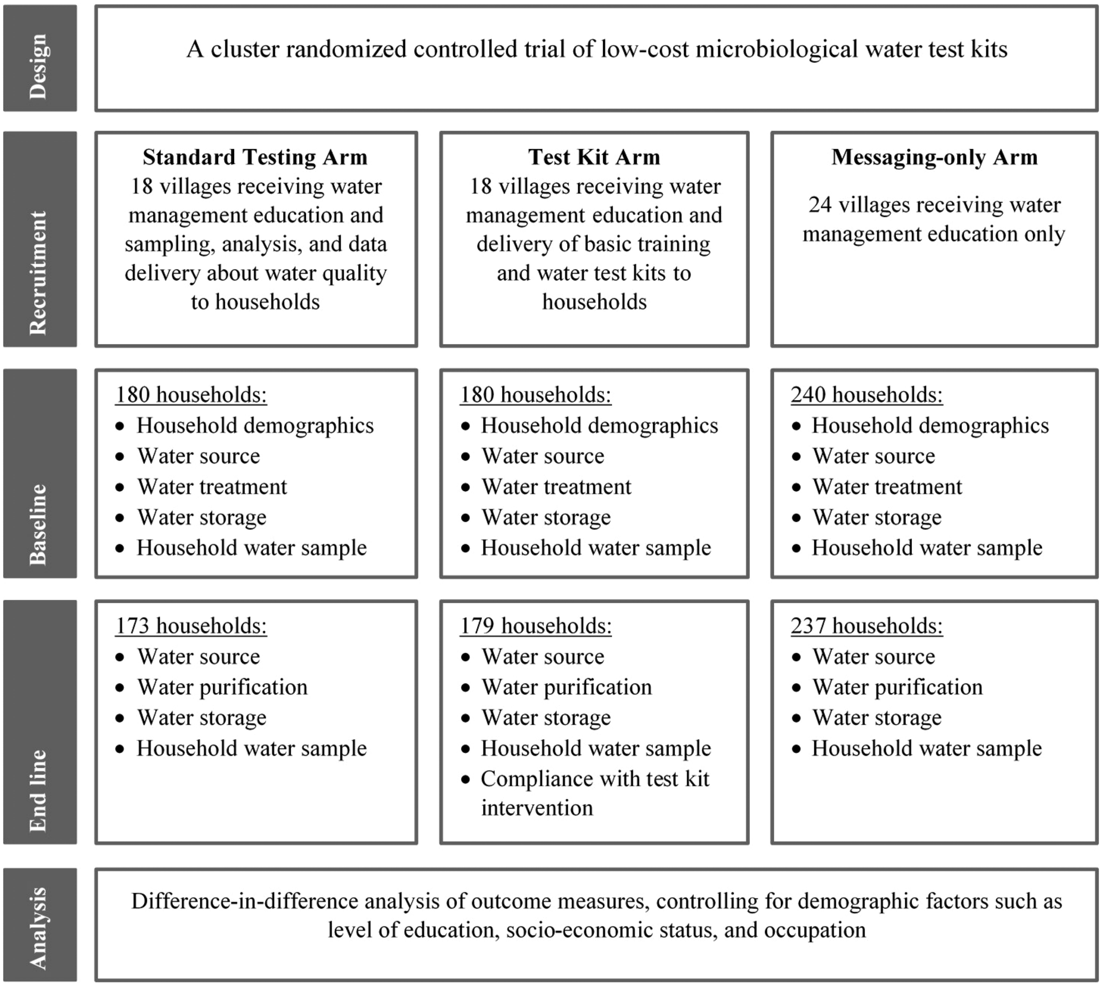

Figure 1. CONSORT[39] diagram describing the cluster randomized controlled trial design of the study.

villages and 15 intervention villages per arm (500 households). This sample size was determined to be sufficient for detecting the MDES between each intervention arm and the messaging-only control but was not intended to detect for differences between the intervention groups. We recruited an additional 10 villages (four control villages, three per intervention arm) to allow for additional qualitative data collection following the conclusion of end line data collection, resulting in a total sample size of 60 villages and 589 households (Figure 1), which also allowed for some loss to follow-up among participants.

Data and Sample Collection. Data collection took place between March and May of 2017, during the dry season in Uttar Pradesh. All of these activities were administered during unannounced baseline and follow up visits conducted one month later. Surveys collected self-reported information related to household demographics, health outcomes (diarrhea, vomiting, abdominal pain), water source(s), water treatment methods and frequency, and water storage habits. We used a two-week recall period for questions regarding water source, treatment, and storage. We also collected self-reported data on source, treatment, and storage of drinking water currently stored in the household. The respondent provided details on children under the age of five, including name, age, and diarrhea episodes in the previous week. Structured observations of household water storage, water treatment materials, and handwashing materials were included in the survey questionnaire. Data collectors conducted the surveys in Hindi and recorded responses electronically using mWater (http://www.mwater.co/) software installed on smartphones. Phones were synched daily to an online database.

At both baseline and the follow up, trained data collectors collected a 330 mL sample of household drinking water for analysis. To collect the sample, we asked study participants to fill the sample container (treated with sodium thiosulfate) as if it was a drinking cup for a child living in the household. Samples were kept on ice in a cooler until delivery to the laboratory and thereafter stored at 4 °C until processing. All samples were processed within 8 h of the time of sampling. *E. coli* in samples were enumerated by membrane filtration and incubation on selective media consistent with EPA Method 1604,[40] though with membrane filters incubated on Compact Dry EC plates (Hardy Diagnostics, Santa Maria, California) rehydrated with 1 mL of sample water. Samples were processed and incubated for 24 h at 35 °C; colony forming units (cfu) were counted and reported as mean cfu per 100 mL sample. For statistical purposes, if zero colony-forming units were observed on the plate, we assigned a value of 0.5.[41] Likewise, if colonies were too numerous to count reliably, we assigned a value of 200 as a conservative estimate of the upper detection limit.

Statistical Analysis. *E. coli* concentrations were log-transformed prior to analysis. Differences in baseline household characteristics and *E. coli* concentration between study arms were assessed using linear and logistic regression models,

Table 1. Selected Baseline Household Characteristics and Outcomes by Treatment Arm

	messaging-only (*N* = 237)	standard testing (*N* = 173)	test kit (*N* = 179)	total (*N* = 589)	*p*-value[a]
Demographic Characteristics					
mean number of household members (SD)	8.0 (3.7)	7.9 (5.5)	7.6 (3.6)	7.8 (4.3)	0.64
mean number of children under 5 per household (SD)	1.5 (0.8)	1.5 (0.7)	1.4 (0.6)	1.4 (0.7)	0.35
proportion of respondents that completed secondary school (SE)	0.51 (0.03)	0.58 (0.04)	0.41 (0.04)	0.50 (0.02)	0.03
proportion of households living below poverty line (receives Antyodaya/BPL ration card) (SE)	0.33 (0.03)	0.45 (0.04)	0.55 (0.04)	0.43 (0.02)	0.03
Water Quality, Source, and Treatment					
proportion reporting primarily using protected dug well to obtain water (SE)	0.86 (0.02)	0.77 (0.03)	0.88 (0.02)	0.82 (0.01)	0.16
proportion reporting ever treating drinking water, all methods (SE)	0.01 (0.01)	0.05 (0.02)	0.04 (0.01)	0.03 (0.01)	0.07
mean log10 *E. coli* cfu/100 mL of household drinking water	1.42 (1.76)	1.38 (1.57)	1.09 (1.54)	1.31 (1.64)	0.29
Health Outcomes					
proportion of households with at least one diarrhea case in the 7 days prior to survey (SE)	0.08 (0.02)	0.12 (0.02)	0.07 (0.02)	0.09 (0.01)	0.38
proportion of households with at least one diarrhea case in a child under 5 in the 7 days prior to survey (SE)	0.04 (0.01)	0.09 (0.02)	0.04 (0.02)	0.06 (0.01)	0.10

[a] We assessed homogeneity across study arms using linear and logistic regression models, accounting for village-level clustering.

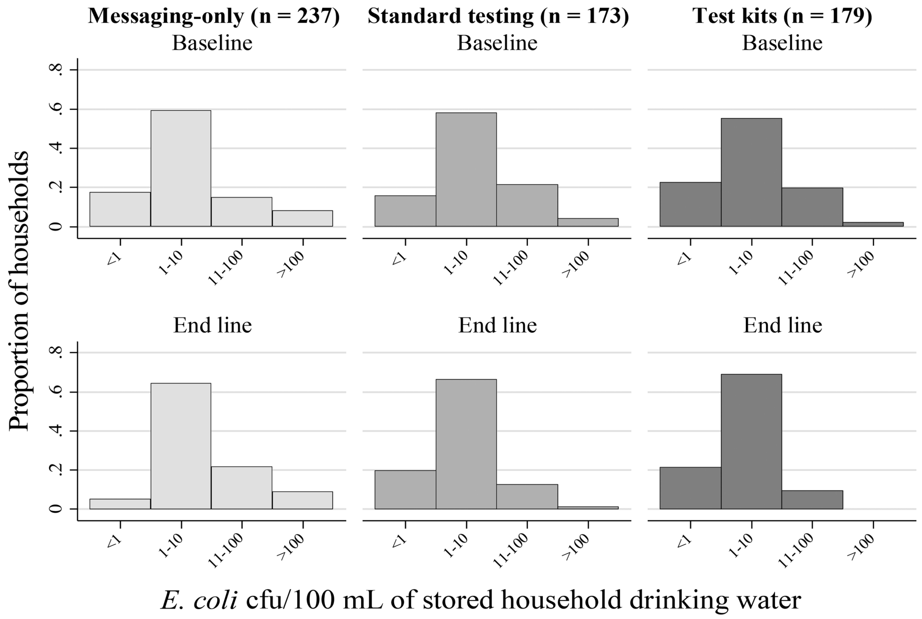

Figure 2. Distribution of categorical[45] *E. coli* concentrations in household stored drinking water samples by surveillance point and study arm.

accounting for clustering at the village level. To determine whether there were significant differences in primary and secondary outcome measures between the intervention arms and comparison arm, we utilized a difference-in-differences (DiD) approach.[42] This method estimates the effect of specific interventions while adjusting for any inherent differences between the intervention and control groups at baseline that may influence results. We completed analysis in Stata v14 (College Station, Texas) using the "xtgee" command, where difference-in-difference analysis is estimated as the interaction term of the data collection round (baseline vs end line) and intervention arm (*standard testing* or *test kit* vs *messaging-only*). Generalized estimating equations (GEE) with robust variance estimation accounted for correlations due to clustering.[43] The GEE model assumes that missing observations are Missing Completely at Random (MCAR), but re-estimation using only the sample of households present over the study duration yielded nearly identical results.[44] All analyses were adjusted for education level completed and below poverty line status, which varied significantly across study groups.

To determine whether the presence of a contamination signal resulted in greater improvements in water quality or reported water management behaviors, we performed a difference-in-difference analysis within each of the two intervention arms comparing households that received a contamination signal versus households that did not. However, this analysis was below the unit of randomization, and therefore results should be interpreted with caution.

■ RESULTS

Household Characteristics. Table 1 summarizes baseline statistics for the three study cohorts, as well as for the total sample. The average household in this sample consisted of 7.9 members, including 1.4 children less than 5 years old. Household composition did not vary significantly across the three study cohorts ($p = 0.64$, $p = 0.35$). Approximately 50% of respondents completed secondary school, although this was lower in the *test kit arm* ($p = 0.03$). 43% of households reported receiving a BPL (below poverty line) ration card from the

Table 2. Differences in Water Quality and Key Behaviors between Treatment Cohorts and Messaging-Only Group

	baseline	end line[1]	DiD[2] (95% CI)	p-value
Mean Log$_{10}$ *E. coli* cfu/100 mL of Household Drinking Water (SD)				
standard testing arm	1.38 (1.57)	0.89 (1.27)	−0.93 (−1.28, −0.58)	<0.01
test kit arm	1.09 (1.54)	0.65 (1.07)	−0.89 (−1.14, −0.64)	<0.01
messaging-only arm	1.42 (1.76)	1.87 (1.55)	(referent)	
Proportion of Households Reporting Boiling Drinking Water Prior to Use in Previous Two Weeks (SE)				
standard testing arm	0.03 (0.01)	0.45 (0.04)	0.38 (0.27, 0.48)	<0.01
test kit arm	0.02 (0.01)	0.34 (0.04)	0.28 (0.18,0.39)	<0.01
messaging-only arm	<0.01 (<0.01)	0.04 (0.01)	(Referent)	
Proportion of Households Reporting Using a Commercial Water Filter in Previous Two Weeks (SE)				
standard testing arm	0.01 (0.01)	0.01 (0.01)	0.00 (−0.01, 0.00)	0.32
test kit arm	0.02 (0.01)	<0.01 (<0.01)	−0.02 (−0.04, 0.01)	0.21
messaging-only arm	<0.01 (<0.01)	<0.01 (<0.01)	(referent)	
Proportion of Households Using a Cover or Lid on Their Water Storage Container (SE)				
standard testing arm	0.96 (0.01)	0.98 (0.01)	−0.03 (−0.08, 0.02)	0.26
test kit arm	0.93 (0.02)	1.00 (<0.01)	0.02 (−0.08, 0.12)	0.66
messaging-only arm	0.96 (0.01)	1.00 (<0.01)	(referent)	
Proportion of Households with Soap Available at Handwashing Station at Time of Survey (SE)				
standard testing arm	0.94 (0.02)	0.97 (0.01)	−0.05 (−0.12, 0.02)	0.17
test kit arm	0.89 (0.02)	0.99 (0.01)	0.02 (−0.08, 0.13)	0.67
messaging-only arm	0.92 (0.02)	1.00 (<0.01)	(referent)	
Proportion of Households with at Least One Case of Diarrhea in the Previous Seven Days (SE)				
standard testing arm	0.12 (0.02)	0.02 (0.01)	−0.02 (−0.09, 0.05)	0.54
test kit arm	0.07 (0.02)	0.01 (0.01)	0.02 (−0.05, 0.10)	0.51
messaging-only arm	0.08 (0.02)	0.01 (0.01)	(referent)	

[1] End line visits were conducted approximately 4 weeks after the initial baseline visit. [2] Difference-in-difference estimator relative to messaging-only arm, adjusted for baseline differences in education level completed and below poverty line status. [3] Baseline was n = 173, end line was n = 173. [4] Baseline was n = 178, end line was n = 179. [5] Baseline was n = 233, end line was n = 233.

government, with fewer households in the messaging-only arm (33%) compared to the *standard testing* and *test kit arms* (45% and 55% respectively) ($p = 0.03$).

Despite these sociodemographic differences, self-reported household water source and treatment practices were comparable across the three arms. Among all households, 82% ($p = 0.16$) reported obtaining drinking water from either a private or public protected dug well, which is considered an "improved" water source. Water treatment, by any method, was uncommon among all cohorts, with only 3% of households reporting ever treating their water. The proportion of households that reported treating their drinking water did not vary significantly across study arms ($p = 0.07$). Of these households, participants reported boiling and using a commercial water filter as methods of treatment. An estimated 8% of households reported that at least one member of the household had experienced diarrhea in the 7 days preceding the survey, which was consistent across study arms ($p = 0.38$). An estimated 6% of households reported diarrhea in a child under 5 in the 7 days prior to the survey, which did not vary significantly across study arms ($p = 0.19$.

Only 11 (1.8%) households were unavailable at the time of the one-month follow-up visit. Additionally, 4.5% of households had incomplete *E. coli* concentration data, since some households did not have stored drinking water available at the time of sampling. To determine whether this affected the GEE results, we re-estimated the models with only households with complete data. The results were nearly identical to those obtained using the full sample (results not shown).

PRIMARY AND SECONDARY OUTCOMES

Water Quality Results. We collected a 1160 water samples in total across all study arms and both data collection rounds. Approximately 18% of samples fell below the detection limit (<1 cfu/100 mL) and 5% of samples were above the detection limit (≥200 cfu/100 mL); the proportion of values censored at 0 and 200 did not vary significantly across treatment arms ($p = 0.16$ and $p = 0.10$, respectively).

Figure 2 presents the distribution of *E. coli* concentrations at baseline and one-month follow up, based on commonly used log$_{10}$ levels indicating potential risk,[45] by study arm. Table 2 outlines the changes in water quality and self-reported water management behaviors between baseline and end line one month later, including differences in changes among treatment cohorts and the messaging-only cohort. In the *messaging-only arm*, water quality did not improve: log$_{10}$ mean *E. coli* cfu/100 mL increased from 1.42 to 1.87 (8.4%) or from an arithmetic mean of 23 cfu/100 mL (95% CI 16−30 cfu/100 mL) to 25 cfu/100 mL (95% CI 19−32 cfu/100 mL). In the *standard testing arm*, water quality improved significantly between baseline and follow up. Log$_{10}$ mean *E. coli* cfu/100 mL decreased from 1.38 to 0.89 (57%), which corresponds to a 0.94 log$_{10}$ cfu/100 mL (65%) reduction compared to the *messaging-only arm* ($p < 0.01$), after adjusting for baseline differences; this corresponds to a decline from an arithmetic mean *E. coli* count of 16 cfu/100 mL (95% CI 10−23 cfu/100 mL) at baseline to 7 cfu/100 mL (95% CI 4−10 cfu/100 mL) at end line. As in the *standard testing arm*, we observed a significant improvement in water quality in the *test kit arm*. Log$_{10}$ mean *E. coli* cfu/100 mL decreased from 1.09 to 0.65 (68%), which corresponds to a 0.84 log$_{10}$ (76%) reduction compared to the messaging-only arm ($p < 0.01$), after adjustment for baseline differences. This represents a decrease from an arithmetic mean *E. coli* count of 12 cfu/100 mL (95% CI 7−16 cfu/100 mL) at baseline to 4 cfu/100 mL (95% CI 3−5 cfu/100 mL) at end line in the *test kit* arm.

Behavioral Outcomes. Measured improvements in water quality align with changes in self-reported water treatment behaviors. In all study arms, there was an increase in the proportion of households that reported boiling drinking water in the previous 2 weeks. In the *messaging-only arm*, reported boiling in the previous 2 weeks increased from <0.01 to 0.04. In the *standard testing arm,* the proportion of households that reported boiling their drinking water in the previous 2 weeks increased from 0.03 to 0.45. This is the equivalent to a 0.38 relative change in a respondent reporting boiling at end line compared to the *messaging-only arm* after adjusting for baseline characteristics ($p < 0.01$). In the *test kit arm,* the percentage of households that reported boiling their drinking water in the previous 2 weeks rose from 0.02 to 0.34; equivalent to a 0.27 relative change compared to the *messaging-only arm* ($p < 0.01$).

There was little change in the proportion of households that reported using a commercial water filter in the previous 2 weeks. In the *standard testing arm*, the percentage of households that reported using a commercial water filter remained constant at 1% between baseline and follow up. In the *test kit arm*, the proportion of households decreased from 2% to less than 1%. Among households in the *messaging-only arm*, the proportion remained constant at less than 1%.

Among all three study arms, the proportion of households that reported using a covered storage container for their household drinking water, as well as the proportion that had soap available at their handwashing station, increased. For households in the *standard testing arm*, the proportion of households that reported using a covered water container increased from 0.96 to 0.98, but improvement was less than what was observed in the *messaging-only arm* ($p = 0.07$). In addition, the proportion of households with soap available at their handwashing station increased from 0.94 to 0.97, though again this was less than the improvement observed in the *messaging-only arm* ($p = 0.05$).

Among households in the *test kit arm,* the proportion of households using a covered water storage container increased from 0.93 to 1.0. The proportion of households with soap available for handwashing increased from 0.89 to 0.99. Neither change was significant compared to the *messaging-only arm* ($p = 0.21$ and $p = 0.36$, respectively).

The proportion of households that reported at least one case of diarrhea in the 7 days prior to the survey decreased by a large amount in all three treatment groups. However, improvements in the *test kit arm* and *standard testing arm* were not statistically significant compared to the *messaging-only arm* ($p = 0.59$ and $p = 0.51$, respectively).

■ CONTAMINATION SIGNAL

Table 3 compares changes in water quality and self-reported water management behaviors between households that received contamination signals and those that did not in both the *standard testing* arm and the *test kit arm*. As this analysis breaks the primary study randomization, results should be interpreted with caution.

***Standard Testing* Arm.** Eighty four percent of households in the *standard testing arm* were informed that their water showed evidence of microbial contamination following baseline data collection. Among households that did not receive a contamination signal, $\log_{10}$ mean *E. coli* cfu/100 mL increased from −0.69 to −0.28. Among households that received a contamination signal, $\log_{10}$ mean *E. coli* cfu/100 mL decreased from 1.78 to 1.13, which corresponds to a 1.08 reduction compared to the households which did not receive a contamination signal ($p < 0.01$).

Table 3. Difference-in-Difference analysis[a] of Water Quality and Reported Water Treatment between Households That Received a Contamination Signal and Households That Did Not Receive a Contamination Signal

	baseline	end line[b]	DiD[c] (95% CI)	*p*-value
		Standard Testing Arm		
Mean $\log_{10}$ *E. coli* cfu/100 mL of Household Drinking Water (SD)				
received contamination signal	1.78	1.13	−1.08 (−1.37, −0.78)	<0.01
did not receive contamination signal	−0.69	−0.28	(referent)	
Proportion of Households Reporting Boiling Drinking Water Prior to Use in Previous Two Weeks (SE)				
received contamination signal	0.04	0.5	0.31 (0.15, 0.47)	<0.01
did not receive contamination signal	0.0	0.15	(referent)	
		Test Kit Arm[e]		
Mean $\log_{10}$ *E. coli* cfu/100 mL of Household Drinking Water (SD)				
received contamination signal	2.50	1.25	−1.25 (−1.58, −0.92)	<0.01
did not receive contamination signal	0.22	0.24	(referent)	
Proportion of Households Reporting Boiling Drinking Water Prior to Use in Previous Two Weeks (SE)				
received contamination signal	0.02	0.67	0.53 (0.39, 0.66)	<0.01
did not receive contamination signal	0.02	0.15	(referent)	

[a] This analysis was below the unit of randomization, and thus results should be interpreted with caution. [b] End line visits were conducted approximately 4 weeks after the initial baseline visit. [c] Difference-in-difference estimator relative to households that did not receive a contamination signal. [d] $n = 147$. [e] $n = 26$. [f] $n = 64$. [g] $n = 103$.

Among households in the *standard testing arm* that did not receive a contamination signal, the proportion that reported boiling their drinking water in the previous 2 weeks increased from 0 to 0.15. Among households in the *standard testing arm* that received a contamination signal, the proportion of households that reported boiling their drinking water increased from 0.04 to 0.50, which corresponds to a 0.31 relative change compared to households that did not receive a contamination signal ($p < 0.01$).

***Test Kit* Arm.** All households in the *test kit arm* reported using at least two of the provided test kits. The mean number of reported test kits used was 5.9. Among households in the *test kit arm*, 38% percent reported at least one test kit yielding a positive result (contamination signal).

Among households in the *test kit arm* that did not receive a contamination signal, $\log_{10}$ mean *E. coli* cfu/100 mL increased from 0.22 to 0.24. Among households that received a contamination signal, $\log_{10}$ mean *E. coli* cfu/100 mL decreased from 2.50 to 1.25, corresponding to a 1.25 reduction compared to the households that did not receive a contamination signal ($p < 0.01$).

Among households in the *test kit arm* that did not receive a contamination signal, the proportion that reported boiling their

DOI: 10.1021/acs.est.8b00035
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drinking water in the previous 2 weeks increased from 0.02 to 0.15. Among households in the *test kit arm* that received a contamination signal, the proportion of households that reported boiling their drinking water increased from 0.02 to 0.67, which corresponds to a 0.53 relative change compared to households that did not receive a contamination signal ($p < 0.01$).

■ DISCUSSION

In this study, we explored the effectiveness of using low-cost, field-deployable microbiological water test kits as informational interventions to trigger household-level water management behaviors intended to increase water quality. We found that when given household-specific information about their drinking water quality, participants were more likely to report boiling their drinking water at the point-of-use and to have safer water overall as indicated by *E. coli* counts in household drinking water after a four-week follow up period. We detected no significant difference in these outcomes between intervention arms, suggesting that both one-time laboratory reports or user-obtained semiquantitative household test data, when combined with basic water management messaging, can result in lower short-term counts of *E. coli* in household drinking water compared with messaging only. We found that changes to drinking water quality were consistent with self-reported changes to behavior and that households receiving information indicating baseline water quality was impaired were more likely to take action to improve water safety.

Behavior change findings are consistent with previous studies in similar populations in India. In a Delhi suburb, Jalan and Somanathan[46] utilized a rapid presence/absence fecal indicator test to inform households whether their drinking water was likely to be contaminated, in addition to providing information on available water purification strategies. Intervention households that were informed their water was contaminated were 11% more likely to adopt a purification strategy after eight weeks than households that received only information on available purification strategies. Hamoudi et al.[47] tested a similar intervention in Andhra Pradesh, India, and found that households that received rapid fecal indicator test results and a list of strategies for preventing contamination were more likely to switch to a community-level commercial water source that was available in most study villages, compared to households that received no test results or information. However, the specific changes in behaviors varied as a function of available options—switching of sources or greater household treatment using boiling, or in the case of the Delhi study, filtering—across these studies.

A randomized trial in Ghana[48] also found the provision of household water quality testing and information to be effective in triggering safe water management behaviors. However, this study differed from ours in that households did not receive individualized visits. Rather, members of the communities were randomly selected to participate in group workshops tailored for either adults or school children, after which they received test kits to use at their own discretion. Demand for the water test kits was relatively high, as approximately 50% of recruited adults and 79% of recruited children chose to attend the two-day workshops. Both treatment groups saw improvements in safe water management behaviors compared to the comparison group that received no information or testing supplies.

Research in other settings has not always found information provision to be effective.[21,41] For example, Davis et al.[41] conducted a study in Dar es Salaam, Tanzania in which households were divided into four groups. The information-only group received educational messaging on how to reduce the risk of waterborne disease. This messaging was also given to the three intervention groups, in addition to the results of household water quality and/or hand-rinse tests. However, there were no significant improvements in water quality among the treatment groups compared to the control households.

Although the majority of households in our study were using an "improved" water source, nearly 80% of drinking water samples at baseline had evidence of contamination. This was unsurprising, as previous studies have found that "improved" water sources in low- and middle-income settings frequently have evidence of contamination.[10,49] Thus, point-of-use treatment and safe water management strategies may have an important role to play in mitigating exposure to enteric pathogens in India. Studies in rural Indian populations suggest that point-of-use water treatment methods, such as boiling, solar disinfection, and chlorination are effective in improving water quality, but uptake of these practices is low.[12,50−53] In our study population, only 3% of participants reported ever treating their drinking water at baseline. This increased significantly among households that received household-specific water quality information. Although long-term effects on behavior and water quality were beyond the scope of this study, results in the short term are promising and warrant further research.

The proportion of households that reported at least one positive test was lower than laboratory confirmed samples. This could be due to difference in sampling times in the household, differential recall, or different sensitivity in test. It is also possible that participants in the *test kit arm* used the test kits on samples other than stored household drinking water, such as samples from source water. We did not compare *E. coli* detection via membrane filtration versus the test kits in duplicate samples; participants tested water separately and reported results back to us up to a month later. However, report of a contamination signal was associated with higher self-reported adoption of safe water management behaviors and greater improvements in household water quality.

Diarrhea prevalence was a tertiary outcome measure for our study; we did not calculate sample size to detect an effect of either intervention on diarrheal prevalence. Low prevalence of diarrhea in the study population ultimately precluded detection of any potential effect on this outcome. We also observed a decrease in diarrhea prevalence in the *messaging-only* arm between baseline and end line, but there was an increase in *E. coli* concentration in this study arm over the same time period. We hypothesize that these changes could reflect inherent variability or seasonal effects.[54]

Our theoretical model, EPPM, posits that behavior change occurs when both efficacy beliefs and perceived threat increase. Our education materials were specifically designed to improve households' ability to improve and maintain the quality of their own water. However, in the absence of a specific contamination signal—and, in turn, a change in perceived susceptibility—behavior change was limited. Information alone may result in only limited adoption of water management behaviors unless strategies are in place to turn abstract information about water quality into specific and actionable information.

Unfortunately, water quality testing via current standard laboratory-based methods is not scalable in many settings, including in India, where the requisite trained staff, specialized equipment, basic laboratory infrastructure, and costly consumables may not be widely available outside major cities. According to Government of India estimates covering the rural population only (920 million people), there are 2281 water testing laboratories serving 1.1 million public and private water supplies; of these, a subset regularly test water supplies for microbial contamination. Of 476 laboratories reporting availability of specific tests, 223 (57%) list capacity for basic water microbial parameters (including *E. coli* specifically).[55] An estimated 2.24 million water quality tests (any parameters) were conducted in the fiscal year ending in October 2017. Overall, availability of water testing data is very limited throughout the country. Where testing exists, results may not be readily available to consumers, partly because of logistical barriers to revisiting communities to communicate results. Under these constraints, consumer self-testing, through models such as the test kit, may represent a compelling alternative and allow for scaling up water quality information access to more people at lower cost.

LIMITATIONS

This study had a number of important limitations. First, the short, one-month timeline precludes any assessment of the long-term effects of the interventions. Ideally, changes in behavior can be sustained over time, but they may fade, and future studies should evaluate the longevity of effects as well as the potential benefits of ongoing testing, either by outside actors or by households themselves. A recent systematic review of behavioral impacts of sanitation and hygiene interventions suggest that interventions that focus on education and information alone often result in short-term improvements in hygiene behaviors but are likely ineffective at ensuring longer-term sustained change.[56] However, the authors noted that interventions going beyond simple messaging and are grounded in psychological or social theory—such as the EPPM model which informed our intervention development—are associated with increased adherence and sustainability of behavior changes, although data are limited. Second, since we based random selection of households on participatory mapping from village leaders, it is possible this introduced bias toward households or areas of the village that the leader prioritized, resulting in a biased sample. Maps clearly defining village boundaries were unavailable; we considered our approach the best available option. Because mapping used similar processes across all study arms, any selection bias introduced through this system is likely to have been nondifferential. Third, though water quality was based on objective measures, data on household behaviors and health outcomes were self-reported. Self-report for water management and treatment behaviors may be biased, with respondents potentially over-reporting safe behaviors.[57−59] Over-reporting due to courtesy bias, social desirability bias, or other biases may be increased when respondents have been primed (during the intervention) with information about safe water management and treatment behaviors. The survey team administering the end line questionnaire were the same individuals who also provided the messaging component that all study groups received. Self-report bias, if present, would be expected to affect all study arms. Further, observed changes in water quality were consistent with changes in self-reported behaviors within the study population. Finally, in our study, test kits that were used and interpreted by household members had a similar impact on household water quality compared to standard lab testing. However, we note that households in the test kit arm still received household visits and information sessions. The potential effects and cost-effectiveness of these kits or other types of self-testing when purchased commercially or distributed at the community level—without a substantial messaging component—warrants further investigation.

Findings from this study suggest that the provision of household-specific water quality information, when coupled with education and information on low-cost water management strategies, can result in improved water management behaviors and improved water quality. However, changes in behavior may be dependent on whether testing data indicate water is unsafe, and therefore whether action is required to improve water quality. Low cost water quality test kits can provide a possible means of both informing households of their own water quality and providing them with resources to test multiple sources or at multiple points in time, generating actionable feedback on household water management. This allows consumers to determine for themselves whether water is safe and to decide on appropriate measures for protecting the household's drinking water quality. Future studies should focus on whether the changes we observed can be replicated in other settings and extended over longer-term periods, given the challenges of achieving sustained behavior change.

ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.8b00035.

Additional information as noted in the text (PDF) (PDF)

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The authors declare the following competing financial interest(s): Following the completion of the research described in this paper, Arjun Bir founded Oasis plc, Bangalore, India, to manufacture microbial water quality tests similar to those described in this manuscript. Joe Brown is a technical advisor to this company.

ACKNOWLEDGMENTS

We thank the data collection team at the Indian Institute of Technology Kanpur, including Shivshankar Mishraa and Harishankar, for their excellent work. We gratefully acknowledge funding support from the Global Innovation Initiative of Institute of International Education (IIE), through grant 222GAT9817 to the Georgia Tech Research Corporation. We thank Biosynth AG and Thermo Fisher Scientific for preparing and donating chromogenic media used in microbial test kits.

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