Evaluating the Hidden Costs of Drinking Water Treatment Technologies

Article · April 2023

DOI: 10.1038/s44221-023-00055-y

3 authors:

Katya Cherukumilli
University of Washington Seattle
15 PUBLICATIONS **162** CITATIONS
SEE PROFILE

Isha Ray
University of California, Berkeley
145 PUBLICATIONS **2,729** CITATIONS
SEE PROFILE

Amy J Pickering
Stanford University
145 PUBLICATIONS **4,206** CITATIONS
SEE PROFILE

Published in *Nature Water*; April 3 2023

DOI: 10.1038/s44221-023-00055-y

Evaluating the Hidden Costs of Drinking Water Treatment Technologies

Katya Cherukumilli[1], Isha Ray[2*], Amy J. Pickering[1*]

[1] Department of Civil and Environmental Engineering, University of California Berkeley, Berkeley, California, 94720-2284, United States
[2] Energy & Resources Group, University of California Berkeley, Berkeley, California, 94720-3050, United States

*Correspondence to: isharay@berkeley.edu; pickering@berkeley.edu

Abstract: Drinking water treatment technologies are largely evaluated based on metrics such as contaminant removal efficiency, capital costs, and health impacts. However, the potential for safe water technologies to lead to positive health outcomes depends greatly on user satisfaction, consistent and sustained operation, and financial viability. In this perspective, we argue for the importance of engineering, public health, and economics researchers to assess the "hidden" costs of drinking water treatment technologies, including affordability, labor burden, user acceptance, and the (often) gendered nature of these. Neglecting these factors underestimates the full costs of drinking water treatment technologies and overestimates the potential for treatment options that require substantial behavior change and time to succeed. Here, we present a set of user-centric evaluation criteria for water service providers, practitioners, governments, and other stakeholders to consider when deciding which drinking water treatment technologies to implement, scale-up, or take to market.

Despite the vast resources and time allocated to promoting and deploying safe water technologies and practices, over 2 billion people worldwide still lack access to safely-managed drinking water services[1]. Drinking water treatment technologies are typically evaluated for effectiveness through lab testing and small-scale field pilots before being installed in households and communities. In the last few decades, many researchers, companies, and NGOs have promoted safe water products based on narrowly specified criteria. For example, engineers might advocate for particular technologies because they are "low-cost" (e.g., solar water disinfection (SODIS)[2]) or "simple and user friendly" (e.g., ceramic filters). Despite widespread usage, the definitions of "low-cost" or "user-friendly" remain vague[3] in the literature and tend to refer to the technology itself rather than the user experience. Social scientists have led safe water interventions focused on instilling behavior change, raising awareness about the importance of water and hygiene, and educating end-users about health risks. However, these campaigns have often underappreciated the realities of highly limited resources, highly stressed time budgets, and the low capacity for behavior change that results from these conditions[4]. Furthermore, these interventions almost never confront the social stereotypes and consequences of water treatment being considered "women's work".

Drinking water treatment technologies targeting the removal of microbial and chemical contaminants have been tested and implemented at various scales, including at the point-of-use (household or individual scale), point-of-collection (community kiosks, shared water sources), and municipal-scale (centralized water treatment plants). User time burdens may be most obvious in home water treatment technologies but unaccounted-for costs are also present in community-based and piped networked systems, especially when centralized treatment technologies are unreliable or incompatible with intermittently supplied water and electricity failures. Further, most utility-scale evaluations are currently conducted from the supplier's perspective rather than that of the users.

In this paper, we argue that the evaluation criteria of water treatment technologies that researchers, technology developers, and implementers typically use are overly-narrow, underrepresenting the true costs of water treatment technologies to users and decision makers (households, communities, institutions) who choose to invest in safe water. A more comprehensive set of evaluation criteria from the user's perspective would facilitate more realistic and equitable assessment, and help elucidate why so many highly-promoted safe water approaches are abandoned after a short uptake period[4,5]. The objectives of this paper are to: (1) discuss limitations of existing approaches used to evaluate and select drinking water treatment technologies; (2) present more user-centric evaluation criteria that incorporate neglected costs and burdens of water treatment technologies; and (3) inform future data collection strategies to advance monitoring towards the United Nations' Sustainable Development Goals (UN SDGs) related to safe water provision.

Dimensions of Existing Evaluation Criteria

Researchers have studied and evaluated drinking water treatment technologies across three main fields: environmental engineering (contaminant removal efficiency, material/energy costs, environmental impact)[6], public health (adoption and consistent use, reduction in disease burden)[7,8], and economics (willingness-to-pay, implementation cost)[9]. While domain-specific evaluations from these fields have been published in the academic literature, there are few existing frameworks for comprehensively evaluating water treatment technologies.

Technical evaluations of water treatment technologies are typically guided by two frameworks developed by the World Health Organization: the Guidelines for Drinking Water Quality[10] and the International Scheme to Evaluate Household Water Treatment Technologies[11,12]. The Guidelines[10] set health-based standards for microbial, chemical, and radiological contaminants and recommend acceptability thresholds for constituents impacting water taste, odor, and appearance. The International Scheme[13] ranks household water treatment (HWT) technologies based on their effectiveness at removing bacteria, viruses, and protozoa[14]. In addition to these frameworks, a product guide by UNICEF (2020)[15] ranks a range of household filters based on their technical efficacy, flow rate, operation and maintenance, capacity/lifetime, transportability, price, installation, and safe storage. The WHO frameworks and UNICEF product guide primarily focus on water quality and technical performance, omitting any in-depth assessment of user-centric metrics such as time and financial burdens placed on households for proper technology operation and maintenance. Others have put forth broader frameworks[16,17] to rank HWT technologies, incorporating sustainability (environmental impact, supply chain), technological performance, financial viability (capital and operating costs), and ease of use. However, these frameworks were designed only for HWT technologies and do not consider gendered burdens.

Health impact evaluations of water treatment technologies typically measure and report field indicators related to water quality (e.g., fecal indicator bacteria concentrations in effluent water), technology usage (e.g., presence of a chlorine residual for chlorination technologies), and health (e.g., under-five child diarrhea prevalence[18,19]). Field studies of water treatment technologies are often finance-limited, precluding the ability to collect longitudinal data[20,21] on multi-year technology usage and performance. Furthermore, because severe outcomes of interest such as child mortality are rare, small sample sizes may prevent precise estimation of health benefits. There is ongoing debate on whether infectious disease and child growth outcomes should be the primary foci of water treatment impact evaluations[22,23], when access to safe water has other important quality of life benefits such as reduced stress and increased time savings, well-being, and security. Very few water treatment evaluations have measured these non-disease outcomes.

Economic evaluations of water treatment technologies in low- and middle- income countries typically use surveys to document stated willingness to pay (WTP) or sell products to measure effective demand (the ability and willingness to pay). Contingent valuation surveys obtain stated WTP for non-market resources, such as a water treatment technology not yet commercialized or for receiving improved quality of water supplied from a utility[24]. Since stated WTP can be biased upwards, some economists use revealed preference to value goods and services by measuring consumer behaviors. For example, one could measure the money households spend on fuel to boil water to approximate their WTP for improved water quality[25,26]. Studies that sell or lease services or products (e.g. at randomized offer prices) are considered to be more robust because they can directly measure effective demand for water treatment technologies (and sustained demand[27], if they continue to monitor user payments for services). Generally, real-money auctions have identified very low effective demand for HWT technologies, with most households being unwilling to pay the market price[28,29]. Evidence suggests that households have higher demand for receiving improved water quality services at the point of consumption[30,31] (e.g., treated utility water, vended water)[32] when they are not responsible for maintaining and operating a treatment technology.

Although a few studies[33,34] have generated evidence for long-term maintenance costs, these dimensions are rarely included in technology evaluations. This may be the result of challenges to securing funding for conducting long-term follow-up studies after the intervention period ends. Furthermore, these studies do not acknowledge any gender disparities that may exist in decision-making power (regarding purchasing durables or consumables) or responsibilities related to routine operation and maintenance. Decision making by governments, utilities, or other stakeholders for investments in water treatment infrastructure thus tends to be driven by capital cost and technical performance. These evaluations are used to implement new technologies, but neglect critical factors such as unpaid labor and time spent on water treatment, long-term maintenance costs, and user convenience, acceptance, and satisfaction. It is important to develop broader, more comprehensive evaluation criteria to capture these omitted costs because: (i) they are not equally borne by all people; and (ii) omitted costs can partially explain why technologies fail to be consistently used or scaled up.

Proposed Dimensions of Additional Evaluation Criteria

In this section, we present existing evidence from the literature on affordability, labor burden, user acceptance, and the (often) gendered nature of these. Drawing on this broad literature, we outline appropriate indicators and criteria for evaluating water treatment technologies from a user-centric perspective.

Affordability of water treatment

Whether or not a technology is affordable is dependent both on its *cost* to the user and to the user's *ability* to bear the cost. The global water sector literature often refers to drinking water treatment technologies designed for low-income households, such as chlorine tablets or ceramic filters, as "low-cost" – a term that suggests affordability. There is no clear definition of this widely-used term, however[3]. The literature, especially work focused on low-income regions, also tends to use stated WTP as proxies for affordability, though stated WTP is unable to distinguish willingness- from ability-to-pay[35,36]. Affordability has remained a poorly defined aspect of water access, although the data typically show that the poorest pay disproportionately more for service, often having to gain access through informal means[36].

In classical microeconomics, the concept of water "affordability" considers water as just one good among many in the household budget[37]. Most actual affordability measures are therefore presented as ratios, with some measure of household income or total household expenditures as the denominator[38]. The most commonly-used measure is the Conventional Affordability Ratio (CAR), or the average household water bill, plus any additional financial costs incurred in storing and treating water[39,40], divided by household income, household expenditures, or, when estimated for a region, the median household income. A more nuanced measure is the Potential Affordability Ratio (PAR), or the cost of an essential-needs or "lifeline" water volume[41] divided by the same denominator used to calculate CAR. Some analysts prefer the PAR to the CAR because a lifeline water volume is the more appropriate way in which to judge affordability, though what that level should be is usually a social and political negotiation[42]. In these measures, water costs are often defined as ongoing costs, which may not include capital costs such as drilling a private well or installing a rooftop storage tank. Counting the full lifecycle costs of ensuring safe drinking water would make for more realistic affordability ratios, but these are difficult to calculate in practice[43] .The calculated affordability ratios are compared to a threshold or benchmark ratio, ranging from 1.5% to 3% of household income depending on the agency setting the threshold; a ratio above the threshold is considered "unaffordable".

A key critique of both the CAR and PAR measures is that their denominator, measured as income or expenditures, does not account for non-discretionary essential expenses such as rent and food. From the human right to water perspective, water is not "affordable" if paying for safe water forces a household to cut down on other essential expenses[44]. In the Residual Income Approach (RIA), a concept borrowed from the affordable housing literature[45], the affordability ratio is calculated using the cost paid for water relative to household income less essential expenses. Another critique of affordability measures where the household is analyzed as a homogeneous unit is that affordability is, in practice, not gender-neutral. Insights from feminist research have helped unpack the complex social relationships that mediate control of water as well as money[46]. This literature argues that the commodification of domestic water (and, by extension, water treatments) marginalizes women who may not control the household budget for purchasing water or water treatment methods[47].

Going forward, we recommend collecting data to calculate the PAR as an improvement over characterizing a technology as "low-cost", a blanket term that lacks an expenses denominator. The PAR is a better measure than the CAR because it can be calculated at a human-rights compatible volume of water, such as 50 liters per person per day[48] (or another agreed-upon lifeline volume). A measure such as CAR might find safe water affordable even if households are under-consuming water in order to keep other costs down[38]. Measuring consumed volume is a challenge when there is no piped water supply, but studies have shown that it can be estimated[49,50]. Although an RIA-type approach is more compatible with the human rights foundations of the Sustainable Development Goals, this measure is more demanding of data, and data collection is itself a non-trivial cost. Overall, a PAR-type measure is more feasible for low-income settings. Both the CAR and the PAR can be used to determine the level of subsidies, if needed, to make water treatments more affordable for the median household.

Table 1. Measures of Water Affordability

Measure	Formula	Limitations
Conventional Affordability Ratio (CAR)[39,40]	$\frac{*\,Cost\ of\ water\ consumed}{**\,Household\ income\ or\ expenditures}$	Does not consider that households may use less water than needed Ignores essential expenses such as food and rent
Potential Affordability Ratio (PAR)[41]	$\frac{Cost\ of\ lifeline\ water\ volume}{Household\ income\ or\ expenditures}$	Difficult to agree upon a lifeline water volume*** Ignores essential expenses such as food and rent
Residual Income Approach (RIA)[45]	$\frac{Cost\ of\ water\ consumed}{(Household\ income\ -\ food\ and\ rent\ costs\ )}$	Does not consider that households may use less water than needed High data collection costs

* Cost of water consumed includes the water bill and cost of water storage and treatment

** Regional median values of household income or expenditures could also be used as the denominators for CAR and PAR

*** Lifeline volume refers to the first tier of utility-supplied water (at a low or zero cost) to meet people's essential needs, sometimes declared to be 50L per person per day[48]

Labor burden of water treatment

Social norms in many countries dictate that women (and girls) be the primary parties responsible for storing and treating drinking water[51–53] ,though there are exceptions[54]. That women are likely to be responsible for safe treatment and management of domestic water is routinely taken for granted at national and international policy levels[55] .The "enabling" components of sustained water treatment programs, such as education, peer-to-peer outreach, or community mobilization[3], mostly target women and these programmatic costs are rarely quantified. HWT is most obviously "women's work", but treated water provided even at utility or community-scales often calls for some degree of gendered labor (e.g., storing and managing water provided intermittently).

Data collected to assess the impact of safe water technologies treat the household as the relevant unit of analysis, and do not disaggregate labor costs by sex within the household. If the labor is unpaid, as domestic labor tends to be, it may not be counted at all. The general paucity of sex-disaggregated data[52,56] makes it difficult to estimate who within the household may have preferential access to safe water, and whose labor goes into collecting, storing and treating water. Social expectations that managing water is women's work, combined with safe water technology evaluations that neglect any unpaid labor costs to use and maintain the technology, inadvertently lead to more, and uncounted, work for (mainly) women and girls. In effect, impact evaluations that are gender-blind support technologies that are gender-unequal[57].

Several studies discuss women's labor in relation to drinking water, but the vast majority of these focus on fetching water. With few exceptions[58,59], the health impacts of a female body doing the work that is elsewhere done by pipes are not analyzed; this is in stark contrast to the several thousand studies that carefully estimate the health impacts of (un)safe water on children. Only a few studies[21,60–62] reported on the effort and time needed to treat water, separately from the effort of collecting and storing it. However, studies in Zambia[63], Morocco[64], Brazil[65], and India[66] report measurable time savings for women upgrading from less reliable mostly untreated water supplies to at-home or reliable piped water supplies[66]. The labor burden associated with operation and maintenance of standard HWT technologies can be approximated by summing the active and waiting time periods involved in treatment practices (**Table 2**). Based on these time values, treating enough water to meet a household's basic needs could take up to *several hours per day* (using a daily treated average of 50 L/person for drinking, cooking, sanitation, and hygiene). Even if households treat water only for drinking (spending approximately 30-60 minutes daily), additional time is still required to clean the treatment systems and water storage containers and to procure any necessary consumables (e.g., filter media, fuel) on a recurring basis.

Table 2: Characterizing labor burdens associated with HWT technologies

Household Water Treatment Technology*	**Standard treatment steps**** (active user input and waiting times as well as flow rates are shown in blue)	**Environmental conditions or maintenance needs**
Boiling[67]	1. Bring a pot of water to a rolling boil for 1 minute (time to boil ranges widely (2-12 minutes), based on water volume, pot material/shape, starting temperature, power source). 2. Wait 30-45 minutes for water to cool naturally to room temperature and store in containers.	fuel/power source (wood, coal, gas, electricity), storage containers
Solar Disinfection (SoDis)[68]	1. Fill multiple bottles with water and expose to sunlight for at least 6 hours (if sunny) or 2 days (if cloudy)	sunlight, plastic bottles
Coagulation + filtration	1. Add coagulant to water and stir vigorously for 10 minutes 2. Wait 30 minutes and filter water through cloth into storage container	dispose settled flocs, coagulant procurement, storage container
Flocculation + chlorination (e.g., PUR packets)[60]	1. Add one PUR packet into 10L of water and stir for 5 minutes 2. Wait 5 minutes for solids to setting and filter water through cloth into storage container 3. Wait 20 minutes (contact time) before first use	PUR packet refills, storage container
Solid Tablet or Liquid Chlorination (e.g., Aquatabs[69] or Waterguard[70])	1. Add 1-2 chlorine tablets (or 1 cap-full, 3mL liquid chlorine) into 20L water and shake or stir 2. Wait 30 minutes (contact time) before first use	low turbidity water, chlorine refills, storage container
UV Disinfection	1. Fill water container 2. Turn device on (average flow rate: ranges widely based on device)	low turbidity water, electricity, UV lamp refills, storage container
Biosand Filters[15]	1. Pour water into filter 2. Wait for gravity-driven flow of water through filter (average flow rate: 15 L/h) 3. Collect water in storage vessel below	when flow rates are reduced below user acceptability, manually swirl top layer of sand, dump out dirty water, and clean the diffuser plate, outlet tube, and lid (cleaning frequency ranges on order of weeks to months)
Gravity-driven membrane filters (e.g., Lifestraw 2.0)[15]	1. Pour water slowly into pre-filter mesh 2. Wait for gravity-driven flow of water through the filter (average. flow rate: 9 -12 L/h) 3. Collect water in storage vessel below	backwash every 2-3 days, replace membranes, storage container

Ceramic filters (e.g., candle or pot)[15]	1. Pour water into filter 2. Wait for gravity-driven flow of water through filter (average flow rate: 2 - 5 L/h) 3. Collect water in storage vessel below	brush ceramic candle/pot and bucket bi-weekly, replace fragile ceramic candles, storage container

* The treatment technologies presented here have variable removal efficiencies for protozoa, bacteria, and viruses and will require proper maintenance and upkeep of water storage containers. Most of the technologies also do not remove chemical contaminants, with the exception of filters.

** Treatment steps were summarized based on technology user manuals.

Monetizing non-market “care work”[71] could facilitate greater emphasis on the time burden for women, but remains controversial. Some studies value women’s water-work at the minimum wage; others use a fraction of the minimum wage to impute a more modest value, especially where actual employment options could be low[72]. A second option is to estimate the time cost of managing a technology, and valuing it at some fraction of the median or average hourly wage for “unskilled” work[73]. A third option is to value women’s labor by a fraction of the average hourly wage by income quintile; this method acknowledges earnings differentials across socio-economic strata but implicitly places a higher value on the labor of higher-income strata[66]. All three options are rooted in the opportunity cost of domestic work. A fourth option is to consider the replacement cost value of care work, meaning, estimating how much someone else would have to be paid to do the work that is otherwise done “for free”[74], or how much would have to be paid to purchase an equivalent good or service (e.g., treated water from tankers).

Stress caused by having to treat water (on top of the existing stress of managing and rationing in water-deprived areas) is another important dimension to characterize. Research on poverty and on scarcity overall has argued that people who are always short of money, time, or both, suffer levels of background stress that then act as a “bandwidth tax”[75]. In the case of water treatment, the “bandwidth tax” may result in women failing to use chlorine daily, maintain a water filter, or boil water, because adding one more time commitment to a day already filled with chores and anxieties can be overwhelming (**Table 2**)[76]. A sustainable water treatment system would then be one that does not add to this “tax” but is able to alleviate it. To our knowledge, no studies of maintaining and using safe water technologies have accounted for stress impacts on the user.

Going forward, we recommend collecting data on the unpaid time costs borne by users of safe water systems, at all relevant scales. Specifically, we propose that nationally representative household survey programs (e.g., Demographic and Health Surveys, Multiple Indicator Cluster Surveys) include questions to capture the gender of the primary duty bearer for water treatment and the time spent on all water management practices (including fetching, treatment, and storage). We urge future research to take seriously the unique stressors faced by low-income families and characterize the stress burdens on women that are imposed by, or alleviated by, effective water treatment technologies. We also suggest that, should such labor be monetized, the replacement cost method be used since it is usually closer to the market value of care work than an arbitrary fraction of an arbitrarily-picked wage – especially where women’s earning opportunities are limited.

User acceptance of water treatment

User adoption and preferences have been documented mainly for water treatment approaches at the household, or point-of-use (POU) scale. The most common of these are: boiling, filtration (biosand, ceramic, membrane, etc.), disinfection (UV, solar, chlorine, etc.), and coagulation/flocculation. Proponents of HWT technologies claim that they: (i) are cost- and time-effective in comparison to establishing centralized treatment infrastructure[77]; (ii) empower underserved communities to take water quality into their own hands[17]; (iii) have the potential to meet WHO guidelines for drinking water quality[78], and (iv) can address upstream recontamination of intermittent water supplies. Advocates in favor of "point-of-collection" community- and utility-scale treatment[76] argue that HWT schemes could divert attention and resources[79] from advancing access to piped water supplies and are limited by inconsistent adoption[5,80], which prevents the realization of desired health impacts[81].

Researchers have developed different methods and frameworks to define and operationalize *"usage", "uptake", "adoption", "compliance", and "adherence"*. Although the terms "compliance" and "adherence" are often used interchangeably to characterize the extent of HWT technology use, researchers define these terms variously as the frequency of use of treated water[82], proportion of drinking water treated[83], proportion of treated water consumed[84], or correct, consistent, and sustained use of HWT technologies[80]. Furthermore, these terms put the burden of intervention success (or failure) on the user rather than on the implementers and designers[85]. Reygadas et al[86] present a framework that builds on components including adoption (initial acceptance), knowledge, resource access, habit, and exclusive use, defined distinctly for procuring and consuming treated water. Daniel et al.[87] characterize HWT adoption by analyzing the interactions between different socio-environmental characteristics and behavioral determinants (e.g., existing pre-intervention HWT technologies, perceived water quality threat, access to piped scheme). Sobsey et al.[17] estimate user adoption using self-reported or measured data collected during or after installation and rank technologies based on "sustainability criteria" factors impacting HWT adoption and sustained use (e.g., supply chain requirements, water volume produced, treatment cost, ease of use and time treating water). The evaluation literature has not converged on a single definition of "adoption", though correct and consistent use are essential for these approaches to yield health benefits[88].

Existing evaluations of HWT technologies have collected extensive data on the regularity and extent of user adoption. Significant reductions in user adoption have been measured in households using solar disinfection in Nepal (78% adoption during-study compared to < 9% post-study)[89] and UV disinfection in Mexico (68% device acquisition compared to 40% exclusive use during intervention periods).[90] Recent evaluations of HWT technologies[21,91] found that confirmed use (i.e., observed treated water presence initially and after 9-14 months) declined for biosand filters in Nicaragua (95% to 78%), electrochlorinators in Haiti (39% to 13%), and ceramic-bromine filters in both Kenya (89% to 68%) and Haiti (93% to 50%). Other studies have raised concerns about the need for high sustained usage of HWT to generate health benefits.[79,80,83,84] Notably, HWT products did not reduce child diarrhea prevalence in two recent large-scale randomized trials in Kenya and Zimbabwe[8,92]. We note that, as discussed above, the burden of consistently using treatment technologies within households (and many communities) falls on women, though this gender aspect usually goes unmentioned in studies that have quantified user adoption.

In addition to user adoption, researchers have also collected data on the interlinked concepts of *user preference, acceptability, and satisfaction*. Researchers have measured these concepts by asking users to: (i) rank product preference[93,94]; (ii) describe products' aesthetic and aspirational design appeal, convenience and ease of use, and connection to social status or cultural/religious beliefs[95]; (iii) rank or describe perceptions of drinking water quality based on water taste, odor, and appearance[96]; and (iv) share perception of risks associated with untreated water[97]. Broadly speaking, these various studies suggest that HWT technologies requiring extensive time for consistent use (such as manual chlorination or SODIS) are often not preferred. Few to no studies have carefully documented the technical skills required for HWT technology installation, operation, maintenance, and repairs, and the availability of reliable local material supply chains and manufacturing capacity for HWT products.

The same indicators used to evaluate user preferences and satisfaction for HWT technologies can be applied at the community- or utility- scale. However, we found only one study[98] that measured users' willingness to contribute money or time towards the operation and maintenance of community-owned groundwater defluoridation plants in India. A majority of drinking water treatment plants are currently evaluated from the perspective of the utility or provider. The International Benchmarking Network for Water and Sanitation Utilities provides data[99] on indicators relating to water service coverage (water production/consumption, service quality, piped network performance, non-revenue water), financial performance (revenue, operational expenses, tariffs, assets/investments, poverty indicators, cost), and customers (residential/commercial/institutional users, population served). Affordability metrics have traditionally been concerned with setting tariffs so they can cover the cost of service[38], which is also a utility-centric perspective. We note that some metrics, such as non-revenue water from a free lifeline volume, are preferable from a utility perspective when the non-revenue water allowance is low, but could be preferable from a low-income user perspective when the allowance is higher; this is one example of how evaluations that center the provider can be in conflict with evaluations that center the user. In order to develop solutions to context-specific water supply challenges, utility managers, community operators, and policymakers need more information about costs and benefits from the user perspective.

Going forward, we recommend that all evaluations of drinking water treatment technologies implemented at the household-, community-, or utility-scale include indicators (or rankings) of user acceptability and taste, especially when alternative water sources are available. We also recommend transparency on how "adoption" or correct and consistent use is being defined, how its extent is measured, and who is expected to do the work of adoption. If reported use is the main measure, it should be asked with reference to water most recently collected or currently stored for drinking, and ideally supplemented by observational indicators (e.g., is water currently in the treatment device) or water quality measurements (e.g., chlorine residual measured in drinking water to be consumed by users)[100].

Towards A User-Centric Evaluation Approach

The literature on safe drinking water has already shown that many existing drinking water treatment technologies have not achieved widespread adoption at different scales (in particular HWT). In this perspective we (partly) explain these failures as a consequence of their designers' and evaluators' incomplete acknowledgment of their user costs and experiences. In **Table 3,** we propose a minimum set of user-centric criteria to more accurately evaluate the (gendered) user burdens associated with water treatment in terms of affordability, time, and labor. Additionally, we include specific evaluation indicators related to real-world performance, financial viability, and user acceptance and uptake of water treatment technologies. We hope these criteria will lead to water treatment options that minimize the time burdens of treatment and maintenance, and for which realistic measures of affordability can be estimated. While we place user experience at the center of the evaluation process, we recognize the importance of consulting additional stakeholders (e.g., local leaders or government officials) to solicit feedback on the feasibility of, and potential negative consequences of, a water treatment technology prior to implementation. We believe these proposed evaluation criteria are particularly important for technology developers, companies, service providers, and governments who make decisions about what types of treatment technologies to commercialize and implement, which then create the choice set that users (households, communities, institutions) have when they want to invest in safer water. For example, including the indicators outlined in **Table 3** when choosing a water treatment technology could better facilitate efforts to meet UN-SDG 6 (clean water and sanitation) and simultaneous efforts towards other synergistic goals including good health and well-being (UN-SDG 3). Estimating the unpaid labor costs borne by women and girls to use and maintain drinking water treatment technologies is compatible with the goal of gender equality (UN-SDG 5). Such considerations can avoid the promotion of water treatment technologies that purport to be gender-blind but are, in fact, gender-unequal.

We believe that the user-centric evaluation approach proposed herein can help integrate research conducted across different fields and further strengthen the methods currently used in engineering, public health, and economic evaluations of drinking water treatment technologies. Establishing comprehensive evaluation criteria to guide the development of new water treatment technologies is especially salient with increased attention to novel chemical contaminants in global drinking water supplies (e.g., microplastics, per- and poly-fluoroalkyl compounds, pharmaceuticals, other micropollutants). In addition to establishing drinking water quality guidelines and standards, international regulatory agencies have a critical role to play in promoting more comprehensive, gender-sensitive guidelines for evaluating water treatment technologies. Researchers and international agencies should also play a more proactive role in making their evaluations transparent and accessible; many low-income markets are currently selling ineffective water treatment devices that users think "treat" their water.

Increasing financial investments in monitoring and evaluation programs that leverage participatory research methods may aid in data collection efforts to characterize – and make more transparent – the effectiveness, unpaid costs, benefits, and risks from the end-user standpoint. In turn, incorporating user preferences, gender-specific stress and labor burdens, long-term maintenance needs, and realistic affordability ratios into future drinking water treatment evaluations will help the development and adoption of technologies that are more likely to equitably and sustainably increase safe water access.

Table 3: Minimum Set of Criteria and Indicators for Evaluating Water Treatment Technologies

Criteria Dimensions	Indicators	Potential data sources (or data collection methods)
Affordability	Potential Affordability Ratio (PAR) (PAR = Cost of lifeline water volume divided by household income or expenditures)	Prices at local store for consumables, water bills Household income and expenditures data from publicly available household surveys (e.g., Demographic Health Surveys)
Effective Demand	Willingness and ability to pay ($) for capital and operation costs	Sales data Real-money auctions (e.g., take-it-or-leave-it at randomized price points, Becker-DeGroot-Marschak) Contingent valuation surveys
Labor Burden	Daily time required to operate technology to treat household's essential water needs	Technology user operation manual User surveys of time spent on water treatment and by whom
	Gender of primary duty bearer for using water treatment technology	Surveys with active users

User Acceptance	Consistent Use (e.g., treatment technology is being used on most recently collected water for drinking)	Evaluations or surveys with active users Water quality, source type, and treatment data from publicly available household surveys (e.g., Multiple Indicator Cluster Surveys)
	User satisfaction with technology, and with taste, odor, and sight of treated water	Evaluations or surveys with active users
Technical Performance	Contaminant removal efficiency	Lab experiments Field pilots
Health Impact	Relative reduction in diarrhea prevalence or enteric pathogen infection burden	Surveys of users Collection and analysis of human samples Hospital data
	Stress caused by responsibility for water treatment	Interviews and focus groups to understand stressors

References

1. Geneva: World Health Organization (WHO) and the United Nations Children's Fund (UNICEF). *Progress on household drinking water, sanitation and hygiene 2000-2020: five years into the SDGs*. https://washdata.org/reports?reports%5B0%5D=date%3A2021&reports%5B1%5D=monitoring-category%3Awater&reports%5B2%5D=report-type%3Aglobal%20updates (2021).
2. McGuigan, K. G. *et al.* Solar water disinfection (SODIS): a review from bench-top to roof-top. *J. Hazard. Mater.* **235-236**, 29–46 (2012).
3. Amrose, S., Burt, Z. & Ray, I. Safe Drinking Water for Low-Income Regions. (2015) doi:10.1146/annurev-environ-031411-091819.
4. Luby, S. P., Mendoza, C., Keswick, B. H., Chiller, T. M. & Hoekstra, R. M. Difficulties in bringing point-of-use water treatment to scale in rural Guatemala. *Am. J. Trop. Med. Hyg.* **78**, 382–387 (2008).

5. Arnold, B., Arana, B., Mäusezahl, D., Hubbard, A. & Colford, J. M., Jr. Evaluation of a pre-existing, 3-year household water treatment and handwashing intervention in rural Guatemala. *Int. J. Epidemiol.* **38**, 1651–1661 (2009).
6. Amrose, S. E., Cherukumilli, K. & Wright, N. C. Chemical Contamination of Drinking Water in Resource-Constrained Settings: Global Prevalence and Piloted Mitigation Strategies. *Annu. Rev. Environ. Resour.* **45**, 195–226 (2020).
7. Pickering, A. J. *et al.* Effect of in-line drinking water chlorination at the point of collection on child diarrhoea in urban Bangladesh: a double-blind, cluster-randomised controlled trial. *Lancet Glob Health* **7**, e1247–e1256 (2019).
8. Cumming, O. *et al.* The implications of three major new trials for the effect of water, sanitation and hygiene on childhood diarrhea and stunting: a consensus statement. *BMC Med.* **17**, 173 (2019).
9. Ahuja, A., Kremer, M. & Zwane, A. P. Providing Safe Water: Evidence from Randomized Evaluations. *Annu. Rev. Resour. Econ.* **2**, 237–256 (2010).
10. Guidelines for drinking-water quality, 4th edition, incorporating the 1st addendum. https://www.who.int/publications/i/item/9789241549950 (2017).
11. World Health Organization. Results of round I of the WHO international scheme to evaluate household water treatment technologies. (2016).
12. Results of round II of the WHO household water treatment evaluation Scheme. https://www.who.int/publications/i/item/9789241516037 (2019).
13. International Scheme to Evaluate Household Water Treatment Technologies. https://www.who.int/tools/international-scheme-to-evaluate-household-water-treatment-technologies.
14. World Health Organization & United Nations Children’s Fund (UNICEF). *A toolkit for monitoring and evaluating household water treatment and safe storage programmes*.

(World Health Organization, 2012).

15. Household water treatment filters - product guide. https://www.unicef.org/supply/reports/household-water-treatment-filters-product-guide.
16. Santos, J., Pagsuyoin, S. A. & Latayan, J. A multi-criteria decision analysis framework for evaluating point-of-use water treatment alternatives. *Clean Technol. Environ. Policy* **18**, 1263–1279 (2016).
17. Sobsey, M. D., Stauber, C. E., Casanova, L. M., Brown, J. M. & Elliott, M. A. Point of use household drinking water filtration: A practical, effective solution for providing sustained access to safe drinking water in the developing world. *Environ. Sci. Technol.* **42**, 4261–4267 (2008).
18. Clasen, T., Schmidt, W.-P., Rabie, T., Roberts, I. & Cairncross, S. Interventions to improve water quality for preventing diarrhoea: systematic review and meta-analysis. *BMJ* **334**, 782 (2007).
19. Wolf, J. *et al.* Effectiveness of interventions to improve drinking water, sanitation, and handwashing with soap on risk of diarrhoeal disease in children in low-income and middle-income settings: a systematic review and meta-analysis. *Lancet* **400**, 48–59 (2022).
20. Clasen, T. F. *et al.* Interventions to improve water quality for preventing diarrhoea. *Cochrane Database Syst. Rev.* CD004794 (2015).
21. Crider, Y. S., Tsuchiya, M., Mukundwa, M., Ray, I. & Pickering, A. J. Adoption of Point-of-Use Chlorination for Household Drinking Water Treatment: A Systematic Review. *Environ. Health Perspect.* **131**, 16001 (2023).
22. Chirgwin, H., Cairncross, S., Zehra, D. & Sharma Waddington, H. Interventions promoting uptake of water, sanitation and hygiene (WASH) technologies in low- and middle-income countries: An evidence and gap map of effectiveness studies. *Campbell Syst. Rev.* **17**, (2021).

23. Pearson, J. & McPhedran, K. A Literature Review of the Non-health Impacts of Sanitation. *Waterlines* **27**, 48–61 (2008).
24. Whittington, D., Briscoe, J., Mu, X. & Barron, W. Estimating the Willingness to Pay for Water Services in Developing Countries: A Case Study of the Use of Contingent Valuation Surveys in Southern Haiti. *Econ. Dev. Cult. Change* **38**, 293–311 (1990).
25. McConnell, K. E. & Rosado, M. A. Valuing discrete improvements in drinking water quality through revealed preferences. *Water Resour. Res.* **36**, 1575–1582 (2000).
26. Vásquez, W. F., Mozumder, P., Hernández-Arce, J. & Berrens, R. P. Willingness to pay for safe drinking water: Evidence from Parral, Mexico. *J. Environ. Manage.* **90**, 3391–3400 (2009).
27. Smith, D. W. *et al.* Effective Demand for In-Line Chlorination Bundled with Rental Housing in Dhaka, Bangladesh. *Environ. Sci. Technol.* **55**, 12471–12482 (2021).
28. Luoto, J. *et al.* Learning to dislike safe water products: results from a randomized controlled trial of the effects of direct and peer experience on willingness to pay. *Environ. Sci. Technol.* **46**, 6244–6251 (2012).
29. Blum, A. G., Null, C. & Hoffmann, V. Marketing Household Water Treatment: Willingness to Pay Results from an Experiment in Rural Kenya. *Water* **6**, 1873–1886 (2014).
30. Vásquez, W. F. Willingness to pay and willingness to work for improvements of municipal and community-managed water services. *Water Resour. Res.* **50**, 8002–8014 (2014).
31. Powers, J. E. *et al.* Design, performance, and demand for a novel in-line chlorine doser to increase safe water access. *npj Clean Water* **4**, 1–8 (2021).
32. Whittington, D., Lauria, D. T. & Mu, X. A study of water vending and willingness to pay for water in Onitsha, Nigeria. *World Dev.* **19**, 179–198 (1991).
33. Kayser, G. L., Moriarty, P., Fonseca, C. & Bartram, J. Domestic water service delivery indicators and frameworks for monitoring, evaluation, policy and planning: a review. *Int. J.*

Environ. Res. Public Health **10**, 4812–4835 (2013).

34. WASHCost global working papers. https://www.ircwash.org/resources/washcost-working-papers.
35. Whittington, D. Administering contingent valuation surveys in developing countries. *World Dev.* **26**, 21–30 (1998).
36. Hutton, G. *Monitoring 'Affordability' of water and sanitation services after 2015: Review of global indicator options*. https://washdata.org/sites/default/files/documents/reports/2017-07/Hutton-2012-monitoring-affordability-of-water-and-sanitation-services.pdf (2012).
37. Kessides, I., Miniaci, R., Scarpa, C. & Valbonesi, P. Toward Defining and Measuring the Affordability of Public Utility Services. (2009).
38. Goddard, J. J., Ray, I. & Balazs, C. Water affordability and human right to water implications in California. *PLoS One* **16**, e0245237 (2021).
39. Nganyanyuka, K., Martinez, J., Wesselink, A., Lungo, J. H. & Georgiadou, Y. Accessing water services in Dar es Salaam: Are we counting what counts? *Habitat Int.* **44**, 358–366 (2014).
40. Amit, R. K. & Sasidharan, S. Measuring affordability of access to clean water: A coping cost approach. *Resour. Conserv. Recycl.* **141**, 410–417 (2019).
41. García-Valiñas, M. A., Martínez-Espiñeira, R. & González-Gómez, F. Affordability of residential water tariffs: alternative measurement and explanatory factors in southern Spain. *J. Environ. Manage.* **91**, 2696–2706 (2010).
42. Martins, R., Cruz, L., Barata, E. & Quintal, C. Assessing social concerns in water tariffs. *Water Policy* **15**, 193–211 (2013).
43. Verhoeven, J., Fonseca, C., Adjei, K., Batchelor, C., Bostoen, K., Jayakumar, N., Klutse, A., Naafs, A., Meijs, B., Murthy, V. *WASHCost data organisation and coding protocol*. https://www.ircwash.org/sites/default/files/20100810_washcost_data_protocol.pdf (2010).

44. Heller, L. *The Human Rights to Water and Sanitation*. (Cambridge University Press, 2022).

45. Kutty, N. K. A new measure of housing affordability: Estimates and analytical results. *Hous. Policy Debate* **16**, 113–142 (2005).

46. Udas, P. B., Roth, D. & Zwarteveen, M. Informal privatisation of community taps: issues of access and equity. *Local Environ.* **19**, 1024–1041 (2014).

47. Nagar, R., Lawson, V., McDowell, L. & Hanson, S. Locating globalization: Feminist (re)readings of the subjects and spaces of globalization. *Econ. Geogr.* **78**, 257–284 (2009).

48. Gleick, P. H. The human right to water. *Water Policy* **1**, 487–503 (1998).

49. Wutich, A. Estimating Household Water Use: A Comparison of Diary, Prompted Recall, and Free Recall Methods. *Field methods* **21**, 49–68 (2009).

50. Kumpel, E., Woelfle-Erskine, C., Ray, I. & Nelson, K. L. Measuring household consumption and waste in unmetered, intermittent piped water systems. *Water Resour. Res.* **53**, 302–315 (2017).

51. Mark Blackden, C. & Wodon, Q. *Gender, Time Use, and Poverty in Sub-Saharan Africa*. (World Bank Publications, 2006).

52. United Nations Women (UN Women). *World Survey on the Role of Women in Development: Gender Equality and Sustainable Development*. (2014).

53. Human development report, 2006: beyond scarcity: power, poverty and the global water crisis. *Choice* **44**, 44–6944–44–6944 (2007).

54. Hawkins, R. & Seager, J. Gender and Water in Mongolia. *Prof. Geogr.* **62**, 16–31 (2010).

55. Rickert, B., Schmoll, O., Rinehold, A. & Barrenberg, E. *Water safety plan: a field guide to improving drinking-water safety in small communities*. (World Health Organization. Regional Office for Europe, 2014).

56. Ray, I. Women, Water, and Development. *Annu. Rev. Environ. Resour.* **32**, (2007).

57. Pederson, A., Greaves, L. & Poole, N. Gender-transformative health promotion for women:

a framework for action. *Health Promot. Int.* **30**, 140–150 (2015).

58. Sorenson, S. B., Morssink, C. & Campos, P. A. Safe access to safe water in low income countries: water fetching in current times. *Soc. Sci. Med.* **72**, 1522–1526 (2011).
59. Venkataramanan, Geere, Thomae & Stoler. In pursuit of ‘safe’water: the burden of personal injury from water fetching in 21 low-income and middle-income countries. *BMJ Glob. Health*.
60. Norton, D. M. *et al.* Flocculant-disinfectant point-of-use water treatment for reducing arsenic exposure in rural Bangladesh. *Int. J. Environ. Health Res.* **19**, 17–29 (2009).
61. Doocy, S. & Burnham, G. Point-of-use water treatment and diarrhoea reduction in the emergency context: an effectiveness trial in Liberia. *Trop. Med. Int. Health* **11**, 1542–1552 (2006).
62. Rangel, J. M., Lopez, B., Mejia, M. A., Mendoza, C. & Luby, S. A novel technology to improve drinking water quality: a microbiological evaluation of in-home flocculation and chlorination in rural Guatemala. *J. Water Health* **1**, 15–22 (2003).
63. Winter, J. C., Darmstadt, G. L. & Davis, J. The role of piped water supplies in advancing health, economic development, and gender equality in rural communities. *Soc. Sci. Med.* **270**, 113599 (2021).
64. Devoto, F., Duflo, E., Dupas, P., Parienté, W. & Pons, V. Happiness on Tap: Piped Water Adoption in Urban Morocco. *American Economic Journal: Economic Policy* **4**, 68–99 (2012).
65. Silva, B. B., Sales, B., Lanza, A. C., Heller, L. & Rezende, S. Water and sanitation are not gender-neutral: human rights in rural Brazilian communities. *Water Policy* **22**, 102–120 (2020).
66. Burt, Z., Ercümen, A., Billava, N. & Ray, I. From intermittent to continuous service: Costs, benefits, equity and sustainability of water system reforms in Hubli-Dharwad, India. *World*

Dev. **109**, 121–133 (2018).

67. World Health Organization. *Boil water*. https://apps.who.int/iris/handle/10665/155821 (2015).
68. CDC. Making water safe in an emergency. *Centers for Disease Control and Prevention* https://www.cdc.gov/healthywater/emergency/making-water-safe.html (2022).
69. How to make water safe using Aquatabs® 67 mg blue or black packet [Haiti]. (2013).
70. How to make water safe using WaterGuard® [Southeast Asia]. (2012).
71. Razavi, S. *The Political and Social Economy of Care in a Development Context: Conceptual Issues, Research in Questions and Policy Options*. https://play.google.com/store/books/details?id=veQESQAACAAJ (2007).
72. Kremer, M., Leino, J., Miguel, E. & Zwane, A. P. *Spring cleaning: Rural water impacts, valuation and property rights institutions*. http://www.nber.org/papers/w15280.pdf (2009) doi:10.3386/w15280.
73. Pattanayak, S. K., Yang, J.-C., Whittington, D. & Bal Kumar, K. C. Coping with unreliable public water supplies: Averting expenditures by households in Kathmandu, Nepal. *Water Resour. Res.* **41**, (2005).
74. Budlender, D. Measuring the economic and social value of domestic work : conceptual and methodological framework. *ILO Working Papers* (2011).
75. Mullainathan, S. & Shafir, E. *Scarcity: Why Having Too Little Means So Much*. (Macmillan, 2013).
76. Ray, I. & Smith, K. R. Towards safe drinking water and clean cooking for all. *Lancet Glob Health* **9**, e361–e365 (2021).
77. Pooi, C. K. & Ng, H. Y. Review of low-cost point-of-use water treatment systems for developing communities. *npj Clean Water* **1**, 1–8 (2018).
78. Bailey, E. S. *et al.* Methods, Protocols, Guidance and Standards for Performance

Evaluation for Point-of-Use Water Treatment Technologies: History, Current Status, Future Needs and Directions. *Water* **13**, 1094 (2021).

79. Schmidt, W.-P. & Cairncross, S. Household water treatment in poor populations: is there enough evidence for scaling up now? *Environ. Sci. Technol.* **43**, 986–992 (2009).
80. Shaheed, A. *et al.* Adherence to Point-of-Use Water Treatment over Short-Term Implementation: Parallel Crossover Trials of Flocculation-Disinfection Sachets in Pakistan and Zambia. *Environ. Sci. Technol.* **52**, 6601–6609 (2018).
81. Parker Fiebelkorn, A. *et al.* Systematic review of behavior change research on point-of-use water treatment interventions in countries categorized as low- to medium-development on the human development index. *Soc. Sci. Med.* **75**, 622–633 (2012).
82. Rosa, G. & Clasen, T. Consistency of Use and Effectiveness of Household Water Treatment among Indian Households Claiming to Treat Their Water. *Am. J. Trop. Med. Hyg.* **97**, 259–270 (2017).
83. Enger, K. S., Nelson, K. L., Rose, J. B. & Eisenberg, J. N. S. The joint effects of efficacy and compliance: a study of household water treatment effectiveness against childhood diarrhea. *Water Res.* **47**, 1181–1190 (2013).
84. Brown, J. & Clasen, T. High adherence is necessary to realize health gains from water quality interventions. *PLoS One* **7**, e36735 (2012).
85. Levy, K. Invited Perspective: Environmental Health Interventions Are Only as Good as Their Adoption. *Environ. Health Perspect.* **131**, 11303 (2023).
86. Reygadas, F., Gruber, J. S., Dreizler, L., Nelson, K. L. & Ray, I. Measuring User Compliance and Cost Effectiveness of Safe Drinking Water Programs: A Cluster-Randomized Study of Household Ultraviolet Disinfection in Rural Mexico. *Am. J. Trop. Med. Hyg.* **98**, 824–834 (2018).
87. Daniel, D., Marks, S. J., Pande, S. & Rietveld, L. Socio-environmental drivers of sustainable

adoption of household water treatment in developing countries. *npj Clean Water* **1**, 1–6 (2018).

88. Brown, J., Hayashi, M. A. L. & Eisenberg, J. N. S. The Critical Role of Compliance in Delivering Health Gains from Environmental Health Interventions. *Am. J. Trop. Med. Hyg.* **100**, 777–779 (2019).
89. Rainey, R. C. & Harding, A. K. Acceptability of solar disinfection of drinking water treatment in Kathmandu Valley, Nepal. *Int. J. Environ. Health Res.* **15**, 361–372 (2005).
90. Gruber, J. S. *et al.* A stepped wedge, cluster-randomized trial of a household UV-disinfection and safe storage drinking water intervention in rural Baja California Sur, Mexico. *Am. J. Trop. Med. Hyg.* **89**, 238–245 (2013).
91. Murray, A. L. *et al.* Evaluation of consistent use, barriers to use, and microbiological effectiveness of three prototype household water treatment technologies in Haiti, Kenya, and Nicaragua. *Sci. Total Environ.* **718**, 134685 (2020).
92. Pickering, A. J. *et al.* The WASH Benefits and SHINE trials: interpretation of WASH intervention effects on linear growth and diarrhoea. *Lancet Glob Health* **7**, e1139–e1146 (2019).
93. Albert, J., Luoto, J. & Levine, D. End-user preferences for and performance of competing POU water treatment technologies among the rural poor of Kenya. *Environ. Sci. Technol.* **44**, 4426–4432 (2010).
94. Burt, Z. *et al.* User preferences and willingness to pay for safe drinking water: Experimental evidence from rural Tanzania. *Soc. Sci. Med.* **173**, 63–71 (2017).
95. Ojomo, E., Elliott, M., Goodyear, L., Forson, M. & Bartram, J. Sustainability and scale-up of household water treatment and safe storage practices: Enablers and barriers to effective implementation. *Int. J. Hyg. Environ. Health* **218**, 704–713 (2015).
96. Amin, N. *et al.* Field trial of an automated batch chlorinator system at shared water points in

an urban community of Dhaka, Bangladesh. *J. Water Sanit. Hyg. Dev.* **6**, 32–41 (2016).

97. Onjala, J., Ndiritu, S. W. & Stage, J. Risk perception, choice of drinking water and water treatment: evidence from Kenyan towns. *J. Water Sanit. Hyg. Dev.* **4**, 268–280 (2014).

98. Alfredo, K. A. & O'Garra, T. Preferences for water treatment provision in rural India: comparing communal, pay-per-use, and labour-for-water schemes. *Water Int.* **45**, 91–111 (2020).

99. About us. https://www.ib-net.org/about-us/.

100. UNICEF. Tools - UNICEF Multiple Indicator Cluster Surveys. https://mics.unicef.org/tools.

Acknowledgements

We would like to thank Lia Clark for helping gather data to make Table 2. Katya Cherukumilli and Amy J. Pickering were supported by a grant from Open Philanthropy during the writing of this manuscript.