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# Adherence to solar disinfection water treatment reduces diarrheal incidence among children in Malawi: a secondary analysis of a cluster quasi-experimental study

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## ABSTRACT

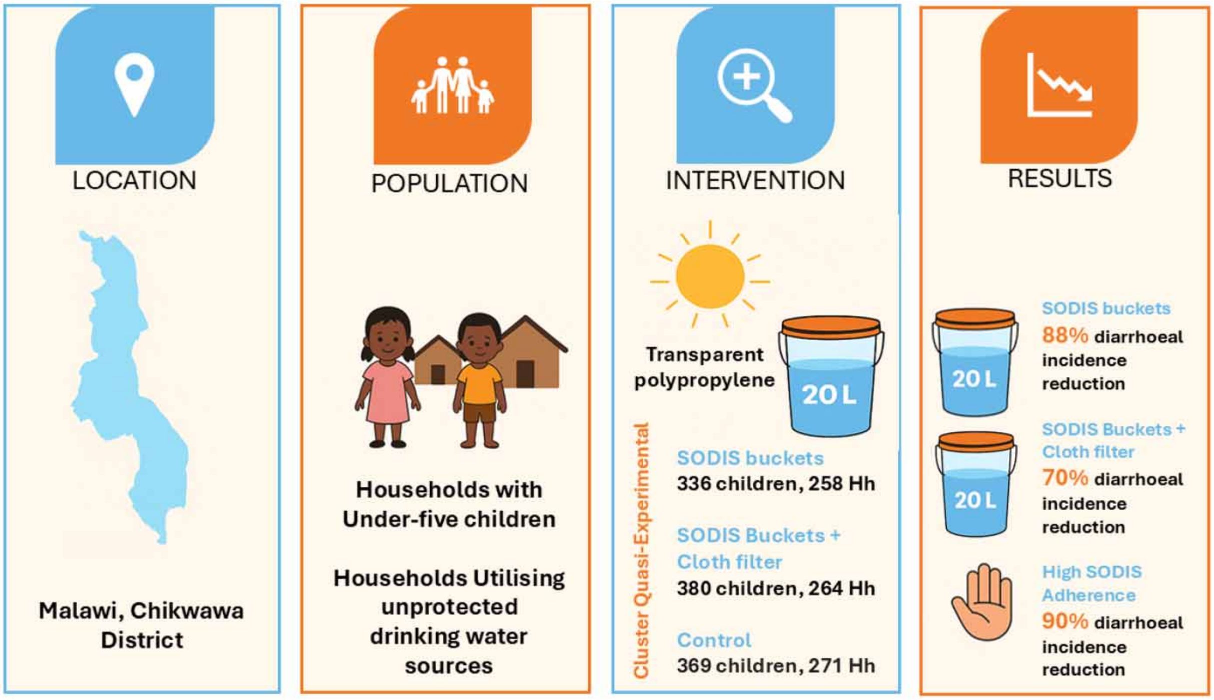
Background: Diarrhoea is a leading cause of morbidity and mortality among children under five in low-income regions. This study assessed the effectiveness of household solar disinfection (SODIS) in reducing diarrhoeal incidence among children in Chikwawa District, Malawi. Methods: We conducted a secondary analysis of a cluster quasi-experimental trial (March 2019–March 2020) involving 985 children from 793 households: control (369 children, 271 households), 20 L transparent polypropylene SODIS bucket (336 children, 258 households), and SODIS bucket with cloth filter (380 children, 264 households). Variables included water source, child age, sex, rotavirus vaccination, SODIS adherence. Analyses employed descriptive statistics, Chi-square, Kruskal–Wallis tests, and Poisson regression with robust standard errors in Stata 17. Results: Overall, diarrhoeal incidence was two cases per child-year. Households using SODIS buckets had an 88% reduction in incidence (adjusted incidence rate ratio (IRR): 0.12; 95% CI: 0.04–0.23), while those using SODIS with a cloth filter saw a 70% reduction (adjusted IRR: 0.30; 95% CI: 0.18–0.50). High SODIS adherence was linked to 90% reduction (adjusted IRR: 0.13; 95% CI: 0.02–0.81); medium adherence showed no significant effect. Conclusion: These findings support SODIS as an effective point-of-use water treatment, with adherence critical to health impact.

**Key words:** diarrhoeal incidence, quasi-experimental trial, SODIS adherence, SODIS bucket and cloth filter, solar disinfection, under-five children

## HIGHLIGHTS

- First study in Malawi to evaluate a 20-L polypropylene bucket for household solar water disinfection (SODIS).
- Demonstrates a significant reduction in under-five diarrhoeal incidence.
- Assesses the impact of SODIS adherence levels on intervention effectiveness after adjusting for water source, child age, and rotavirus vaccination.
- Contributes to evidence on scalable, low-cost water treatment in rural Africa.

## GRAPHICAL ABSTRACT




## INTRODUCTION

Diarrhoea remains a significant public health concern, particularly among children under 5 years, accounting for 9% of child mortality globally in 2019 (World Health Organization 2019). The burden is disproportionately higher in low-income countries, with under-five diarrhoeal mortality rates exceeding 100 deaths per 100,000 children, compared to just 1 death per 100,000 in high-income countries (Dattani *et al.* 2019). In sub-Saharan Africa, the prevalence of under-five diarrhoea was 15.3% between 2009 and 2018, with the region experiencing over 211 deaths per 100,000 children in 2019 (Dattani *et al.* 2019). Malawi, in particular, reported a prevalence of 22.0% during the 2015–2016 demographic health survey (DHS), contributing to 7% of under-five mortality (National Statistical Office & ICF 2017).

The consequences of diarrhoea extend beyond immediate illness, contributing to long-term issues such as malnutrition, developmental delays, and cognitive impairments in surviving children (Pinkerton *et al.* 2016; Haworth *et al.* 2017; Tickell *et al.* 2017). These problems have lasting effects on future generations and may affect the economic stature of households and nations (Ngabo *et al.* 2016; Giglio *et al.* 2017). Inadequate access to Water, Sanitation, and Hygiene (WASH) is a significant risk factor for under-five diarrhoea (World Health Organization 2014; Adedokun & Yaya 2020; Demissie *et al.* 2021). The World Health Organization reports that poor WASH access accounts for over 58% of under-five diarrhoeal deaths (World Health Organization 2014). Furthermore, the lack of access to improved water sources, sanitation facilities, and hygiene practices exacerbates the risk of diarrhoeal disease transmission (Moon *et al.* 2019; Miggo *et al.* 2023; Freeman *et al.* 2024).

In Malawi, the WASH sector faces significant challenges, including limited access to improved water sources, inadequate sanitation facilities, and poor hygiene practices (Mughogho & Kosamu 2012; Kumpel & Nelson 2013; Mpakati-gama & Mkandawire 2015; National Statistical Office 2019). Despite reports of 85.3% basic safe drinking water coverage, the reality on the ground includes high non-functionality rates of water points and inconsistent piped water supply, leading to the use of unimproved water sources (Mughogho & Kosamu 2012; Mpakati-gama & Mkandawire 2015; National Statistical Office 2019). Moreover, studies have shown that even improved water sources can yield contaminated water, highlighting the need for effective household water treatment methods (Mkandawire 2008; Nhlema *et al.* 2020).

Solar disinfection (SODIS) has emerged as a promising household water treatment method, particularly in resource-limited settings (Luzi *et al.* 2016). The typical SODIS method involves filling transparent PET bottles with contaminated water and exposing them to direct sunlight for 6 h (Luzi *et al.* 2016). SODIS is effective against most bacteria, including *Escherichia coli*, but less effective against certain viruses and protozoa (McGuigan *et al.* 1998, 2012; Luzi *et al.* 2016). The effectiveness of SODIS in reducing diarrhoeal disease is well documented, with a meta-analysis of randomised controlled trials showing an average reduction of 44% (95% CI: 48%, 65%) and 38% (95% CI: 28%, 47%) in diarrhoeal incidence (Waddington & Snilstveit 2009; Soboksa *et al.* 2020). Field studies in Kenya, Bolivia, and India have demonstrated significant reductions in diarrhoeal incidence in households using SODIS, particularly when adherence is high (Rose *et al.* 2006; Mäusezahl *et al.* 2009; Du Preez *et al.* 2011).

Several factors contribute to the variance in observed outcomes, including environmental conditions, human behavioural factors, and adherence to SODIS practices (McGuigan *et al.* 1998, 2012; Luzi *et al.* 2016). Measuring adherence is essential to understanding the impact of SODIS on health (Mcguigan *et al.* 2011; Brown & Clasen 2012). Adherence involves consistent and correct practice, which can be influenced by multiple factors such as motivation, education, and socio-economic position (Du Preez *et al.* 2010; Christen *et al.* 2011).

The adoption of SODIS remains low in rural Malawi, including Chikwawa district, despite its proven effectiveness in reducing diarrhoea (National Statistical Office & ICF 2017). Barriers include the small water volume per bottle, the need for pre-filtration in cases of high turbidity, concerns about PET bottle safety, changes in water taste, and longer treatment times compared to other methods (Mosler *et al.* 2013; Borde *et al.* 2016; Keogh *et al.* 2017; Martínez *et al.* 2020).

A SODIS project known as 'Water Sustainable Point of Use Treatment Technologies' (WaterSPOUTT), funded by the European Union Horizon 2020 (Grant I 688928), was carried out in Chikwawa District from 2017 to 2020 (WaterSPOUTT 2018). The project piloted a SODIS system using a 20-L transparent polypropylene bucket and cloth filtration to improve access to safe drinking water through solar technologies, emphasising social design and local adaptation (WaterSPOUTT 2018). The research team within the project carried out a quasi-experimental trial to assess the effectiveness of the SODIS system in reducing the incidence of diarrhoea. The results revealed lower rates of diarrhoea among the intervention groups, showing incidence rate ratios (IRRs) of 0.34 (95% confidence interval (CI): 0.25 to 0.45) for the SODIS bucket and cloth filter group, and 0.09 (95% CI: 0.06–0.12) for the SODIS bucket group (WaterSPOUTT 2018).

The analysis employed by the WaterSPOUTT project had some limitations. It focused only on diarrhoeal incidence without considering key factors like child age, vaccination status, and water source. Adherence to SODIS practice was also not accounted for, and they defined diarrhoea as the presence or absence of stools, which did not align with the recommended definition of two or more loose stools in 24 h; this potentially affected the result's accuracy.

This study aimed to address the gaps in the primary analysis. It assessed SODIS effectiveness in reducing diarrhoea while considering confounding factors, evaluated adherence to SODIS practices and their influence on diarrhoeal incidence.

## METHODS

### Study design

This study was a secondary analysis of a cluster quasi-experimental study conducted in Chikwawa District, Malawi. The primary trial aimed to evaluate the effectiveness of SODIS in reducing diarrhoeal incidence among children under 5 years old. This secondary analysis was built on the original study by introducing additional child, household, and intervention adherence factors to comprehensively understand the intervention's effectiveness.

### Intervention delivery

The primary trial consisted of one control group and two intervention groups: 20 L transparent polypropylene SODIS bucket only, and 20 L transparent polypropylene SODIS bucket with cloth filtration. The intervention delivery utilised a behaviour-centred design based on the risks, attitudes, norms, abilities, and self-regulation model (Mosler 2012; Morse *et al.* 2020). Households in the intervention groups received training, SODIS buckets, storage buckets, and leaflets, while the SODIS cloth filter group also received filters. The control group received training on health outcome recording and storage buckets to keep water from their chosen sources. Community key informants monitored health outcomes bi-weekly using monthly health diaries and assessed SODIS practice using observational checklists.

### Study location and setting

The primary trial was conducted in 17 villages from the Traditional Authorities Lundu and Ngabu of Chikwawa District. The district lies at 100–500 m above sea level and is characterised by low-lying plains (National Statistical Office 2019). It is intersected by the Shire River, creating floodplains and wetlands (National Statistical Office 2019). The district experiences a tropical climate with hot summers reaching temperatures as high as 45 °C and mild winters (Ministry of National Resources & Climate Change 2023). The study area was selected in consultation with the Chikwawa District Water Office, focusing on communities with limited access to safe drinking water due to high groundwater salinity.

## Study population

The primary trial's study population included households with children under 5 years old. Households were eligible if they had at least one child in this age group and relied on untreated surface or groundwater as their main drinking water source.

## Study period

The primary trial was conducted from March 2019 to March 2020. This secondary analysis was conducted from August 2023 to September 2024.

## Sampling and sample size

The primary trial enrolled 1,115 children from 825 households across 17 villages and divided them into three geographic clusters based on location. A manual randomisation process was conducted to assign study groups to the clusters; the SODIS bucket group had 392 children from 293 households, the SODIS bucket and cloth filter group had 392 children from 281 households, and the control group had 332 children from 261 households.

For the secondary analysis, the sample size from the primary trial was validated with the following assumptions: a diarrhoeal incidence rate of 17.2% in the control group based on a cohort study in Chikwawa (Tizifa *et al.* 2021), and an expected decrease of over 35% in intervention groups based on a systematic and meta-analysis study on SODIS effectiveness (Soboksa *et al.* 2020). The analysis had a power of 0.9, an alpha level of 0.05, and an intra-cluster correlation coefficient of 0.002. The final sample size after data cleaning was 1,085 children from 793 households, split into a control group (369 children from 271 households), SODIS buckets only group (336 children from 258 households), and SODIS buckets plus cloth filters group (380 children from 264 households). This reduction from the trial's initial enrolment of 1,115 children from 825 households accounts for participants lost to follow-up due to a variety of factors, including households that dropped out of the study and those with incomplete data. The final sample size was used for all subsequent analyses.

## Data collection

The primary trial conducted a baseline survey that captured household and child characteristics, such as vaccination status, age, and sex of children, among other variables. The survey utilised interviewer-administered digital questionnaires lasting a maximum of 40 min. During the trial, diarrhoeal outcomes were captured using health diaries. The diaries were filled out by the children's parents, recording the number of daily diarrhoea episodes experienced by each child. SODIS adherence was monitored through an observational checklist completed by Community Key Informants who visited the households bi-weekly.

## Data management and analysis

To conduct the secondary analysis, three datasets were combined: (1) diarrhoeal outcomes, (2) child and household characteristics, and (3) SODIS adherence data. The datasets were merged using a unique household identification number assigned to each household.

### Data cleaning

Data cleaning involved removing duplicate records of under-five children, correcting misallocated records, and verifying age, sex, and vaccination status against baseline survey data for consistency.

### Exposure and outcome measurement

Child characteristics (age, sex, vaccination status) and household water sources were recorded. SODIS adherence was measured using a scoring system based on data from household visits. Community Key Informants used an observational checklist for data collection. The checklist included questions with binary 'yes/no' responses, which were scored as 1 for 'yes' and 0 for 'no'. An example is whether the SODIS buckets were exposed to the sun on the day of the visit. It also included questions about the frequency of SODIS use, such as the number of days SODIS was used per week and the number of days a child consumed SODIS-treated water. The numerical answers to these questions were used as scores. The average of these scores throughout the study period determined a household's overall SODIS adherence score. These average scores were then rounded to the nearest whole number to classify adherence into three categories: low (1), medium (2), or high (3).

Diarrhoeal outcome was defined as ≥3 loose stools in 24 h, following recommendations of the WHO. Diarrhoeal incidence was calculated as the number of new cases per person-day observation time.

### Dealing with missing data

Missing values were handled using conditional mean imputation for continuous variables (age and SODIS adherence scores) and random sampling for categorical variables (vaccination status, water source, and sex). The imputation process was performed using Stata 17.

### Statistical analysis

Descriptive statistics were calculated for child characteristics and household water sources. The median was used as a measure of central tendency for age (in months) to account for outliers. Proportions were used for categorical variables such as sex, household water source, vaccination statuses, and SODIS adherence-related variables.

The relationship between the variables of interest and the diarrhoeal outcome was examined using correlated data analysis methods. Poisson regression models with robust standard errors and an allowance of clustering on households were used to calculate IRRs as the measures of effect. Another analysis was conducted to explore interaction effects. Due to limited variability in vaccination status – most children received at least one dose of the rotavirus vaccine – a binary variable was created to represent vaccination status. This variable was used to examine the interaction between SODIS adherence and vaccination status in a Poisson regression model. The models were adjusted for confounders such as child age, sex, vaccination status, and household water source.

All data manipulation and analysis were conducted using Stata 17, with a significance level of 0.05 and a 95% CI.

## RESULTS

### Child characteristics and household water sources

The majority of children were female (63.3%), with a median age of 28 months (Interquartile Range (IQR) 26.5, 32). Most children had received rotavirus vaccinations (75.6% for rotavirus 1 and 74.7% for rotavirus 2). Over 80% of households in the intervention groups used water from unprotected sources, compared to 59% in the control group (Table 1).

Statistical differences were observed in age, rotavirus vaccination status, and household water source across study groups. However, no statistical difference was found in the distribution of sex across study groups (Table 1).

### SODIS practice and adherence in intervention groups

The secondary analysis revealed that nearly 80% of households properly exposed their covered SODIS buckets to sunlight (Figure 1). Storage buckets contained water, and households practiced SODIS for an average of 6 days per week. Children also consumed SODIS water for the same number of days (Table 2).

**Table 1** | Child characteristics and household water sources for the study participants

| Characteristics | | SODIS bucket | SODIS cloth filter | Control | *P*-value |
|---|---|---|---|---|---|
| Number of households | | 258 | 264 | 271 | |
| Number of children | | 336 | 380 | 369 | |
| Children's age (Months) | Median | 28 | 29.4 | 27 | 0.001* |
| | IQR | 28, 28.4 | 26, 39 | 26, 27.8 | |
| Children's sex n (%) | Female | 218 (**64.9**) | 244 (**64.2**) | 225 (**61.0**) | 0.508 |
| | Male | 136 (**35.1**) | 136 (**35.8**) | 144 (**39.0**) | |
| Children's rotavirus 1 *n* (%) | Unvaccinated | 109 (**32.4**) | 93 (**24.5**) | 63 (**17.1**) | 0.001* |
| | Vaccinated | 227 (**67.6**) | 287 (**75.5**) | 306 (**82.9**) | |
| Children's rotavirus 2 *n* (%) | Unvaccinated | 108 (**32.2**) | 93 (**24.5**) | 74 (**20.1**) | 0.001* |
| | Vaccinated | 228 (**67.8**) | 287 (**75.5**) | 295 (**79.9**) | |
| Household water source *n* (%) | Improved | 42 (**16.3**) | 28 (**10.6**) | 111 (**41.0**) | 0.001* |
| | Unimproved | 216 (**83.7**) | 236 (**89.4**) | 160 (**59.0**) | |

*Indicates significant results, P < 0.05.

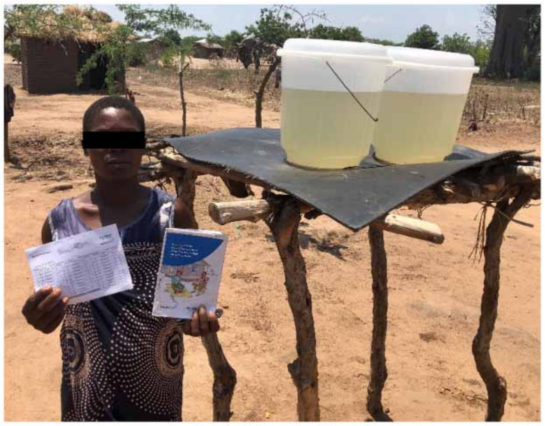


**Figure 1** | An example of SODIS buckets exposed to the sun during the trial.

**Table 2** | Observed and reported household SODIS practice

| SODIS use parameter | | SODIS bucket | SODIS cloth filter |
|---|---|---|---|
| Bucket in sun, *n* (%) | Yes | 211 (**81.8**) | 209 (**79.2**) |
| | No | 47 (**18.2**) | 55 (**20.8**) |
| Proper placement in the sun, *n* (%) | Yes | 211 (**100**) | 209 (**100**) |
| | No | 0 (**0**) | 0 (**0**) |
| Bucket covered, *n* (%) | Yes | 210 (**99.5**) | 208 (**99.5**) |
| | No | 1 (**0.5**) | 1 (**0.5**) |
| Water in the storage bucket, *n* (%) | Yes | 245 (**95.0**) | 225 (**85.2**) |
| | No | 13 (**5.0**) | 39 (**14.7**) |
| Days for SODIS practice in a week | Mean | 4.6 | 3.6 |
| | SD | 2 | 2.1 |
| Days child drank SODIS water in a week | Mean | 6.5 | 5.8 |
| | SD | 1.4 | 2.0 |

After calculating SODIS adherence scores, it was found that more than half of the households had a medium level of adherence to SODIS in both intervention groups. However, more households in the SODIS bucket group (33.7%) showed high adherence compared to those in the SODIS plus cloth filter group (14.2%) (Figure 2). The chi-square statistic revealed a *p*-value of 0.001, indicating an association between the intervention group and SODIS adherence.

## Diarrhoeal incidence during the trial

A total of 2,292 diarrhoea cases were recorded during the trial, representing an incidence of 2 cases per child-year at risk. The incidence of diarrhoea was highest in the control group (4 cases per child-year at risk) compared to the SODIS bucket plus cloth filter (1 case per child-year at risk) and SODIS bucket groups (0.5 cases per child-year at risk) (Table 3).

The trend of diarrhoea incidence across all groups decreased during the trial. However, the incidence in the control group remained higher than in the intervention groups throughout the study. Peak incidences were recorded between April and May during the trial: 3.2% for the control, 1.1% for the SODIS cloth filter, and 0.8% for the SODIS bucket group (Figure 3).

## Comparison of diarrhoeal incidence in study groups

Bivariate analysis revealed that diarrhoea incidence was associated with the type of intervention (study group) and household water source ($p$-values $<0.05$). After adjusting for other variables, the significant factors were the type of intervention and the child's vaccination status for rotavirus 1.

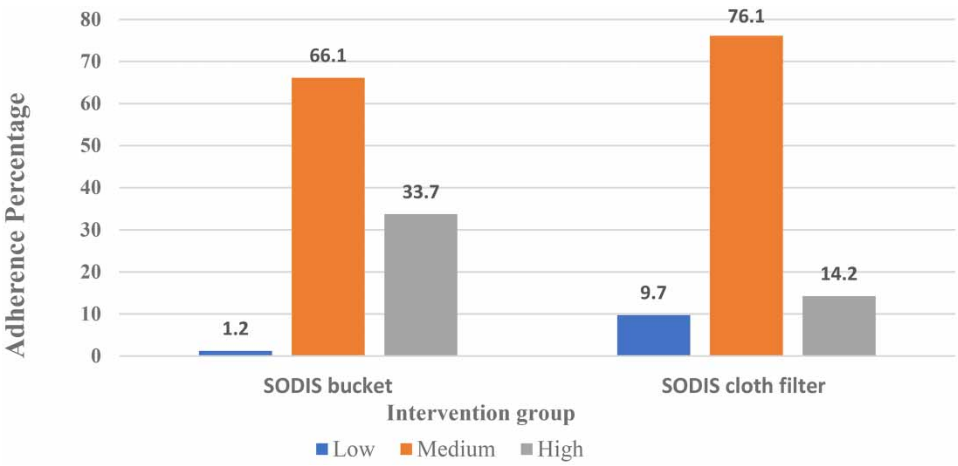



**Figure 2** | SODIS adherence in intervention groups.

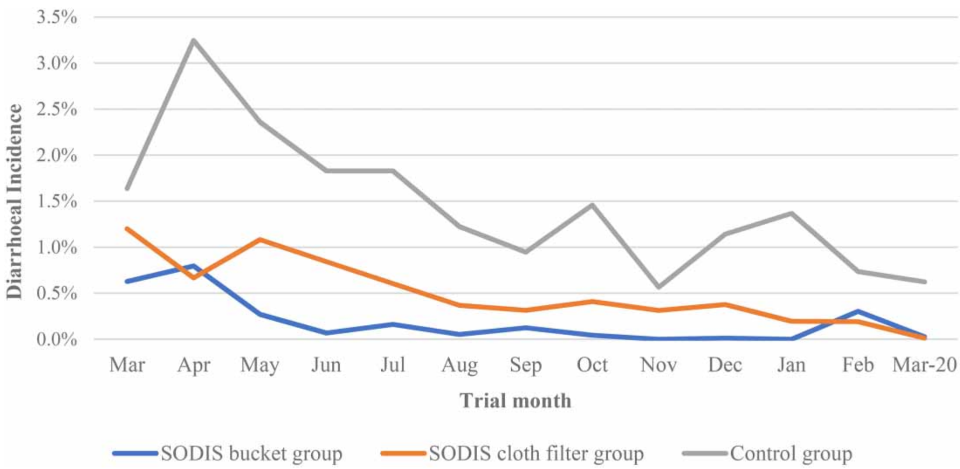



**Figure 3** | Trend of under-five diarrhoeal incidence during the trial across study groups.

**Table 3** | Overall diarrhoea incidence during the trial according to intervention

| | Study group | | |
|---|---|---|---|
| | Control | SODIS bucket | SODIS cloth filter |
| Number of children | 369 | 336 | 380 |
| Number of cases | 1,611 | 181 | 500 |
| Days on trial | 141,309 | 132,953 | 143,131 |
| Incidence during trial | 0.011 | 0.001 | 0.003 |
| Incidence per child year at risk | 4.167 | 0.498 | 2.277 |

The intervention groups showed a significant reduction in diarrhoea incidence compared to the control group. The adjusted IRR for the SODIS bucket group was 0.12 (95% CI: 0.06, 0.23), indicating an 88% (95% CI: 77, 94) reduction in diarrhoea. For the SODIS cloth filter group, the adjusted IRR was 0.30 (95% CI: 0.18, 0.50), corresponding to a 70% (95% CI: 50, 83) reduction in diarrhoea. Children who received the first dose of rotavirus vaccine also had lower chances of having diarrhoea than those who did not, adjusted IRR 0.54 (95% CI 0.31, 0.94) (Table 4).

**Table 4** | Multivariable analysis of SODIS in reducing diarrhoea incidence among under-five children

| Factors | | Unadjusted IRR (95% CI) | *P*-value | Adjusted IRR (95% CI) | *P*-value |
|---|---|---|---|---|---|
| Study group | Control | 1 | | 1 | |
| | SODIS bucket | 0.12 (0.07, 0.23) | 0.001* | 0.12 (0.06, 0.23) | 0.001* |
| | SODIS Cloth filter | 0.30 (0.18, 0.52) | 0.001* | 0.30 (0.18, 0.50) | 0.001* |
| Children's sex | Female | 1 | | 1 | |
| | Male | 1.09 (0.82, 1.44) | 0.56 | 1.10 (0.80, 1.51) | 0.563 |
| Children's rotavirus 1 | Unvaccinated | 1 | | 1 | |
| | Vaccinated | 1.04 (0.65, 1.67) | 0.86 | 0.54 (0.31, 0.94) | 0.028* |
| Children's rotavirus 2 | Unvaccinated | 1 | | 1 | |
| | Vaccinated | 1.050 (0.664, 1.661) | 0.835 | 1.476 (0.883, 2.466) | 0.137 |
| Household water source | Improved | 1 | | 1 | |
| | Unimproved | 0.623 (0.420, 0.924) | 0.019* | 1.091 (0.702, 1.696) | 0.698 |
| Children's age | Months | 0.978 (0.954, 1.00) | 0.082 | 0.989 (0.966, 1.012) | 0.338 |

*Indicates significant results, $P < 0.05$.

**Table 5** | Under-five diarrhoeal incidences in intervention groups with different SODIS adherence levels

| | SODIS bucket | | | SODIS cloth filter | | |
|---|---|---|---|---|---|---|
| SODIS adherence scores | Low | Medium | High | Low | Medium | High |
| Number of children | 4 | 222 | 110 | 37 | 289 | 54 |
| Number of cases | 2 | 165 | 14 | 41 | 458 | 1 |
| Days on trial | 1,588 | 87,777 | 43,588 | 13,209 | 109,563 | 20,359 |
| Incidence during trial | 0.001 | 0.002 | 0.000 | 0.003 | 0.004 | 0.000 |
| Incidence per child year at risk | 0.460 | 0.687 | 0.117 | 1.134 | 1.528 | 0.018 |

### Diarrhoeal incidence and SODIS adherence

In both intervention groups, diarrhoea incidence was lower among children from households with high SODIS adherence compared to those with low or medium adherence. High-adherent households experienced 0.11 cases per child-year at risk in the SODIS bucket group and 0.02 cases per child-year at risk in the SODIS cloth filter group (Table 5).

Bivariate analysis revealed that diarrhoea incidence was linked to the child's age and high scores of SODIS adherence. These findings remained significant in the multivariate analysis. The effects of the two interventions were not statistically different ($p$-value = 0.053). After accounting for other factors, households with high SODIS adherence experienced a 90% reduction in diarrhoea (95% CI: 20, 98) compared to those with low SODIS adherence, adjusted IRR 0.131 (95% CI 0.021, 0.810). Meanwhile, households with medium SODIS adherence did not show a statistically significant reduction in diarrhoea incidence compared to those with low adherence, IRR 1.256 (95% CI: 0.345, 4.575). Diarrhoeal incidence also decreased with increasing child age; adjusted IRR 0.961 (95% CI: 0.921, 1.003) (Table 6).

The secondary analysis also found a statistically significant interaction between SODIS adherence and rotavirus vaccination status ($p = 0.050$). Specifically, the protective effect of medium SODIS adherence on diarrhoeal incidence was significantly more pronounced among vaccinated children (IRR: 0.12, 95% CI: 0.01–1.00) than among unvaccinated children.

## DISCUSSION

The primary analysis of the cluster quasi-experimental trial conducted by the WaterSPOUTT project reported a 66% reduction in diarrhoeal cases for the group using the SODIS bucket with a cloth filter (95% CI: 55, 75) and a 91% reduction for the group using the SODIS bucket alone (95% CI: 88, 94) water (WaterSPOUTT 2018). However, this analysis did not account for potential confounding variables. In contrast, this secondary analysis revealed significant differences in child and household characteristics across study groups, including variations in household water source, rotavirus vaccination status, and child age. These differences validated the need to adjust for these variables to ensure the reliability of the findings.

**Table 6** | Adjusted associations between diarrhoeal incidence and SODIS adherence in intervention groups

| Factors | | Unadjusted IRR (95% CI) | *P*-value | Adjusted IRR (95% CI) | *P*-value |
|---|---|---|---|---|---|
| Intervention | SODIS bucket | 1 | | 1 | |
| | SODIS cloth filter | 2.44 (1.13, 5.30) | 0.024* | 2.17 (0.99, 4.76) | 0.053 |
| SODIS score | Low | 1 | | 1 | |
| | Medium | 1.16 (0.33, 4.07) | 0.814 | 1.26 (0.35, 4.58) | 0.729 |
| | High | 0.08 (0.32, 3.39) | 0.007* | 0.13 (0.02, 0.81) | 0.029* |
| Children's sex | Female | 1 | | 1 | |
| | Male | 1.44 (0.91, 2.29) | 0.124 | 1.41 (0.67, 2.98) | 0.364 |
| Children's rotavirus 1 | Unvaccinated | 1 | | 1 | |
| | Vaccinated | 1.06 (0.34, 3.32) | 0.918 | 1.52 (0.54, 4.22) | 0.426 |
| Children's rotavirus 2 | Unvaccinated | 1 | | | |
| | Vaccinated | 1.05 (0.34, 3.30) | 0.983 | 0.65 (0.20, 2.15) | 0.477 |
| Household water source | Improved | 1 | | 1 | |
| | Unimproved | 1.14 (0.35, 3.69) | 0.833 | 1.18 (0.39, 3.62) | 0.769 |
| Children's age | Months | 0.95 (0.92, 0.99) | 0.011* | 0.96 (0.93, 0.99) | 0.008* |

*Indicates significant results, $P < 0.05$.

The secondary analysis revealed slight variations in the effectiveness of SODIS compared to the initial findings. For the SODIS bucket group, the adjusted incidence rate ratio (IRR) was 0.12 (95% CI: 0.06, 0.23), indicating an 88% reduction in diarrhoeal incidence (95% CI: 77, 94). In the case of the SODIS cloth filter group, the adjusted IRR was 0.30 (95% CI: 0.18, 0.50), reflecting a 70% reduction in diarrhoeal incidence (95% CI: 50, 83). These results show wider confidence intervals with smaller lower boundaries, suggesting that the true effect of SODIS may have been lower than initially reported.

Compared to other studies, the observed reductions in diarrhoeal incidence are substantial. A meta-analysis conducted by Soboksa *et al.* (2020) reported a 38% (95% CI: 28, 47) reduction in diarrhoeal incidence associated with SODIS use (Soboksa *et al.* 2020). Similarly, studies conducted in Ethiopia, Kenya, and South Africa reported reductions in diarrhoeal incidence ranging from 36 to 44% (Du Preez *et al.* 2010, 2011; Bitew *et al.* 2018). The higher reductions observed in this study may be attributed to the high adherence levels reported by households in the intervention groups. Over 94% of households in the intervention groups showed a medium to high SODIS adherence level. Previous studies have indicated that the effectiveness of SODIS, like other household water treatment methods, depends on its correct and consistent use (Mcguigan *et al.* 2011; Brown & Clasen 2012).

Consistent and sustained use of household water treatment is essential to reduce diarrhoeal diseases. For instance, a cluster randomised control trial conducted in Bolivia reported an estimated compliance rate of 35%, which did not result in significant reductions in diarrhoeal incidence compared to the control group (Mäusezahl *et al.* 2009). In contrast, a study conducted in Cambodia reported a SODIS compliance rate of over 90%, resulting in a 50% reduction in diarrhoeal incidence (Mcguigan *et al.* 2011). While the high levels of adherence in this study contributed to this notable effect, it is important to acknowledge that differences in study design, context, and sample sizes across studies can influence these comparisons (Nordmann *et al.* 2012; Bulthuis *et al.* 2020). The results, however, provide a compelling example of the potential impact of interventions with high adherence.

The two SODIS interventions were not statistically different in reducing diarrhoeal incidence, with an adjusted IRR of 2.17 (95% CI 0.99–4.76). However, more households in the SODIS bucket group had high SODIS adherent scores than those in the SODIS cloth filter group. The lower adherence observed in the SODIS plus cloth filter group may be attributed to several factors. The addition of a filtering step, which increases the complexity and number of required actions, likely contributed to the reduced compliance. This finding is consistent with the literature on medication adherence, where increased regimen complexity is a known barrier to consistent practice (Pantuzza *et al.* 2017). Other studies have thus pointed out that interventions should simplify the SODIS process and address barriers to consistent use, such as labour intensity and concerns about water safety and taste (Keogh *et al.* 2017; Martínez *et al.* 2020).

A field experimental study conducted in the same area under the WaterSPOUTT project demonstrated that the 20 L SODIS buckets required optimal sunlight exposure of more than 6 h to reduce *E. coli* to acceptable levels (less than 1 Colony-Forming Unit (CFU)/100 mL) (Brockliss *et al.* 2022). This was attributed to a combination of factors, including water quality and the volume of the buckets. The buckets performed less efficiently when compared to PET bottles under similar conditions (Brockliss *et al.* 2022). The implication of the field experiment findings for the primary trial is that intense sunlight was needed to reach microbial reduction in the buckets. This is supported by the trend data showing that diarrhoeal incidence in the intervention groups was at its lowest from October to December, a period in Malawi characterised by high temperatures and abundant solar radiation (Ministry of National Resources & Climate Change 2023). This aligns with a period of the year when the SODIS method would be expected to be most effective. The data showed a peak in diarrhoeal incidences between April and May, which aligns with the latter part of the wet season and the beginning of the dry season, when sunlight is less intense and the risk of water contamination from runoff is higher (Ministry of National Resources & Climate Change 2023). These findings suggest that the effectiveness of SODIS may fluctuate seasonally in response to changes in environmental conditions and highlight the importance of adapting interventions to local climate patterns.

The observed health benefits could not be solely attributed to the SODIS intervention; other factors also play a role within a broader public health context. The multivariable analysis showed that the child's rotavirus vaccination status for the first dose and age were significant factors. Receiving the initial dose of the rotavirus vaccine lowered the risk of diarrhoeal incidence, with an adjusted IRR of 0.54 (95% CI 0.31, 0.94). The overall impact of rotavirus vaccination in decreasing diarrhoeal cases has been widely documented, with a median reduction of up to 59% (IQR, 46–74) in rotavirus-related hospitalisations (Bar-Zeev *et al.* 2015, 2018; Burnett *et al.* 2020; Mandolo *et al.* 2021). The observed interaction between adherence to SODIS and rotavirus vaccination status also indicates a potential synergistic effect between these two interventions. Although both are effective independently, these findings suggest that the protective effect of moderate SODIS adherence is notably higher among children who have received at least one dose of the rotavirus vaccine. This indicates the potential for a combined, multi-faceted strategy to reduce the burden of diarrhoeal disease. However, it should be noted that most of the study population (76%) had received at least one dose of the rotavirus vaccine, which may limit the variability of results and their applicability to populations with lower vaccination coverage.

The incidence of diarrhoea among under-five children in the study also decreased as they got older; adjusted IRR of 0.96 (95% CI: 0.93, 0.99). This finding is consistent with the global literature that shows a general decrease in risk for diarrhoeal incidence attributed to improved immunity after repeated exposure to pathogens over time (Webb & Cabada 2018; Manetu *et al.* 2021).

It is also important to note that the study was conducted in the aftermath of Cyclone Idai, which caused widespread destruction and flooding in the area (Bedi & King 2020; Nhlema *et al.* 2020; Hussein *et al.* 2023). The influx of aid from various organisations may have contributed to reducing diarrhoeal incidence through the distribution of water purification tablets and the construction of new water sources. Although data to quantify these effects were not available, a decreasing trend in diarrhoeal incidence was observed across all study arms, including the control group, throughout the study period. This parallel trend indicates that any such interventions probably affected all groups equally.

This study has some limitations that warrant acknowledgement. Firstly, relying on caregiver self-reports for diarrheal cases and SODIS adherence may introduce biases, including reporter bias, which could underestimate diarrheal incidence despite training and verification efforts. The Hawthorne effect and social desirability bias may also have influenced participant behaviour and self-reporting, potentially leading to overestimated adherence. Secondly, while statistical imputations addressed missing data, this method may not have fully captured the complexity of the missing information, affecting estimate precision. Lastly, although key confounders were accounted for, unmeasured factors like caregiver education, household income, nutritional status, and seasonal water quality variations may still impact diarrhoeal incidence and limit the generalisability of our findings. Future research should incorporate these variables to better understand intervention impact heterogeneity.

## CONCLUSIONS

This secondary analysis evaluated the effectiveness of SODIS in reducing diarrhoeal incidence among children under five in Malawi. The results showed significant reductions in diarrhoeal incidence in both SODIS intervention groups compared to the control group, with high adherence rates being crucial for effectiveness. The SODIS bucket group registered an 88% (95% CI: 77, 94) reduction in diarrhoeal incidence, while the SODIS cloth filter bucket had a 70% (95% CI: 50, 83) reduction compared to the control group. These results align with previous research on SODIS and confirm its effectiveness as a viable household water treatment method.

Based on the findings, we recommend that studies measuring SODIS effectiveness use standard definitions for diarrhoeal diseases, adjust for potential confounders, and consider the influence of SODIS adherence. Community education programmes should emphasise correct and consistent SODIS use, and future promotion efforts may simplify the SODIS process by minimising additional steps, such as pre-filtration, especially where water is of better quality.

Integrating SODIS with vaccination programmes, particularly for rotavirus, can provide a comprehensive approach to diarrhoeal disease prevention. Collaborative efforts between public health authorities and non-governmental organisations can facilitate this integration and ensure broader reach and impact. Targeted interventions for households with younger children, who are more vulnerable to diarrhoeal diseases, should also be prioritised for SODIS distribution and education efforts.

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## AUTHOR CONTRIBUTIONS

KL conceptualised the study, designed the methodology, performed the data extraction and analysis, and drafted the manuscript. EZS, KLG, TM, RMC, LB and KGM provided substantial insights and feedback throughout the research and writing process.

## ETHICS STATEMENT

Ethical approval for the primary study was obtained from the Royal College of Surgeons in Ireland and additional approvals from Maynooth University and the National Health Sciences Research Committee in Malawi. Written consent was obtained from participating households, with the possibility of using data for further studies. For the secondary analysis, permission to use the data was obtained from the Principal Investigator, and additional ethical approval was granted by the College of Medicine Research and Ethics Committee, protocol number P08/23-022.

## DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

## CONFLICT OF INTEREST

The authors declare there is no conflict.

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