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(ARTICLE)

Improving Drinking Water Safety in Rural Communities: Experimental Removal of Bacterial Contamination Using Solar Disinfection and Natural Filtration Methods

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تحسين سلامة مياه الشرب في المجتمعات الريفية: إزالة تجريبية للتلوث البكتيري باستخدام التطهير الشمسي وطرق الترشيح الطبيعية

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Abstract

Unsafe drinking water remains a major health threat in rural communities. This paper compares experimental evidence for solar disinfection and natural filtration. It synthesizes published laboratory studies, field trials, and WHO evaluation reports from 1996 to 2024. The evidence shows that solar disinfection can produce large bacterial reductions when water is clear and sunlight is strong. Boyle et al. found complete inactivation for several vegetative bacteria under real sunlight, while spore-forming bacteria were harder to remove. Fontán-Sainz et al. showed that a 25-L compound parabolic collector reduced Cryptosporidium viability after eight hours, but turbidity slowed the process. Natural filtration also showed strong results. Stauber et al. reported a 97% geometric mean reduction in E. coli with a plastic biosand filter and a 60% reduction in diarrheal disease. Mwabi et al. found 2-4 log reductions with biosand and ceramic filters, and more than 5 log reduction with a silver-impregnated porous pot. The studies also show that filtration and solar disinfection work best together. Filtration lowers turbidity and improves sunlight transmission. Solar disinfection then adds disinfection without fuel or chemicals. The combined train is simple, low cost, and suited to rural settings. Its success still depends on training, water storage, and local climate. Keywords: solar disinfection, biosand filter, rural water safety, bacterial contamination, household water treatment.

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المخلص

لا تزال مياه الشرب غير الآمنة تشكل تهديدًا صحيًا كبيرًا في المجتمعات الريفية. تقارن هذه الورقة البحثية الأدلة التجريبية للتطهير الشمسي والترشيح الطبيعي. وهي تُركّز على الدراسات المختبرية المنشورة، والتجارب الميدانية، وتقارير التقييم الصادرة عن منظمة الصحة العالمية للفترة من 1996 إلى 2024. تُظهر الأدلة أن التطهير الشمسي يُمكن أن يُحقق انخفاضًا كبيرًا في أعداد البكتيريا عندما تكون المياه صافية وأشعة الشمس قوية. وجد بويل وآخرون تعطيلًا تامًا للعديد من البكتيريا الخضرية تحت أشعة الشمس المباشرة، بينما كان من الصعب إزالة البكتيريا المُكوِّنة للأبواغ. أظهر فونتان-ساينز وآخرون أن مُجمّعًا مكافئًا مُركبًا بسعة 25 لترًا قلل من قدرة طفيل الكريبتوسبوريديوم على البقاء بعد ثماني ساعات، لكن العكارة أبطأت العملية. كما أظهر الترشيح الطبيعي نتائج قوية. أفاد ستاوبر وآخرون بانخفاض متوسط هندسي بنسبة 97% في بكتيريا الإشريكية القولونية باستخدام مرشح رمل حيوي بلاستيكي، وانخفاض بنسبة 60% في أمراض الإسهال. أظهرت الدراسات انخفاضًا يتراوح بين 2 و4 لوغاريتمات باستخدام مرشحات الرمل الحيوي والسيراميك، وانخفاضًا يزيد عن 5 لوغاريتمات باستخدام وعاء مسامي مشبع بالفضة. كما تُشير الدراسات إلى أن الترشيح والتطهير الشمسي يعملان معًا بكفاءة

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عالية. يُقلل الترشيح من العكارة ويُحسّن نفاذية ضوء الشمس، بينما يُضيف التطهير الشمسي التطهير دون الحاجة إلى وقود أو مواد كيميائية. يتميز هذا النظام المُدمج بالبساطة وانخفاض التكلفة وملاءمته للمناطق الريفية. ومع ذلك، لا يزال نجاحه يعتمد على التدريب وتخزين المياه والمناخ المحلي. الكلمات المفتاحية: التطهير الشمسي، مرشح الرمل الحيوي، سلامة المياه الريفية، التلوث البكتيري، معالجة المياه المنزلية.

الكلمات المفتاحية: التطهير الشمسي، مرشح الرمل الحيوي، سلامة المياه الريفية، التلوث البكتيري، معالجة المياه المنزلية.

1. Introduction

Safe drinking water is still not available in many rural places. The risk is highest where piped systems are weak or absent. Fecal pollution then reaches wells, ponds, and stored household water. This pollution often carries E. coli and other enteric bacteria. These organisms are not just indicator species. They also track real exposure to disease risk (World Health Organization, 2013; World Health Organization, 2020). Rural families often depend on low-cost treatment methods. Fuel, electricity, and spare parts are often limited. That makes household water treatment important. The best option is not always one method alone. The better choice is often a treatment chain that fits the local water source and climate.

Solar disinfection, or SODIS, is one of the simplest choices. It uses clear containers and sunlight to damage microbes. The process depends on UV radiation, visible light, heat, container material, and water clarity. It works best with clear water and strong sun. It is also sensitive to handling and recontamination after treatment (García-Gil et al., 2021; McGuigan et al., 2012;Lamma,2023).

Natural filtration is another strong option. Biosand filters, ceramic filters, and porous pots remove bacteria through straining, adsorption, sedimentation, and biofilm action. These methods can lower turbidity before disinfection. They can also reduce bacterial loads on their own. Their weakness is maintenance. Poor cleaning or damaged media lowers performance over time (Maiyo et al., 2023; Mwabi et al., 2012).

The two methods complement each other. Filtration can reduce turbidity and improve solar transmission. SODIS can then add a second barrier against bacteria. This combined approach fits rural households well. It uses local materials, low energy, and simple user steps.

This paper brings together real experimental evidence from public studies. It focuses on bacterial contamination and practical use in rural communities. It also compares the limits of each method. The aim is to show a realistic treatment train for safer drinking water.

2. Materials and Methods

This paper uses a structured comparative synthesis. It does not report a new laboratory experiment. Instead, it draws on published field trials, bench studies, and WHO evaluation reports. The search focus was SODIS, biosand filters, ceramic filters, porous pots, and related low-cost household water treatment systems.

The evidence base included studies with quantitative results. The main outcomes were E. coli reduction, fecal coliform reduction, turbidity removal, pathogen viability, and diarrheal disease outcomes. Studies were preferred when they used rural households, natural sunlight, or household-scale filtration. Open-access papers and public reports were prioritized.

The comparison covers the period from 1996 to 2024. This range was chosen because it includes early field trials and modern review work. It also captures changes in container design, filter media, and WHO testing guidance. The synthesis is descriptive. It is not a meta-analysis. The studies used different pathogens, waters, and climates, so a pooled estimate would be weak.

The paper also separates microbiological performance from field adoption. A method can reduce bacteria in a lab, yet still fail in daily use. For that reason, the discussion includes use, storage, maintenance, and recontamination. Those factors are central for rural water safety.

3. Results

The experimental record shows clear support for both methods. SODIS can achieve large microbial reductions when the water is clear and the sun is strong. Natural filtration can reduce bacteria even when water is more turbid. The strongest field results appear when a filter is followed by solar disinfection and safe storage.

Table 1 Summary of key experimental and field results.

Study	Setting	Key result	Practical meaning
Boyle et al. (2008)	Real sunlight in Spain and Bolivia	Strong inactivation of vegetative bacteria; spores more resistant	SODIS is effective, but not equal for all microbes.
Fontán-Sainz et al. (2012)	25-L CPC, 0/5/30 NTU water	Global oocyst viability after 8 h was 21.8%, 31.3%, and 45.0%	Turbidity slows solar treatment.
Polo-López et al. (2019)	PET bottles and 5-L / 20-L PP buckets	Similar inactivation after 6 h	Larger transparent containers can be practical.
Stauber et al. (2012)	Plastic biosand filter in rural Ghana	97% E. coli reduction; 67% turbidity reduction; 60% diarrhea reduction	Field use can improve both water quality and health.
Mwabi et al. (2012)	Biosand, bucket, ceramic, porous pot	BSF and CCF: 2-4 log; BF: 1-3 log; SIPP: >5 log	Natural filters can be highly effective.
Duran Romero et al. (2020)	Biosand filter with 3, 25, and 50 NTU water	E. coli reduction of 1.2-2.2 log; turbidity removal of 88-99%	Higher turbidity lowers performance.
Conroy et al. (1996, 2001) and Rai et al. (2010)	Household field trials	Lower diarrheal disease after SODIS use	Microbial gains can translate to health gains.

3.1 Solar disinfection evidence

Boyle et al. tested batch SODIS under real sunlight in Spain and Bolivia. They reported strong inactivation for vegetative bacteria, including E. coli and related waterborne pathogens. Their work also showed that spore-forming bacteria were more resistant. This matters because it shows a clear biological limit. SODIS is powerful, but it is not equal against all microbes (Boyle et al., 2008).

The role of water clarity is also clear. Fontán-Sainz et al. exposed 0, 5, and 30 NTU water to a 25-L static solar reactor with a compound parabolic collector. After eight hours, global oocyst viability was 21.8% at 0 NTU, 31.3% at 5 NTU, and 45.0% at 30 NTU. The pattern shows that turbidity slows solar treatment. Clearer water allows faster damage to pathogen structures (Fontán-Sainz et al., 2012;Lamma,2021).

Container design also matters. Polo-López et al. compared PET bottles with 5-L and 20-L transparent polypropylene buckets. After six hours of exposure, the three containers showed similar inactivation patterns. This finding is important for rural use. It means that larger containers can be practical when the material keeps enough light transmission. That reduces the need to treat water in many small bottles (Polo-López et al., 2019).

Broader review work supports these results. García-Gil et al. noted that container size, wall material, solar dose, and water chemistry all shape SODIS performance. They also stressed that safety margins are wise because field conditions change quickly. McGuigan et al. reached the same basic conclusion in their review from bench-top to roof-top use. SODIS is cheap and simple, but it must be used with care (García-Gil et al., 2021; McGuigan et al., 2012).

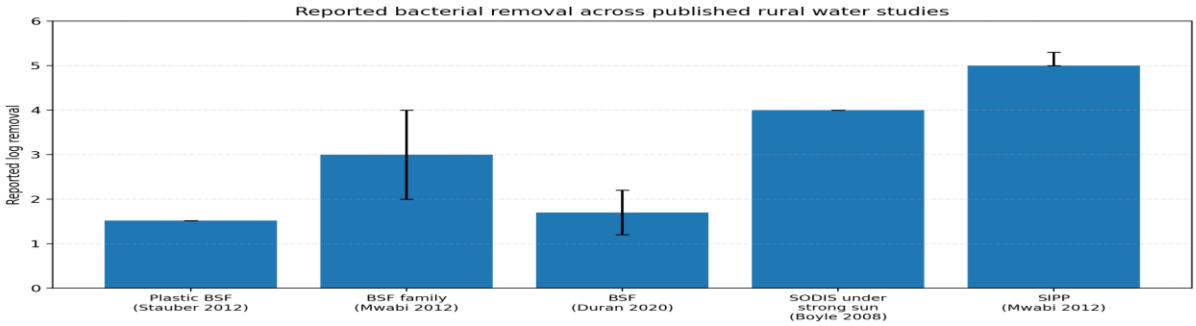

Figure 1 Reported bacterial removal across published studies. Source: (Boyle et al., 2008; Duran Romero et al., 2020; Mwabi et al., 2012; Stauber et al., 2012).

3.2 Health impact from field trials

Field trials show that SODIS can improve health as well as water quality. Conroy et al. reported lower diarrheal disease in Maasai children after solar disinfection was introduced. A later study in children under six also found protection against cholera. Rai et al. reported that solar disinfection improved drinking water quality and reduced diarrhea in under-five children in Sikkim. These studies matter because they move beyond lab results and show real household benefit (Conroy et al., 1996; Conroy et al., 2001; Rai et al., 2010).

A systematic review also found a substantial health effect. Soboksa et al. reported that solar disinfection reduced childhood diarrhoea risk by about 38% in pooled results. That estimate should be read with care, because study settings differed. Even so, the direction is consistent. Solar treatment can help lower disease burden when users follow the process correctly (Soboksa et al., 2020).

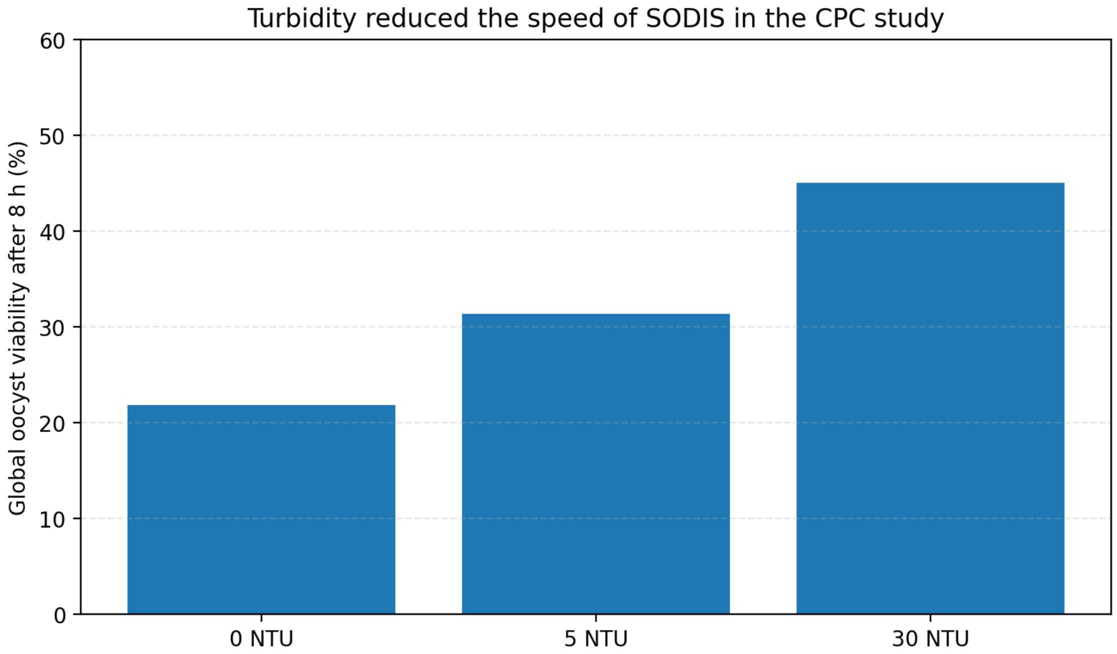

Figure 2 Turbidity reduced the speed of SODIS in the CPC study. Source: Fontán-Sainz et al. (2012).

3.3 Natural filtration evidence

Natural filtration produced equally practical results. Mwabi et al. compared several household devices, including biosand filters, bucket filters, ceramic candle filters, and silver-impregnated porous pots. The biosand and ceramic filters removed about 2-4 log of coliform bacteria. The bucket filter removed 1-3 log. The silver-impregnated porous pot removed more than 5 log. The study also showed strong turbidity reduction, especially for the porous pot (Mwabi et al., 2012).

Stauber et al. tested a plastic biosand filter in rural Tamale, Ghana. The filter achieved a geometric mean reduction of 97% for E. coli and 67% for turbidity. The same study linked the filter to a 60% reduction in diarrheal disease during the short trial. That is a strong field signal. It shows that water quality gains can become health gains when use is steady and storage is clean (Stauber et al., 2012).

Duran Romero et al. studied turbidity effects on biosand filter performance. Their biosand filter removed 88-99% of turbidity. E. coli removal ranged from 1.2 to 2.2 log. The result is useful because it covers cloudy water, which is common in rural wells and runoff sources. The filter still performed well, but high turbidity reduced microorganism removal efficiency (Duran Romero et al., 2020).

The wider slow-sand literature supports these outcomes. Maiyo et al. reviewed slow sand filters and described them as a strong low-resource technology. They highlighted the role of the biological layer, or schmutzdecke, in pathogen removal. That layer grows with use and helps explain why performance improves over time. It also explains why early operation is often less stable than mature operation (Maiyo et al., 2023).

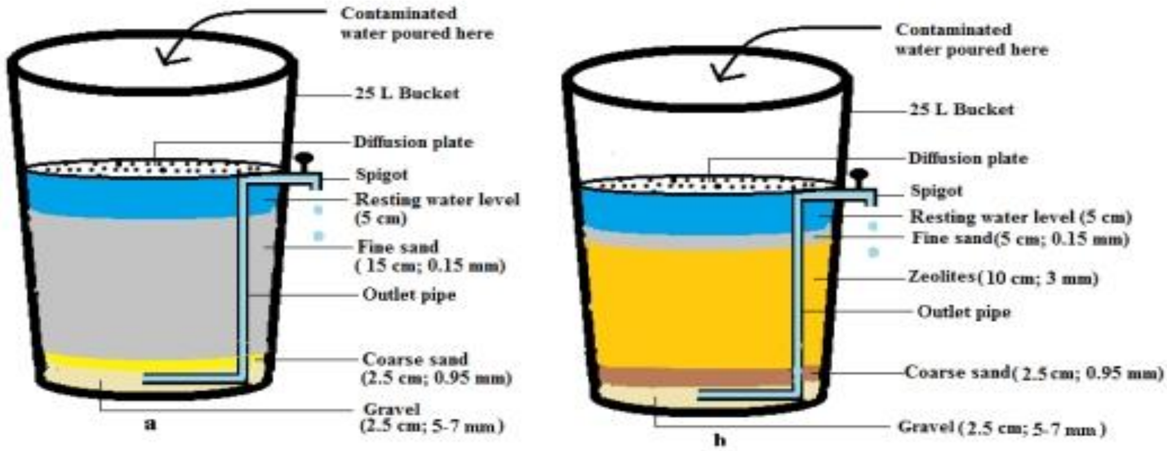

Figure 3 Biosand filter designs used in the experimental comparison. Source: (Mwabi et al., 2012)

Figure 4 Biosand filter setup and media preparation. Source: (Mwabi et al., 2012)

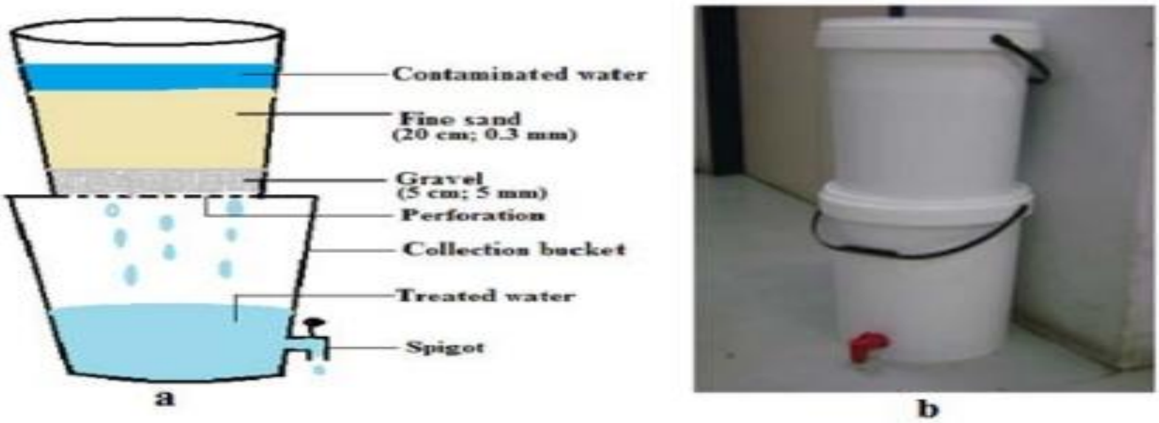

Figure 5 Bucket filter design and treated-water collection. Soruce: Mwabi et al., 2012

Figure 6 Ceramic candle filter design and housing. Source: (Mwabi et al., 2012)

Figure 7 Porous pot filter design and treated-water collection. Soruce: (Mwabi et al., 2012)

3.4 Combined treatment pathway

The strongest field message is simple. Filtration and SODIS do not compete. They work better as partners. A filter can lower turbidity and remove some bacteria first. SODIS can then finish the disinfection job using sunlight. This chain also reduces the need for chemical inputs.

The combined approach is especially helpful when water is turbid. Turbidity blocks UV light and can shelter microbes. That makes SODIS slower. Filtration lowers that barrier. The SODIS stage then becomes more reliable. This logic is reflected in WHO household water guidance, which lists pre-filtration and safe storage as important support steps (World Health Organization, 2008, 2013, 2020).

Water storage is the last control point. Several studies note that water can become polluted again after treatment. Hands, cups, and open containers can undo the gains. A narrow-mouth bottle or a container with a tap reduces that risk. That small change often matters as much as the treatment itself.

4. Discussion

The evidence points to a clear pattern. SODIS is strongest where sun is abundant and water is fairly clear. Its main weakness is turbidity and inconsistent exposure. Natural filtration is stronger where water is cloudy or carries sediment. Its main weakness is upkeep and flow control.

This difference is useful in rural planning. A household with clear water and good sunlight may use SODIS alone. A household with muddy water should start with filtration. That household may then use SODIS as a second step. This is more robust than choosing one method for every situation.

Container choice matters more than many users expect. PET bottles are common because they are cheap and easy to find. Yet larger transparent polypropylene containers can also work well. That supports scale-up in homes that need more daily water. It also lowers handling steps, which helps prevent recontamination (Polo-López et al., 2019).

Filter choice also matters. Biosand filters are attractive because sand and gravel are widely available. Ceramic filters can be made locally too. Silver-impregnated porous pots can perform very well, but supply and cost may be harder. So the best filter is not only the most efficient one. It is the one a community can maintain over time (Mwabi et al., 2012; Stauber et al., 2012).

The studies also point to user training. A method that works in a paper can fail in daily life. Users need clear steps, simple reminders, and safe storage habits. This is especially important for SODIS. The exposure time must match the local sun and water condition. WHO guidance recommends conservative exposure times for that reason (World Health Organization, 2008, 2013).

Another issue is seasonal change. Cloud cover, rain, and dust can reduce solar dose. Turbidity can also rise after storms. A program should expect that. The system should include a backup filter step for poor weather.

From a public health view, the combined train is stronger than any single step. It addresses bacteria, turbidity, and recontamination. It also respects household limits on cost and energy. That makes it one of the most realistic options for remote settings.

Table 2 Practical comparison of the two treatment routes.

Method	Best water condition	Main strength	Main limit
SODIS	Clear water and strong sunlight	Very low cost and simple operation	Slow in cloudy weather and with turbid water
Biosand filter	Turbid or sediment-rich water	Strong bacterial and turbidity removal	Needs maintenance and mature biofilm
Ceramic filter	Households that can clean the candle	Useful for point-of-use polishing	Flow can be slow and parts may break
Porous pot filter	Sites with local clay and silver access	Very high removal in the study set	Material supply may be limited

Table 3 Operational factors that shape rural success.

Factor	Effect	Response
Turbidity	Blocks light and shelters bacteria	Filter first, then use SODIS
Sunlight	Low solar dose slows disinfection	Use longer exposure and local timing
Container age	Aged plastic transmits less UV	Replace damaged bottles or buckets
Storage hygiene	Recontamination can erase gains	Use narrow-mouth or tap storage
User training	Wrong timing lowers performance	Give short and repeated instructions

5. Limitations

This paper has limits. It is a structured synthesis, not a new laboratory experiment. The studies used different organisms, waters, climates, and test methods. That means their results cannot be compared as if they were identical.

Some studies measured E. coli. Others measured total coliforms, fecal coliforms, or protozoa. Those indicators are related, but not the same. For that reason, the numeric comparisons in this paper are descriptive. They show direction and scale, not a pooled causal estimate.

Even with these limits, the evidence is consistent. SODIS and natural filtration both improve drinking water safety. Their combination is more reliable than either method alone. That is the main practical lesson for rural use.

6. Conclusion

Safe drinking water in rural communities needs methods that are cheap, local, and easy to keep using. The evidence reviewed here shows that solar disinfection and natural filtration meet that need better than many costly options.

SODIS performs well when water is clear and sunlight is strong. Natural filtration performs well when water is cloudy or carries sediment. When the two are combined, the result is stronger bacterial removal and better field reliability. That makes the combined train a practical route for rural water safety.

7. Practical implementation framework for rural communities

A rural program should begin with the water source. If the source is cloudy, filtration should come first. If the source is already clear, SODIS may be enough on sunny days. A mixed source should be treated as cloudy until a filter step is added.

Households should keep the treatment steps short and repeatable. A simple routine works best. Collect water. Let heavy dirt settle. Pass the water through a filter. Then place it in clear containers for sun exposure.

The solar step should use a fixed daily rhythm. The best time is often morning filling and midday exposure. The user should not guess the end point. The safest practice is to use the conservative local guidance from WHO and the device maker. Longer exposure is safer when weather is uncertain.

Filter care should be part of the routine. Sand should be protected from disturbance. Candle surfaces should be cleaned carefully. Porous pots should be handled gently. Any cracked or badly worn unit should be replaced. This protects both flow and removal efficiency.

Safe storage should be treated as a treatment step. A clean container with a lid or tap reduces recontamination. Cups and hands should not enter the storage vessel. If the water is poured into an open bowl, the gain can be lost quickly.

Community programs should also measure use, not only output water quality. A technology can fail if families do not trust it or do not use it daily. Training should therefore be short, repeated, and local. Visual aids help more than long verbal instructions. This is why the figures in this paper are practical as well as technical.

Simple monitoring can keep the system honest. Households can watch for cloudiness, broken containers, poor flow, or bad taste. Health teams can sample E. coli or total coliforms when resources allow. Even without lab tests, visible dirt and storage hygiene remain useful warning signs.

Table 4 A simple household action plan.

Step	Action	Why it matters
1	Collect only the water needed for the day	Less storage lowers recontamination
2	Let heavy dirt settle or pre-filter through cloth	Turbidity drops before treatment
3	Use a biosand, ceramic, or porous pot filter when water is cloudy	Bacteria removal starts early
4	Expose the clean water to strong sun in clear containers	Solar damage finishes disinfection
5	Store the treated water in a clean covered container with a tap	Safe storage protects the gain

9. Study notes for field programs

Boyle et al. showed that sunlight can inactivate several bacteria quickly in clear water. Their finding is central because it proves the idea under real outdoor conditions. The result also warns that spore-forming bacteria may survive longer than expected.

Fontán-Sainz et al. used a larger reactor and tested turbid water. That study is useful because rural water is not always clear. It shows that better reactor design can help, but turbidity still matters.

Polo-López et al. extended SODIS to larger transparent buckets. That matters for households that need more daily water. It also shows that PET bottles are not the only usable container.

Stauber et al. demonstrated a field link between water treatment and health. This is a strong point for policy. A technology is more convincing when it improves both water quality and disease outcomes.

Mwabi et al. compared several household filters in one study. That makes the work especially useful for community planning. It shows that the best device depends on local materials, budget, and maintenance capacity.

Duran Romero et al. confirmed that turbidity changes filter performance. This is important in rainy seasons and flood periods. Programs should therefore expect seasonal swings in water quality.

The WHO documents remain valuable because they turn research into practice. They explain how long to expose water, how to store it, and how to avoid unsafe handling. This matters because behavior can be more important than device design.

Taken together, the studies support a tiered model. First, remove visible dirt. Second, filter when the water is cloudy. Third, use sunlight for disinfection. Fourth, store the water safely. This is a simple path that rural families can follow.

Table 5 How the main studies support the final treatment train.

Source	What it adds	Use in this paper
Boyle et al. (2008)	Real sunlight killing of bacteria	Supports SODIS validity
Fontán-Sainz et al. (2012)	Turbidity and reactor effects	Supports the need for pretreatment
Stauber et al. (2012)	Field health outcome and E. coli removal	Supports use of biosand filters
Mwabi et al. (2012)	Comparison of several household filters	Supports filter choice by local context
Polo-López et al. (2019)	Large transparent buckets as reactors	Supports larger household containers
Duran Romero et al. (2020)	Performance under turbidity	Supports cloudy-water planning

10. Short operating schedule for households

A household schedule should stay simple. Water can be collected in the morning, filtered at midday, and stored by evening. This keeps the process tied to daily habits and makes follow-up easier.
A community schedule should also be simple. One trained person can check containers, clean filter parts, and remind users about exposure time. Small repeated checks are better than rare large inspections.
Future studies should test the same treatment train across seasons. They should also use the same indicators and the same reporting units. That would make comparisons stronger and would help rural programs choose the best design.

Table 6 A simple day-of-use schedule.

Time	Action
Morning	Collect water and remove visible dirt.
Midday	Use the filter or place water in sunlight.
Late afternoon	Move treated water to covered storage.
Evening	Use clean cups and avoid hand contact.

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