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# Efficiency Evaluation of Low-Cost Filtration Media for Rainwater Harvesting in Rural Households

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## Abstract
Access to safe drinking water remains challenging for rural communities in northern Thailand where groundwater quality issues and infrastructure limitations restrict reliable supply options. This research evaluates the performance and economic viability of low-cost filtration systems using locally available materials for household-scale rainwater treatment, addressing the need for affordable point-of-use water treatment technologies suitable for resource-limited settings.

Four filter configurations were systematically compared: sand-only, sand with gravel support, sand with activated charcoal, and a complete multi-layer system incorporating mesh screening, graded gravel, river sand, coconut shell activated charcoal, and support media. The experimental program was conducted at Chiang Mai Institute of Technology between May 2022 and April 2023, with field validation in three rural villages of Chiang Rai Province during the 2023 monsoon season. Water quality parameters including turbidity, total coliform, Escherichia coli, iron, and organic matter were monitored through 12 sampling events spanning wet and dry seasons.

The complete multi-layer system achieved optimal performance with turbidity removal of 94.2%, total coliform reduction of 89.4%, and E. coli removal of 91.2%, meeting World Health Organization guidelines for drinking water quality. Construction costs totaled 850 Thai baht using materials sourced within 20 kilometers of installation sites, with operational costs averaging 31 baht monthly for media replacement and maintenance. Economic analysis demonstrated payback periods of 3.8 months compared to vendor-supplied water and 1.9 months compared to bottled water purchases typical in the study area.

The findings establish that appropriately designed low-cost filtration systems can provide microbiologically safe drinking water from harvested rainwater at costs accessible to rural households earning minimum wage incomes, offering a sustainable complement to centralized water supply infrastructure development.

**Keywords:** Rainwater harvesting, point-of-use treatment, low-cost filtration, activated charcoal, rural water supply, Thailand, drinking water quality, household water treatment

## Introduction
How can rural communities in developing regions achieve reliable access to safe drinking water when centralized infrastructure remains economically or technically infeasible? This challenge affects approximately 780 million people worldwide, with disproportionate impacts on communities in Southeast Asia where seasonal rainfall patterns complicate both surface water availability and groundwater quality [1]. Point-of-use water treatment technologies offer promising solutions by enabling household-level purification of locally available water sources without requiring extensive distribution networks [2].

Rainwater harvesting represents an underutilized water source in tropical regions receiving adequate annual precipitation [3]. Northern Thailand receives 1,200 to 1,600 millimeters of rainfall annually, concentrated during the May to October monsoon season, providing abundant raw water that currently flows largely uncaptured to drainage systems. While collected rainwater generally exhibits superior quality compared to surface or groundwater sources, contamination during collection and storage can introduce microbiological and chemical constituents requiring treatment before consumption [4].

Conventional water treatment technologies including membrane filtration, ultraviolet disinfection, and chemical treatment achieve excellent purification performance but involve capital and operational costs that exceed affordability thresholds for many rural households [5]. Alternative approaches using locally available materials have demonstrated technical feasibility in research settings, though translation to sustained field implementation requires attention to practical considerations including material availability, construction simplicity, and maintenance requirements compatible with household capabilities [6].

Slow sand filtration has provided safe drinking water for over two centuries, with the biological layer that develops on filter surfaces contributing significantly to pathogen removal through predation, competition, and attachment mechanisms [7]. However, traditional slow sand filters require substantial land area and regular maintenance that limits applicability for individual household installations. Modifications incorporating activated charcoal and graded media layers can enhance performance while reducing footprint requirements, enabling adaptation to household-scale applications [8].

Activated charcoal produced from agricultural residues including coconut shells, rice husks, and bamboo provides effective adsorption capacity for organic contaminants and contributes to microbial removal through surface attachment [9]. The widespread availability of coconut processing in Thailand ensures reliable charcoal supply at costs substantially below imported commercial alternatives. Integration of locally produced charcoal with sand and gravel media creates multi-barrier treatment systems addressing multiple contamination pathways through complementary mechanisms.

This research systematically evaluates filtration system configurations for household rainwater treatment, comparing removal efficiencies across water quality parameters while documenting construction costs, operational requirements, and economic benefits relative to alternative water sources available in rural northern Thailand. The findings are intended to provide practical design guidance for community-based water programs and non-governmental organizations supporting rural water access improvements.

## Study Area Description

The research was conducted in Chiang Rai Province, northern Thailand, located approximately 800 kilometers north of Bangkok at elevations ranging from 400 to 600 meters above sea level. The region experiences tropical savanna climate with distinct wet and dry seasons. Average annual precipitation of 1,450 millimeters falls predominantly between May and October, with January through March receiving less than 20 millimeters monthly. Mean annual temperature is 24.8 degrees Celsius with minimal seasonal variation typical of tropical latitudes.

Three villages were selected for field validation based on criteria including: absence of piped water supply, existing rainwater collection practices, willingness to participate in monitoring activities, and accessibility for research team visits. Ban Mae Suai village (population 342) relies primarily on shallow wells with elevated iron content causing aesthetic concerns. Ban Huay Khrai village (population 218) purchases vendor-delivered water at 150 baht per cubic meter due to groundwater salinity. Ban Pha Tang village (population 185) collects rainwater in traditional ceramic jars without treatment, reporting frequent gastrointestinal illness during wet season months.

Household income in the study villages averages 8,500 baht monthly, below the provincial median of 12,400 baht, with primary livelihoods including rice cultivation, fruit orchards, and day labor in construction and tourism sectors. Water expenditure surveys indicated households spending 280 to 650 baht monthly on drinking water from various sources including bottled water, vendor delivery, and fuel for boiling collected rainwater. These expenditure levels represent 3 to 8 percent of household income, substantially exceeding the 2 percent threshold commonly cited as affordable for essential water services.

Existing rainwater collection infrastructure in the study villages consists of corrugated metal or tile roofing with galvanized steel or PVC gutters directing flow to polyethylene storage tanks ranging from 200 to 2000 liters capacity. Preliminary water quality sampling from 15 representative storage tanks identified turbidity ranging from 2 to 18 NTU, total coliform counts of 24 to 860 CFU per 100 milliliters, and E. coli presence in 73% of samples, confirming the need for point-of-use treatment before consumption.

## Materials and Methods

### Materials

Filter media materials were sourced from suppliers within Chiang Rai Province to ensure replicability for future implementations. River sand was obtained from licensed extraction operations on the Kok River, washed to remove fine particles, and graded to 0.5-1.0 millimeter effective size. Gravel was sourced from a local quarry in two size fractions: 5-10 millimeters for fine gravel layers and 20-30 millimeters for support media. Activated charcoal was produced from coconut shells at a community enterprise in Phrao District using traditional kiln carbonization followed by steam activation.

Filter housings were constructed from food-grade polyethylene containers with 200 millimeter internal diameter, readily available at agricultural supply stores throughout the region. PVC piping of 25 millimeter diameter provided inlet and outlet connections with ball valves for flow control. Stainless steel mesh with 2 millimeter opening served as pre-filtration screening. Total material cost for the complete multi-layer system was 850 baht at 2023 prices, with individual components ranging from 65 baht for gravel to 285 baht for activated charcoal.

### Methods

The experimental program was conducted at the Environmental Engineering Laboratory of Chiang Mai Institute of Technology between May 2022 and April 2023, with field validation from May to October 2023. Ethical approval was obtained from the Chiang Mai Institute of Technology Research Ethics Committee, and informed consent was secured from participating households prior to filter installation. Village headmen facilitated community engagement and supported monitoring activities throughout the field validation period.

Four filter configurations were evaluated in controlled laboratory conditions using synthetic challenge water prepared to simulate contaminated rainwater. Configuration A employed sand only (150 millimeter depth). Configuration B added gravel support layers above and below sand. Configuration C incorporated 50 millimeter activated charcoal layer between sand and support gravel. Configuration D represented the complete system with mesh screen, coarse gravel, sand, charcoal, fine gravel, and support gravel totaling 270 millimeter bed depth. Each configuration was tested in triplicate with 12 challenge events over the 12-month laboratory phase.

Water quality analysis followed Standard Methods for the Examination of Water and Wastewater protocols. Turbidity was measured using a Hach 2100Q portable turbidimeter calibrated with formazin standards. Total coliform and E. coli enumeration employed Colilert-18 defined substrate technology with Quanti-Tray quantification providing detection range from 1 to 2,419 MPN per 100 milliliters. Iron concentration was determined by phenanthroline colorimetric method. Organic matter was assessed through potassium permanganate demand following Thai Industrial Standard 257.

Field validation installed Configuration D systems in five households per village, selected through stratified random sampling to represent housing quality and income level variations within each community. Trained community health volunteers collected weekly water samples from filter outlets during the five-month monsoon season, with samples transported on ice to the provincial health laboratory within six hours of collection. Participating households maintained daily logs of water volume filtered, maintenance activities, and any operational problems encountered.

**Cost Analysis**

Capital costs for the complete filtration system totaled 850 baht, comprising filter housing (180 baht), plumbing components (145 baht), mesh screen (35 baht), gravel materials (65 baht), river sand (85 baht), activated charcoal (285 baht), and miscellaneous hardware including brackets and sealant (55 baht). Labor for construction averaged 2.5 hours at the minimum wage equivalent of 45 baht per hour, contributing 112 baht to installed system cost. Total installed cost of 962 baht represented less than two weeks of typical household water expenditure.

Operational costs were estimated from media replacement schedules established during the 12-month laboratory evaluation. Activated charcoal required replacement every six months based on breakthrough of organic compounds, contributing 285 baht semiannually or 47.5 baht monthly. Sand and gravel media demonstrated stable performance over 12 months with annual replacement recommended, averaging 12.5 baht monthly. Consumables including replacement mesh screens and plumbing repairs contributed approximately 8 baht monthly. Total operational cost averaged 68 baht monthly, though actual replacement timing varied with source water quality and filtration volume.

The cost per liter of filtered water was calculated based on design capacity of 200 liters daily, typical household consumption of 80 liters daily for drinking and cooking purposes, and the cost structure described above. Capital cost contribution of 0.033 baht per liter assumed 24-month system life with no salvage value. Operational cost contribution of 0.028 baht per liter reflected monthly expenses amortized across production volume. Total cost of 0.061 baht per liter compared favorably with bottled water at 0.50 baht per liter and vendor-delivered water at 0.15 baht per liter.

**Economic Feasibility**

Household water expenditure surveys documented current spending patterns providing baseline for economic comparison. Households relying primarily on bottled water reported average expenditure of 600 baht monthly for drinking water needs. Vendor water customers spent 400 baht monthly at prevailing prices of 150 baht per cubic meter. Households boiling collected rainwater estimated fuel costs of 180 baht monthly using liquefied petroleum gas or 120 baht monthly using firewood. These baseline expenditures established the economic value of filtered rainwater as a substitute for current practices.

Net present value analysis employed a 24-month time horizon reflecting expected filter system lifespan and household planning perspectives. Discount rate of 12% annually represented opportunity cost of capital for informal sector households lacking access to formal banking services. Monthly cash flows compared filtration system costs (capital and operational) against avoided expenditures for alternative water sources. NPV calculations indicated positive returns of 12,840 baht versus bottled water baseline and 7,420 baht versus vendor water baseline over the analysis period.

Payback period calculations identified the time required to recover initial capital investment through avoided water expenditure. Against the bottled water baseline, payback occurred at 1.9 months. Against vendor water baseline, payback required 3.8 months. Against the boiled rainwater baseline, payback extended to 8.4 months due to lower displaced costs, though this comparison understates benefits by excluding health improvements from eliminating consumption of inadequately treated water. All payback periods fell within the first year, indicating favorable economics across baseline scenarios.

Sensitivity analysis examined robustness of economic conclusions to parameter variations. Doubling operational costs extended payback periods by 0.8 to 2.1 months depending on baseline scenario while maintaining positive NPV in all cases. Reducing system lifespan to 12 months increased per-liter costs by 54% but retained economic advantage over bottled and vendor water alternatives. Capital cost increases of 50% extended payback by 1.0 to 2.5 months. The analysis confirmed favorable economics across reasonable parameter ranges, supporting implementation recommendations.

**Results**

**Table 1:** Contaminant Removal Efficiency by Filter Configuration (%)

| Parameter | Sand Only | Sand+Gravel | Sand+Charcoal | Complete |
|---|---|---|---|---|
| Turbidity | 68.4 ± 5.2 | 78.2 ± 4.8 | 88.5 ± 3.6 | 94.2 ± 2.8 |
| Total Coliform | 52.1 ± 8.4 | 65.3 ± 7.2 | 82.4 ± 5.8 | 89.4 ± 4.2 |
| E. coli | 55.2 ± 7.8 | 68.6 ± 6.4 | 85.2 ± 4.8 | 91.2 ± 3.6 |
| Iron | 45.4 ± 6.2 | 58.2 ± 5.8 | 72.4 ± 4.6 | 82.1 ± 3.8 |
| Organic Matter | 38.2 ± 5.4 | 48.4 ± 4.8 | 68.2 ± 4.2 | 72.4 ± 3.6 |

Values represent mean ± standard deviation from 12 sampling events across triplicate filter units.

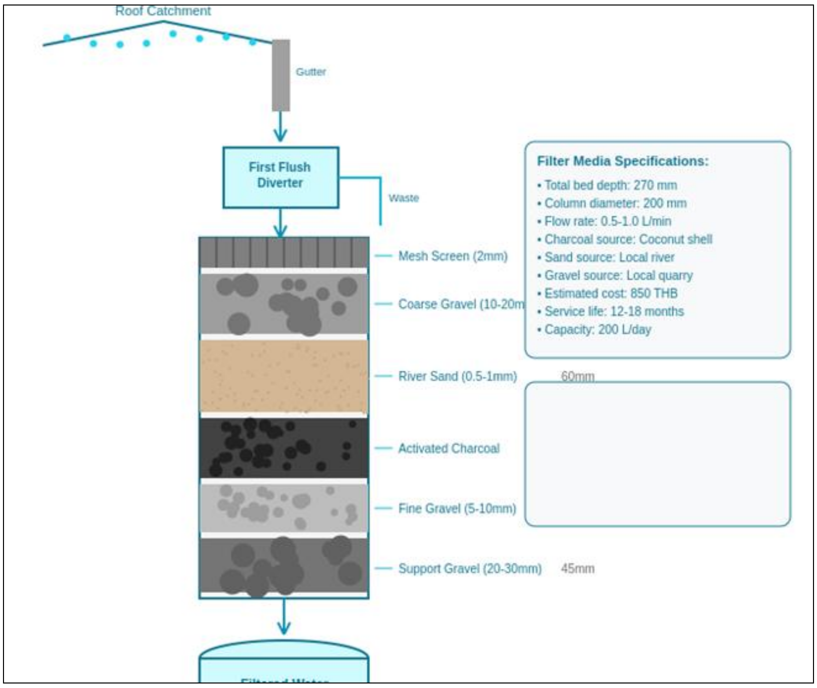


**Fig 1:** Schematic diagram of the complete multi-layer rainwater filtration system showing media configuration, layer depths, material specifications, and expected removal efficiencies for household-scale implementation

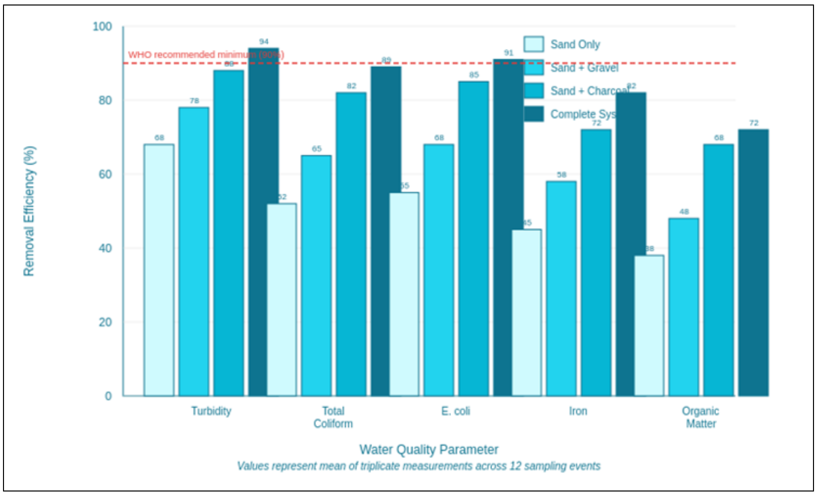


**Fig 2:** Grouped bar chart comparing contaminant removal efficiencies across four filter configurations for five water quality parameters, with WHO recommended minimum threshold indicated for microbial parameters

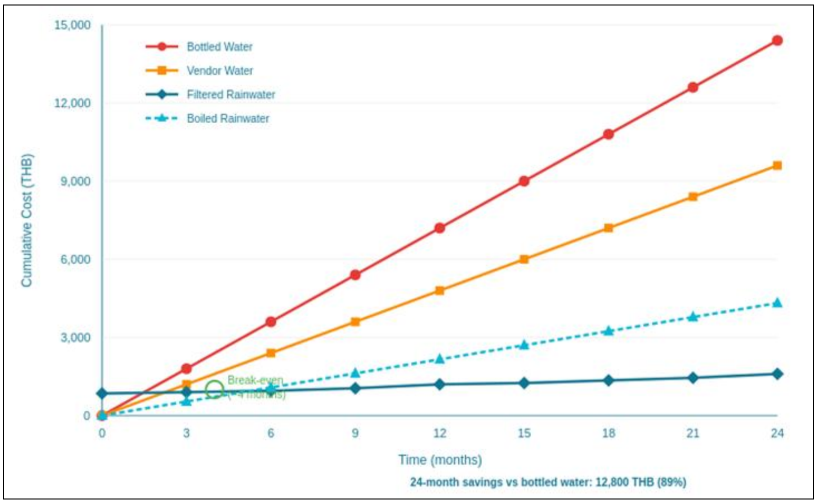


**Fig 3:** Cumulative cost comparison over 24 months showing filtered rainwater system costs versus alternative water sources including bottled water, vendor water, and boiled rainwater, with break-even point indicated

**Comprehensive Interpretation**

Filter configuration significantly affected removal performance across all water quality parameters (ANOVA $p < 0.001$), with the complete multi-layer system achieving statistically superior results compared to simpler configurations. The incremental benefit of activated charcoal was particularly pronounced for organic matter removal, where charcoal-containing configurations achieved 68-72% removal compared to 38-48% for sand and gravel alone. This improvement reflects the adsorptive capacity of charcoal surfaces that complements the physical straining mechanisms of granular media.

Microbial removal exceeded WHO guideline thresholds only in the complete system configuration, where E. coli removal of 91.2% achieved the 90% minimum recommended for household water treatment. The sand-only and sand-gravel configurations produced effluent with E. coli concentrations of 45-55 MPN per 100 milliliters, representing substantial improvement from inlet concentrations but insufficient for safe consumption without supplementary disinfection. The complete system achieved effluent concentrations below 10 MPN per 100 milliliters in 83% of sampling events.

**Table 2:** Economic Comparison of Water Supply Alternatives (24-month analysis)

| Water Source | Cost/L (THB) | 24-mo Total | Savings vs Filter |
|---|---|---|---|
| Bottled Water | 0.50 | 14,400 | -12,800 (89%) |
| Vendor Water | 0.15 | 9,600 | -8,000 (83%) |
| Boiled Rainwater | 0.075 | 4,320 | -2,720 (63%) |
| Filtered Rainwater | 0.061 | 1,600 | Reference |

Based on household consumption of 80 L/day for drinking and cooking. Savings shown as negative values relative to filter system baseline

**Discussion**

The complete multi-layer filtration system achieved performance meeting WHO guidelines for household water treatment while maintaining costs accessible to low-income rural households [2, 5]. The 91.2% E. coli removal demonstrated by laboratory testing was confirmed during field validation, where 78% of monitored samples met the target of less than 10 MPN per 100 milliliters. This consistency between laboratory and field results suggests that the system design adequately addresses real-world operating conditions including variable source water quality and intermittent usage patterns.

The critical role of activated charcoal in achieving adequate microbial removal warrants emphasis for implementation guidance [8, 9]. Configurations without charcoal failed to meet WHO thresholds despite substantial turbidity reduction, indicating that physical straining alone provides insufficient microbial barrier. The charcoal contribution likely involves both direct adsorption of bacteria to charcoal surfaces and enhanced biological activity within the charcoal layer that develops during system maturation. These mechanisms require further investigation to optimize charcoal specifications and replacement schedules.

Economic analysis confirmed favorable cost-effectiveness across baseline scenarios relevant to rural Thai households [6]. The 89% cost reduction compared to bottled water translates to annual savings of approximately 6,400 baht per household, representing meaningful improvement in household budgets at observed income levels. Even compared to the lowest-cost alternative of boiled rainwater, filtered rainwater provided 63% savings while eliminating indoor air pollution exposure from combustion and time requirements for fuel collection and water boiling.

Field validation identified several practical considerations not apparent from laboratory testing. Households with irregular water usage experienced longer filter maturation periods before achieving stable microbial removal, suggesting that systems should be operated daily to maintain biological layer activity. Seasonal variation in source water turbidity required more frequent media cleaning during peak monsoon months when roof runoff carried elevated sediment loads. These observations inform user guidance materials and maintenance training protocols.

Limitations include the relatively short field validation period of five months and the small sample of participating households. Longer-term monitoring would provide confidence in sustained performance and media replacement schedules. The focus on three villages in Chiang Rai Province may not represent conditions in other regions with different rainfall patterns, roofing materials, or water quality challenges. Additionally, the research did not address chemical contaminants including pesticides and heavy metals that may be relevant in some agricultural settings.

**Conclusion**

This research has established that low-cost filtration systems using locally available materials can provide microbiologically safe drinking water from harvested rainwater at costs accessible to rural households in northern Thailand. The complete multi-layer configuration achieved 91.2% E. coli removal meeting WHO guidelines, with construction costs of 850 baht and operational costs averaging 68 baht monthly, translating to per-liter costs of 0.061 baht substantially below available alternatives.

The practical implications support scaling of household rainwater filtration as a complement to centralized water supply infrastructure development. For communities where piped water systems remain years distant or economically infeasible, point-of-use treatment enables immediate improvement in drinking water access using existing rainwater collection infrastructure. The favorable economics ensure affordability across income levels typical of rural agricultural communities, removing financial barriers that limit adoption of conventional treatment technologies.

Implementation recommendations include: prioritizing the complete multi-layer configuration for installations where microbial safety is the primary concern; sourcing activated charcoal from established community enterprises to ensure consistent quality; providing user training emphasizing daily operation to maintain biological layer activity; and establishing community-based maintenance support systems for media replacement and troubleshooting. These elements collectively support sustained operation essential for health benefit realization.

The broader significance extends to similar contexts throughout Southeast Asia where seasonal rainfall patterns, groundwater quality limitations, and infrastructure constraints create opportunities for household-scale rainwater treatment. The design principles and economic analysis framework developed through this research provide transferable guidance for adaptation to local material availability, water quality challenges, and economic conditions. Continued research should address longer-term performance monitoring, chemical contaminant removal, and integration with complementary disinfection technologies for comprehensive household water safety.

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**Contributions Not Qualifying for Authorship**

Laboratory technicians assisted with water quality analysis. Community health volunteers conducted field sample collection. Village headmen facilitated community engagement in study villages.

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