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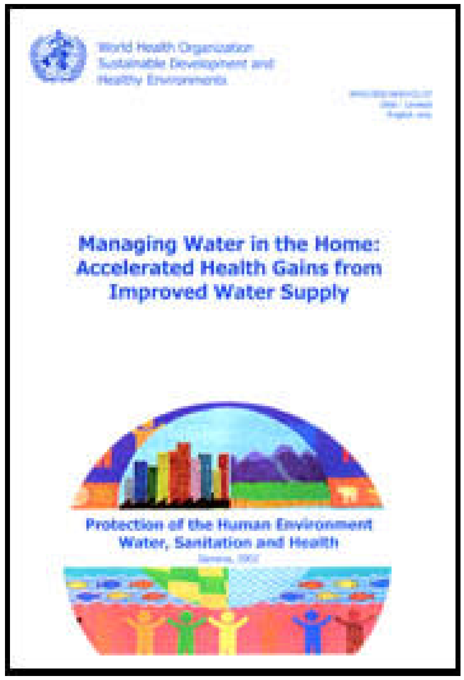

Managing Water in the Home: Accelerated Health Gains from Improved Water Supply

World Health Organization
Sustainable Development and Healthy Environments

Protection of the Human Environment
Water, Sanitation and Health
Geneva, 2002

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Foreword

Around 2.2 million die of basic hygiene related diseases, like diarrhoea, every year. The great majority are children in developing countries. Interventions in hygiene, sanitation and water supply make proven contributors to controlling this disease burden. For decades, universal access to safe water and sanitation has been promoted as an essential step in reducing this preventable disease burden.

Nevertheless the target of "universal access" to improved water sources and basic sanitation remains elusive. The "Millenium Declaration" established the lesser but still ambitious goal of halving the proportion of people without access to safe water by 2015. Achieving "universal access" is an important long-term goal. How to accelerate health gains against this long-term backdrop and especially amongst the most affected populations is an important challenge.

There is now conclusive evidence that simple, acceptable, low-cost interventions at the household and community level are capable of dramatically improving the microbial quality of household stored water and reducing the attendant risks of diarrheal disease and death.

Many different water collection and storage systems and strategies have been developed, described and evaluated on the basis of various criteria for household and community use in developed and developing countries. A variety of physical and chemical treatment methods to improve the microbial quality of water are available and many have been tested and implemented to varying extents in developed and developing countries. Some of these water treatment and storage systems have been tested under controlled conditions in the laboratory and implemented in field to evaluate their ability to produce drinking water of acceptable microbiological quality and to maintain this quality during storage and use. Some of them also have been evaluated in the field for their ability to reduce diarrheal and other waterborne diseases among users.

Because of the importance of education, socio-cultural acceptance, changing people's beliefs and behaviors, achieving sustainability and affordability in the provision of safe water, some of the most promising household water treatment and storage systems and their implementation strategies include or are accompanied by efforts to address these considerations.

This report describes and critically reviews the various methods and systems for household water collection, treatment and storage. It also presents and critically reviews data on the ability of these household water treatment and storage methods to provide water that has improved microbiological quality and lower risk of waterborne diarrheal and other infectious disease.

The target audience for this report is intended to be scientists, engineers, policy makers, managers and other public health, environmental health and water resources professionals who are knowledgeable about the fundamentals of drinking water and related health sciences and water engineering technology.

The report is not intended to be a comprehensive guidance or "how to" manual on household water treatment and storage or a practical guide for the average drinking water consumer. It is hoped that this document provides a scientifically sound basis for identifying, accepting and promoting household water treatment and storage systems and technologies so that such documents in support of the implementation of household water treatment and storage can be developed and disseminated elsewhere.

This report has been prepared as part of a programme of activity towards the updating of WHO's Guidelines for Drinking-water Quality. Following a process of development and review it is released in draft form. Comments upon this draft care welcome and should be sent to:

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Executive Summary

A large fraction of the World's population around 1.1 billion people - does not have access to improved sources of water. For these and many others, contamination of water during transport and in the household presents a significant health risk. For this segment of the world's population, use of effective technologies for household water treatment and storage is likely to have direct beneficial effects in the form of reduced infectious diseases and also contribute to greater productivity and other associated benefits from improved health. Household treatment often can provide these benefits to underserved populations much more quickly than it will take to design, install and deliver piped community water supplies.

Identifying the most accessible and effective methods for household water storage and treatment are matters of considerable importance and are the subject of this report.

The purpose of this report is to critically review the various candidate technologies and systems for providing microbiologically improved household water and to identify the most promising ones based on their technical characteristics and performance criteria. The characteristics and performance criteria for these are: effectiveness in improving and maintaining microbial water quality, reducing waterborne infectious disease, technical difficulty or simplicity, accessibility, cost, socio-cultural acceptability, sustainability and potential for dissemination.

This critical review considers methods and systems to protect water during storage, collection and use that improve microbial quality and thereby reduce pathogen

exposure and risks of diarrheal and other waterborne diseases. Because the most important and immediate risks to human health from using contaminated drinking water are those from enteric microbes of fecal origin or other sources, this review focuses on strategies and systems to protect and improve the microbiological quality of household water to prevent and control waterborne microbial diseases.

Systems for Household Storage of Collected Water to Protect Microbiological Quality

A review of the existing literature on collection and storage of household water revealed that such water often comes from fecally contaminated sources and therefore poses infectious disease risks to consumers. Furthermore, regardless of whether or not collected household water is initially of acceptable microbiological quality, it often becomes contaminated with pathogens of fecal origin during transport and storage due to unhygienic storage and handling practices.

Studies show that the use of containers with narrow openings for filling, and dispensing devices such as spouts or taps/spigots, protect the collected water during storage and household use. Many container designs also have handles, are lightweight, are made from durable, UV-resistant plastic and are affixed with a label containing informational/educational messages on their cleaning and use. Other appropriate containers for safe storage are those in which water can be directly treated by the physical method of solar radiation and then directly stored and dispensed for household use. These improved containers protect stored household water from the introduction of microbial contaminants via contact with hands, dippers, other fecally contaminated vehicles or the intrusion of vectors.

Treatment Technologies to Improve the Microbiological Quality of Household Water

A variety of candidate technologies for treatment of household water have been described and many are widely used in different parts of the world. The technologies to improve the microbial quality of household water and reduce waterborne disease include a number of physical and chemical treatment methods. The physical methods, include boiling, heating (fuel and solar), settling, filtering, exposing to the UV radiation in sunlight, and UV disinfection with lamps. The chemical methods include coagulation-flocculation and precipitation, adsorption, ion exchange and chemical disinfection with germicidal agents (primarily chlorine). Some water treatment and storage systems use chemicals and other media and materials that can not be easily obtained locally at reasonable cost and require relatively complex and expensive systems and procedures to treat the water. Such systems may be too inaccessible, complex and expensive to employ for treatment and storage of household water in some places and settings.

The efficacy of some treatment methods to physically remove particles (turbidity) and microbes or to inactivate microbes in household water has been documented, primarily for indicator bacteria. Some treatment methods, such as boiling, solar disinfection, UV disinfection with lamps, chlorination and the combined treatments of chemical coagulation-filtration and chlorination have been evaluated for reductions of bacteria, viruses and in some cases protozoans. However, the ability of some of these methods to remove or inactivate a wide range of known waterborne pathogens has been inadequately investigated and documented. The differences in the technologies of candidate treatment and water storage systems as well as the differences in the types, sizes and other properties of waterborne microbes that need to be removed or inactivated, have contributed to a lack of documentation of the efficacy of these methods for household treatment and storage of water.

With exception of chlorination and storage in a safe container and solar disinfection "SODIS" (UV plus heat), most technologies for household water treatment and storage have not been studied for their ability to reduce diarrheal and other waterborne disease in household use. Such epidemiological studies of an intervention are essential in establishing the performance of the technology as well as its acceptance and sustainability by users.

Several candidate technologies for household water treatment and storage appear to be accessible, simple and economical for use in both the developed and developing countries. Some of these systems have been characterized for microbial efficacy and reduction of waterborne disease, and for community acceptance sustainability and cost recovery. Of the systems now available, the following appear to be the most widespread and promising for further development, characterization, implementation and dissemination:

- Solar disinfection by the combined action of heat and UV radiation
- Solar disinfection by heat alone ("solar cooking")
- Chlorination plus storage in an appropriate vessel
- Combined systems of chemical coagulation-filtration and chlorine disinfection.

The performance characteristics, advantages, disadvantages and estimated costs of these most promising technologies for household water treatment to improve microbial quality and reduce diarrheal disease are presented in the report.

Treating turbid water: a special concern

For the most promising household water treatment systems of chlorination with an improved storage vessel, and solar disinfection with UV plus heat in clear bottles for sunlight penetration (SODIS), effective treatment of turbid water remains a challenge. This is because microbial reductions are decreased or prevented by turbidity particles that reduce access to target microbes or otherwise protect them from inactivation by other mechanisms. Suspended matter in water reduces the microbiocidal efficacy of chlorine and other chemical disinfectants, and it physically shields microbes from the UV radiation that is present in sunlight and responsible for much of its disinfection activity. There is a need to investigate, characterize and implement physical and physical-chemical technologies for practical and low cost pre-treatment of treatment of household water prior to chlorination and solar disinfection with UV plus heat. Appropriate physical and physical-chemical methods for effective pre-treatment for household water needed to be established, taking into consideration turbid waters of different quality with respect to particle characteristics and their removal efficiencies. In principle, some physical or physical-chemical methods may be highly effective for treatment of stored household water on their own. Pre-treatment technologies for removal of turbidity (suspended matter) from water suitable for such applications potentially include:

- Settling or plain sedimentation
- Fiber, cloth or membrane filters

- Granular media filters and
- Slow sand filter.

These methods will vary in their ability to remove interfering turbidity from water, depending on the nature of the turbidity particles. Especially important in this regard is their size and density. Of the listed methods, slow sand filtration is the least likely to be implementable and sustainable at the household level. This is because the preferred filter designs and installations often are larger and capable of treating more water than needed by individual households and because they require technical skills for maintenance and operation that may not be accepted by individual users.

Need for behavioral, motivational, and economic support

The use of technologies to treat and safely store household water is best accomplished if it is accompanied by or supported with economic incentives and other cost recovery methods and with programs designed to support community participation, education and other efforts to achieve acceptance and sustainability. Where such additional socio-cultural, behavioral and economic components of household water treatment and storage technologies are absent or lacking, successful implementation and sustained use are unlikely to be achieved. The importance of economic analyses and community participation, education and responsibility for household water treatment and safe storage can not be over stressed in future efforts to establish and disseminate this intervention for water sanitation.

Conclusions

Studies have shown that improving the microbiological quality of household water by on-site or point-of-use treatment and safe storage in improved vessels reduces diarrheal and other waterborne diseases in communities and households of developing as well as developed countries. The extent to which improving drinking water quality at the household level reduces diarrheal disease probably depends on a variety of technology-related as well as site-specific environmental and demographic factors that require further investigation, characterization and analyses. Reductions in household diarrheal diseases of 6-90% have been observed, depending on the technology and the exposed population and local conditions.

Further development, refinement, implementation, evaluation and comparison of household water treatment and safe storage technologies is both justified and encouraged.

Greater efforts to disseminate information about household water treatment and storage technologies and their benefits and advantages are merited.

The most promising and accessible of the technologies for household water treatment are filtration with ceramic filters, chlorination with storage in an improved vessel, solar disinfection in clear bottles by the combined action of UV radiation and heat, thermal disinfection (pasteurization) in opaque vessels with sunlight from solar cookers or reflectors and combination systems employing chemical coagulation-flocculation, sedimentation, filtration and chlorination. All of these systems have been shown to dramatically improve the microbiological quality of water. At least two of them: solar disinfection in clear plastic bottles (heat plus UV radiation) and chlorination plus storage in an improved vessel, have been shown in epidemiological studies of the intervention type to significantly reduce diarrheal and other infectious diseases, including cholera. These household water treatment and storage systems are considered the most promising and effective, based on their documented ability to improve the microbiological quality of water and reduce waterborne infectious disease risks.

All of the household water treatment technologies described here have been tested independently and so far none have been tested in combination. Historically and with renewed recent interest, water treatment technology and practice have focused on the use of two or more treatment technologies as a multiple barrier approach. There is considerable interest and potential merit in the use of two or more treatment systems in succession for improved treatment and the creation of multiple barriers. In particular those treatments that provide no residual disinfectant, such as solar treatment and filtration could be followed by chlorination and storage in a protected or improved vessel to prove a multibarrier approach that would result in appreciable microbial reduction, continued protection with a disinfectant residual and storage that is less prone to post-treatment contamination. Research and demonstration of such multibarrier treatment and storage approaches deserve consideration and are recommended as next steps in the development, evaluation and implementation of improved treatment and storage of water at the household level.

The introduction of improved water treatment and storage at the household level, if done effectively, is likely to increase personal and community knowledge and awareness of the importance of water hygiene and sanitation and the benefits to be derived therefrom. It is likely that involvement in preparing and using safe water at the household level results in increased knowledge of water hygiene and sanitation, recognition and appreciation of its contribution to infectious disease prevention and control and improved health. Such awareness of the role of safe drinking water in health promotion and diseased prevention support and facilitate the ultimate goal of providing all of the world's population with community piped water that is accessible, safe and affordable.

1. Introduction

1.1. Background

A large proportion of the World's people do not have access to improved or microbiologically safe sources of water for drinking and other essential purposes: (WHO/UNICEF, 2000) has estimated that 1.1 billion people do not have access to "improved drinking-water sources". Consumption of unsafe water continues to be one of the major causes of the 2.2 million diarrheal disease deaths occurring annually, mostly in children (WHO/UNICEF, 2000).

Despite major efforts to deliver safe, piped, community water to the World's population, the reality is that water supplies delivering safe water will not be available to all people in the near term (Argawal et al., 1981; Feachem et al., 1978; IDRC, 1980). The millenium declaration established as a goal halving the proportion of the global population without access to safe water by 2015. One reason for this is that fecal contamination of source and treated water is a persistent, worldwide problem. Sanitation coverage is inadequate in many parts of the world and is likely to persist for the foreseeable future. Fecal contamination of source and treated water is further exacerbated by increasing populations, urban growth and expansion, peri-urban settlement and continued and perhaps increasing pollutant transport into ground and surface water due to deforestation, global climate change, recurrent disastrous weather events (hurricanes, cyclones, floods, tsunamis, etc.) and increasing coverage of the earth's surface with impervious materials.

Current estimates of the number of people using microbiologically unsafe water are probably low. This is because the assumptions about the safety or quality of water based on its source, extent of treatment or consumer handling do not take into consideration several well-documented problems. One problem is that co-called protected or improved sources, such as boreholes and treated urban supplies, can still be fecally contaminated and deliver microbially unsafe water. In some cities the water systems abstract unsafe water from unprotected or contaminated sources and deliver it to consumers with no or inadequate treatment, yet these water systems are classified or categorized as improved and safe. Another problem contributing to the underestimation of the population served by unsafe water is contamination of water during distribution whether water is piped or carried into the home. Many communities have protected or improved water supplies and treated water that is microbiologically safe when collected or when it leaves a treatment plant. However, substandard water distribution systems, intermittent water pressure due to power outages and other disruptions, and illegal connections to the distribution system often lead to the introduction of fecal contamination and therefore, microbiologically contaminated water at the consumer's tap or collection point. In some urban water supplies the infrastructure for water distribution to consumers is so inadequate that pressure drops, losses and other intermittent pressure changes, deteriorating, open or leaking conveyances and other distribution system deficiencies lead to infiltration or intrusion of contaminated water and increased waterborne disease risks. Such deficiencies result in the delivery of unsafe water to consumers, even though the water may have been obtained from a high quality, protected source and centrally treated by physical and chemical methods to improve quality. Furthermore, in many large cities, including some of the World's megacities, peri-urban settlements are not served by the centralized water system for socio-cultural, economic, political, technological and other reasons. Because these unserved urban dwellers are forced to obtain water from any available source, including informal and clandestine connections to the central water supply system, their water is typically contaminated.

People now drinking unsafe household water also include those in rural as well as urban settings. Many rural dwellers lack indoor plumbing or nearby outdoor piped water from a safe supply (from wells, boreholes, protected or upland surface water sources, etc.). Often they have to travel considerable distances to reach any water source, regardless of quality, for collection and household use (White et. al., 1972). Many urban dwellers are also lack safe water (WHO, 2000; Swerdlow et. al., 1992; Ries et. al., 1992; Weber et. al., 1994).

A further problem is that water collected for domestic use often becomes re-contaminated or further contaminated by unsafe consumer storage and handling practices at the household level. Many of the world's people continue to obtain their water on a daily or other frequent basis from any available source and either carry it or otherwise have it delivered to the home for personal use. Typically, this water is gathered and stored in vessels of various designs and materials. Often, the water is not treated or otherwise protected from subsequent contamination during use. Such household water is at high risk of being contaminated by various pathogenic viruses, bacteria and parasites associated with fecal wastes and other sources. This is because water is typically obtained from the most convenient source, which is often fecally contaminated, and typically, additional contamination occurs due to a variety of unsanitary conditions and practices during storage and use. Microbial contamination of collected and stored household water is caused not only by the collection and use of fecally contaminated water that was not safe to begin with but also by contamination of initially microbiologically safe water after its collection and storage. Factors contributing to this problem are unsanitary and inadequately protected (open, uncovered or poorly covered) water collection and storage containers, the use of unsanitary methods to dispense water from household storage vessels, including fecally contaminated hands and dippers, lack of protection against contamination introduced by vectors (flies, cockroaches, rodents, etc.) and inadequate cleaning of vessels to prevent biofilm formation and accumulation of sediments and pathogens.

Improving and protecting the microbial quality and reducing the infectious disease risks to consumers of collected water stored in households requires alternative or interim strategies and approaches that can be implemented effectively, quickly and affordably. As will be described in this report, technically feasible, effective, socio-culturally acceptable and affordable methods for treatment and storage of household water to improve microbial quality and reduce waterborne disease risks are now available. Waiting for the provision of piped, microbiologically safe community water systems to the many people lacking such services is an inappropriate response to the basic need for safer drinking water that can be met on at least a provisional basis by available technologies. Effective measures are needed immediately to provide at risk populations with safer water at the household level until the long-term goal of providing safe, piped, community water supplies can be achieved.

There is now conclusive evidence that simple, acceptable, low-cost interventions at the household and community level are capable of dramatically improving the microbial quality of household stored water and reducing the risks of diarrheal disease and death in populations of all ages in the developed and developing world. A variety of physical and chemical treatment methods to improve the microbial quality of water are available and many have been tested and implemented to varying extents in a variety of settings and for a diverse range of populations. Many different water collection and storage systems and strategies have been developed, described and evaluated on the basis of various criteria for household and community use. Some of them have been tested under controlled conditions in the laboratory and implemented in field to evaluate their ability to produce drinking water of acceptable microbiological quality and to maintain this quality during storage and use. Some of them also have been evaluated in the field for their ability to reduce diarrheal and other waterborne diseases among users. Because of the importance of education, socio-cultural acceptance, changing people's beliefs and behaviors, achieving sustainability and affordability in the provision of safe water, some of the most promising household water treatment and storage systems and their implementation strategies include or are accompanied by efforts to address these considerations.

The purpose of this report is to critically review the various candidate technologies and systems for providing microbiologically improved household water and to identify the most promising ones based on their technical characteristics and performance criteria. These characteristics and performance criteria are: effectiveness in improving and maintaining microbial water quality, reducing waterborne infectious disease, technical difficulty or simplicity, accessibility, cost, socio-cultural acceptability, sustainability and potential for dissemination. The focus of this critical review is on technologies and systems to protect water during storage collection and use, improve the microbial quality of the collected water, and thereby reduce pathogen exposure and risks of diarrheal and other waterborne diseases. This is not intended to be a comprehensive review of water treatment methods that reduce and thereby minimize exposures to various chemical contaminants. While toxic chemicals in drinking water are an important public health concern, it has been repeatedly demonstrated and generally accepted that the most important and immediate risks to human health by using contaminated drinking water are those from enteric microbes of fecal origin or other sources. Hence, the focus herein is on strategies and systems for protection and improvement of the microbiological quality of household water and prevention and control of waterborne microbial diseases. However, some of the technologies that reduce waterborne microbes also reduce certain toxic chemicals, such as arsenic.

1.2. Purposes and Benefits of Household Water Treatment and Storage

The purposes of household water treatment and storage addressed in this review are those intended to improve and maintain the microbial quality of the water for drinking and other potable purposes, such as food preparation and essential hygiene in child care and treatment of illness (breast feeding and preparation of infant foods and oral rehydration solutions) and thereby reduce disease transmission. The main benefit of microbiologically safe water for these purposes should be obvious: reducing the risks of diarrheal and other waterborne infectious diseases. The alternative, unsafe water, is a major source of pathogen exposure and increased risk of waterborne infection, illness and death. Hence, the provision of microbiologically safe household water has the potential to reduce the infectious burden of the developing world's population. Recent estimates put this burden at 4 billion cases of diarrhea and 2.2 million deaths annually, mostly in children under five years of age. A compelling reason to accept and promote treatment and safe storage of collected household water to improve microbial quality is the ability of this health-related intervention to reduce the infectious disease burden of the user population. Notably, it is now well documented that the provision of safe water alone will reduce diarrheal and other enteric diseases by 6 to 50%, even in the absence of improved sanitation or other hygiene measures. Reducing household diarrheal disease by more than 5% is an important achievement, because this is the minimum achievable target reduction in disease burden considered worthy of promotion and implementation by health authorities. Furthermore, as will be documented later in this report, reductions in diarrheal disease burdens in excess of 5% by household water treatment and safe storage have been achieved for children under 5 years of age. This outcome clearly shows that children under age 5 are protected by the intervention of household treatment and safe storage of collected water, despite the likely opportunities for transmission of these diarrheal disease agents by other exposure routes. Hence, treating water at the household level and storing it safely to improve microbial quality apparently reduces the frequency and magnitude of encounters of children under age 5 with diarrheal pathogens in the home.

Although the combined roles of safe water and adequate hygiene and sanitation in reducing diarrheal and other diseases are clear and well documented, there is uncertainty and even debate over the magnitude of the contribution of safe water to this outcome (Esrey et al., 1985; 1991). Some studies have suggested that improved hygiene and sanitation are more important than safe water in reducing diarrheal and other water-borne and water-washed diseases (US Agency for International Development, 1993). In the minds of some, the provision of safe water alone is unlikely to result in reductions of diarrheal and other infectious diseases. This is because the other transmission routes of these potentially waterborne diseases, such as person-to-person contact, food, fomites and vectors are not being controlled and continue to be major sources of pathogen transmission. Hence, it is assumed that provision of microbiologically safe water alone will have little or no beneficial effect on infectious disease transmission in the absence of improved sanitation and other hygiene measures. This assumption is now known to be incorrect. Recent studies of only safe water interventions clearly document not only the improved microbiological quality of household water but also significant reductions in diarrheal disease (Handzel, 1998; Mintz et. al., 2001; Quick, 1997; Quick et. al., 1999; Semenza et. al., 1998). This beneficial effect is especially achieved when the technological intervention for improved household water treatment and storage is supported by educational and motivational efforts to transfer the technology and develop individual and community understanding and support to maintain compliance and assume responsibility for its continued use and dissemination. It is also clear that the combined roles of safe water and adequate hygiene and sanitation are likely to achieve the greatest reduction in infectious disease burden compared to either intervention alone. However, it is now apparent that improving household water collection, treatment and storage is one option for achieving a beneficial health effect by reducing diarrheal and other infectious diseases. Household water treatment and storage systems are one of many waster, sanitation and hygiene options that deserve due consideration in the identification, prioritization and implementation of water, sanitation and hygiene measures for use at household, community and regional levels.

It is assumed that treated community water supplies in developed countries generally are of high microbiological quality and therefore safe with respect to waterborne microbial disease risks. However, significantly increased risks of waterborne gastrointestinal illness have been attributed to a centralized community water supply system in a large city of a developed country (Laval, Quebec, Canada) where water was extensively treated by modern methods and met all microbial quality requirements (Payment et al, 1991; 1996). These findings suggest that pathogens at levels below detection but high enough to cause measurable gastrointestinal illness either penetrated the multiple treatment barriers or they entered the treated water subsequently in the community distribution system or within household plumbing. Hence, even extensively treated community drinking water of high microbiological quality and assumed to be of low risk in developed countries may still be contributing significantly to community diarrheal illness. It is noteworthy that the apparent risks of waterborne diarrheal illness from the treated community water delivered by the distribution system were significantly decreased either by point-of-use water treatment or by protecting the treated water from post-treatment contamination (i.e., bottling it at the treatment plant and delivering the bottles to consumers). Additionally, the infectious disease risks from fecally contaminated and microbially unsafe water in developed countries is considered even greater in the water supplies of smaller communities than the larger ones. Small community water supplies are at greater risk than larger ones because they often lack the technical expertise and financial resources to adequately protect source waters, provide sufficient and technically reliable treatment and maintain the integrity of their distribution systems. For example, most waterborne outbreaks in the United States of America are due to systems with no or inadequate treatment, vulnerable watersheds and aquifers, distribution system deficiencies and serving smaller communities. Therefore, it should come as no surprise that in communities throughout the world, improving household water quality by point-of-use treatment reduces risks of diarrheal disease and significantly improves microbial quality.

In this review the candidate technologies and approaches for household water treatment and storage are examined on the basis of their technical feasibility, practicality and availability, effectiveness in improving the microbiological quality of the water and reducing waterborne disease, cost, and potential for sustainability and dissemination.

2. Storage and Treatment of Household Water

2.1. Household Water Storage, Microbial Quality and Infectious Disease Risks

Key factors in the provision of safe household water include the conditions and practices of water collection and storage and the choice of water collection and storage containers or vessels. As shown in Table 1, numerous studies have documented inadequate storage conditions and vulnerable water storage containers as factors contributing to increased microbial contamination and decreased microbial quality compared to either source waters or water stored in improved vessels. Some studies also have documented increased risks of waterborne infectious diseases from inadequately stored water compared to water stored in an improved vessel (safe storage), treated in the home to improve microbial quality, or consumed from a quality source without storage (Table 1). Higher levels of microbial contamination and decreased microbial quality are associated with storage vessels having wide openings (e.g., buckets and pots), vulnerability to introduction of hands, cups and dippers that can carry fecal contamination, and lack of a narrow opening for dispensing water. Some studies have noted the vulnerability of storage vessels with these undesirable characteristics to fecal and other contamination without having reported microbiological data on water quality or increased levels of diarrheal disease (Miller, 1984). Other factors contributing to greater risks of microbial contamination of stored water are higher temperatures, increased storage times, higher levels of airborne particulates (dust storms), inadequate handwashing and the use of stored water to prepare weanling and other foods that also become microbiologically contaminated and contribute to increased infectious disease risks (Black et al., 1983; Dunne, 2001; Echeverria et al., 1987: Iroegbu et al., 2000; Knight et al., 1992; Luby et al., 2001a, van Steenbergen et al., 1983).

Table 1. Evidence for Increased Microbial Contamination (Decreased Microbial Quality) and Increased Infectious Disease Risks from Inadequately Stored Household Water

Location	Storage Vessel	Storage Times	Impact on Microbial Quality?	Disease Impact?	Reference
Rural Bangladesh	Water jars	1-2 days	Increased *V. cholerae* presence	Increased (~10-fold higher) cholera rates	Spira et al., 1980
Bahrain	Capped plastic vessels, jars, pitchers	Not reported	*V. cholerae* present in stored but not source water	Uncertain. No significant association with stored water in a case-control study	Gunn et al., 1981

Calcutta, India	Wide- mouth vs. narrow-necked	Not reported	Not measured	Cholera infections 4-fold higher using wide-mouth storage vessel	Deb et al., 1982
Khartoum, Sudan	Clay jars ("zeers") in homes, etc.	2 days to 1 month	Increased fecal indicator bacteria over time, in summer and during dust events	Not Measured	Hammad and Dirar, 1982
Rural Egypt	Clay jar ("zir") in homes	<1 to 3 days	Algae growth and accumulated sediment	Not detected based on protozoan infection rates	Miller, 1984
Abeokuta, Nigeria	Elevated tanks in hospitals	Not reported	Higher plate count bacteria and *E. coli* in tanks than in central supply	Not Measured	Mascher and Reinthaler, 1987
Rural Malawi	Stored household water & other sources	Not reported	Higher fecal coliforms compared to other sources	Not measured	Lindskog and Lindskog, 1988
South Sudan	Nor reported	Not reported	Increased fecal bacteria levels	Not Measured	Mascher et al., 1988
Rangoon, Burma	Buckets	Up to 2 days	Higher levels of fecal coliforms than source	Not Measured	Han et al., 1989
Urban slum and rural villages, Liberia	Large containers, open or closed	"A long time"	Higher levels of enterobacteria in stored than source water	Not Measured	Molbak et al., 1989
Kurunegala, Sri Lanka	Earthen pots and others	Not reported	Higher levels of fecal coliforms in stored unboiled water	Not Measured	Mertens et al., 1990
Venda, South Africa	Plastic vessel ("tshigubu")	4 hours	Higher levels of coliforms over time	Measured; no effect	Verwejj et al., 1991
Rural Africa	Traditional and metal jars	24 hours or more	Higher levels of total and fecal coliforms	Not Measured	Empereur et al., 1992
Rural Malaysia	Various containers	Not reported	Higher levels of fecal coliforms in unboiled than boiled water	Higher diarrhea risks from water unboiled or stored in	Knight et al., 1992

				wide-necked than narrow-necked containers	
Rural Zimbabwe	Covered and uncovered containers	12 hours or more	Higher *E. coli* and Aeromonas levels with storage and use	Not Measured	Simango et al., 1992
Trujillo, Peru	Wide-mouth storage containers	Not reported	Higher fecal coliform levels in stored than source waters	Increased cholera risks	Swerdlow et al., 1992
The Philippines					VanDerslice and Briscoe, 1993
Rural Bangladesh	Traditional pots ("kulshis")	Not Reported	Increased fecal coliform levels and multiple antibiotic resistance	Increased fecal coliforms and multiply antibiotic resistant flora	Shears et al., 1995
Merica, Mexico	Not reported	Not reported	Increased bacterial levels in some locales	Not Measured	Flores-Abuxapqui et al., 1995
Malawi, Africa			Increased *V. cholerae*	Increased cholera risks	Swerdlow et al., 1997
Rural Trinidad	Open (drum, barrel, bucket) vs. tank or none	Not reported	Increased fecal bacteria levels in open vessel storage than in tank	Not measured	Welch et al., 2000
Abidjan, Cote d'Ivoire			Increased *E. coli* levels	Not Measured	Dunne et al., 2001

As summarized in Table 1, collection, storage and use of fecally contaminated water containing excessive levels of fecal bacteria poses health risks to consumers, regardless of where or how the water have become contaminated. In some cases water is collected from a contaminated source to begin with. In other cases water is obtained from a source of high microbiological quality, including treated supplies containing residual chlorine, but it becomes contaminated in the home due to inadequate and unsanitary storage conditions that allow for the introduction and/or proliferation of disease-causing microbes. In either situation, the microbially contaminated water poses health risks that can be reduced by improved storage conditions and household treatment, as will be further documented in this report. A few studies in the literature suggest that contamination of water within households does not pose increased health risks to consumers, perhaps because these pathogens are already present in household members and their contacts. However, evidence to support this interpretation based on sound study design with adequate data and data analyses are lacking. The majority of studies suggesting such lack of risk are based on inadequate study designs, low sample sizes, measurement of waterborne microbes not adequately predictive of health risks (e.g., plate count or coliform bacteria) and/or inadequate data analyses. The majority of studies document decreases in microbial quality, including increased pathogen levels, and increased health risks from consumption of fecally contaminated and inadequately stored household water.

2.2. Collection Methods and Storage Vessels for Household Water

Since ancient times, water for household use is collected by a variety of physical methods ranging from manual (e.g., dipping), to passive (e.g., roof catchments and diversions) to mechanical (e.g., pumps), and it is stored in a variety containers. In developing countries, many of the traditional types of water collection and storage methods employing vessels of various compositions and sizes are still widely used today (CDC, 2001; Mintz et al., 1995; White et al., 1972). These include traditional pots or urns fashioned from natural materials (e.g., gourds or wood) or fabricated from clay, copper, brass and other impervious materials, and flexible bags or other vessels made of animal hides, other animal parts or fabrics treated to seal and prevent leakage. Today, other metals, including aluminum, steel and iron, as well as other materials, primarily plastics, have come into widespread use for water collection and storage in the form of buckets, jerry cans, picnic coolers and other vessel types and shapes. Cisterns and other basins are also still widely used for water collection and bulk storage near or adjacent to dwellings, as they have been since ancient times.

Some of the key factors influencing the impact of storage vessels and conditions on household water quality are: (1) portability and ease of use, based on capacity, size, shape, weight, presence of handles, (2) durability, weight and other properties related to resistance and longevity, (3) presence of a coverable (preferably screw-cap) opening for filling and cleaning access but small enough to reduce the potential for introducing contaminants by contaminated hands, dipping utensils and other vehicles (e.g., airborne dust), vectors, or other sources, (3) ability to withdraw water in a sanitary manner, such as via a tap, spigot, spout or other narrow orifice, and (4) presence and accessibility of documentation describing how to properly use the container for water treatment and sanitary storage. The advantages and disadvantages of different types of water collection and storage containers in relation to the development of systems for safe storage and use of household water have been reviewed and summarized by the US Centers for Disease Control and Prevention and their collaborators (Mintz et al., 1995; Reiff et al., 1995; USA CDC, 2001). The key findings and recommendations of their investigations and experiences are summarized in Table 2.

Table 2. Alternative Household Water Storage Vessels: Advantages and Disadvantages of Different Designs and Materials

Type of Vessel	Protected Opening for Filling and Cleaning	Size or Volume	Material/ Cleanability/ Composition Compatible with Use	Protected Dispenser (Spigot, Spout, etc.)	Shape/Weight/ Portability
Pot, Jug or Urn	Varies; some yes, some no	Varies; usually 4-40L	Varies/ Varies/Varies	No, often; Yes, some	Varies/Varies/ Moderate-High
Bucket	No	Varies:	Plastic or Metal/High/	No	Cylindrical/Light/ Moderate-

		usually 4-40L	Varies		High
Cooking Pot	Yes (lid) No (no lid)	Varies; usually 4-20L	Metal or Clay/High/High	No	Cylindrical/Varies/Moderate-High
Gourd (Calabash)	Yes	Varies, usually 1-10 liters	Plant fruit/moderate/moderate	Yes, usually	Globular or elliptical, with a curved neck
Flexible Bags, Flagons, etc.	Yes	Varies; typically 1-10L	Animal hide or bladder; canvas, rubber, plastic, etc./Varies/ Varies	Yes	Elliptical, oval or rectangular/Light/High
Storage Drum or Barrel	No	Varies, often 200 L (55 gal.)	Metal/Moderate/High	No	Cylindrical/Heavy/Low
Cistern or Basin	No, typically	Varies; often large (>200L)	Varies: concrete, metal, clay/Low-moderate/High	Often No	Cylindrical; Rectangular/ Heavy/Low
Plastic Beverage Bottle	Yes, if cap is available	Usually 1-2 L	Plastic/High-Moderate/Varies by type of plastic and use conditions	Yes, narrow mouth	Cylindrical/Light/ High
Jerry Can	Yes	Usually 4-40 L	Metal; Plastic/Medium/varies	Yes, narrow mouth	Rectangular/Light/High
CDC Vessel	Yes	20L	Plastic/High/ High for chlorination Treatment; low for solar Treatment	Yes, spigot	Rectangular/Light/High
Oxfam Vessel[a]	Yes	14L	Plastic/High/ High for chlorination Treatment; low for solar Treatment	Yes, spigot	Cylindrical/Light/High

[a] Oxfam vessel is used primarily for emergency water storage and delivery. But, vessels of similar size and shape have been used for household water collection and storage worldwide.

The most desirable water storage vessels for many household treatment and storage options are: (1) between 10-25 liters capacity, rectangular or cylindrical with one or more handles and flat bottoms for portability and ease of storage, (2) made of lightweight, oxidation-resistant plastic, such as high-density polyethylene or polypropylene, for durability and shock resistance, (3) fitted with a 6-9 cm screw-cap opening to facilitate cleaning, but small enough to discourage or prevent the introduction of hands or dipping utensils, (4) fitted with a durable, protected and easily closed spigot or spout for dispensing water, and (5) provided with pictorial and/or written instructions for use affixed permanently to the container, as well as an affixed certificate of approval or authenticity. The cost of water storage vessels is also an important consideration, as they must be affordable or be subsidized. Locally available buckets, pots, urns, jerry cans, barrels, used beverage containers and flexible bags and flagons are usually low in cost and readily available. However, only some of these, in particular jerry cans, some plastic beverage containers, some urns and some flexible vessels, have properties and characteristics that are preferred or desirable as readily transported water storage vessels. Others, such as some buckets, cooking pots, some plastic beverage containers and other cylindrical vessels are less desirable for household water storage, but may be suitable for water collection and transport, especially if they are lightweight, have protective lids and are composed of easily cleaned materials (e.g., plastics).

Another consideration of household water storage vessels is their compatibility with household water treatment methods. In some cases, water treatment takes place in the collection and storage vessel or the treated water is delivered to the storage vessel. The design and composition of the vessel should be compatible with these tasks and also protect water quality. In some household water treatment systems, multiple containers are needed, for example, one for raw, untreated water and another for treated water. The materials of which the vessel is composed must be compatible with the physical and chemical agents used for water treatment. In the case of treatment chemicals, such as oxidant disinfectants (e.g., chlorine), the vessel must not exert excessive oxidant demand or result in chemical reactions forming excessive concentrations of toxic disinfection by-products. In the case of solar or heat treatments, the vessel must be capable of withstanding high temperatures, and depending on the type of solar treatment, they must allow the penetration of UV radiation and/or the absorption of heat energy.

Overall, the properties of household water collection, treatment and storage vessels must be compatible with the intended uses (collection, treatment and storage), meet the daily water volume needs of the household, be practical and manageable for the users (women, men or children) and be socio-culturally acceptable.

2.3. Water Treatment Methods - Overview and Historical Perspective

The various physical and chemical methods for water treatment at the household level or point-of-use are summarized in Tables 3 and 4, respectively. These methods are listed along with categorizations (listed as high medium and low) of their availability and practicality, technical difficulty, cost and microbial efficacy. Availability, practicality and technical difficulty are considered on a worldwide basis, including availability, practicality and technical difficulty for use at the household level. Cost is categorized as low, medium and high on a worldwide basis including the poorest people. Categories for annual household cost estimates in US dollars are less than \$10 for low, >\$10-100 for moderate and >\$100 for high. Clearly, these cost categories will be different for different economic situations in different regions and countries of the world. The categories for microbial efficacy are based on estimated order-of-magnitude or $\log_{10}$ reductions of waterborne microbes by the treatment technology. The categories are <1 $\log_{10}$ (<90%) is low, 1 to 2 $\log_{10}$ (90-99%) is moderate and >2 $\log_{10}$ (>99% is high). The values of these categories also may differ in different situations and settings, but they are intended to distinguish among the various water treatment technologies available for use at the household level. On this basis, clear differences are discernable in the available candidate technologies for household water treatment.

Most of the methods or processes to purify water and make it safe for drinking and other potable purposes can be historically traced to ancient versions of them used since recorded history (Baker, 1948; Jahn, 1980). The practice of many of these water purification methods since ancient times has been documented by pictorial, written and archaeological records from a variety of original sources and recounted by scholars and historians of water treatment and water quality (Baker, 1948). Although the ancients may not have been aware of how such treatments improved the microbiological quality of water, they apparently were aware of and appreciated the benefits of these methods in making the water more healthful by reducing disease and improving its aesthetic qualities. Recorded in ancient history are the physical methods of sedimentation, filtration, boiling or heating, and exposure to sunlight (UV irradiation and heating), and the chemical methods of coagulation or adsorption with alum, lime, and plant extracts, adsorption with carbon (charcoal), clay and plant materials, and exposure to germicidal metals such as silver and copper. However, the development and use of chlorine and other chemical oxidants, such as ozone and chlorine dioxide, for water disinfection are more recent developments, dating back only to the mid-nineteenth century or later, when modern chemistry emerged as a science. Two of the earliest methods of generating chlorine, electrolyzing brine (NaCl) to produce sodium hypochlorite and reacting lime with chlorine gas to produce bleaching powder (calcium hypochlorite), are still widely used today. They are the basis for some of the most promising systems to produce chlorine for water treatment at the household level.

Most of the physical and chemical methods for on-site or point-of-use treatment of household water in developing countries are also employed in developed countries, either at point-of-use or in community (municipal) water treatment systems, using the same or similar technologies (AWWA, 1999; LeChevallier and Au, 2000). In developed countries, a number of point-of-use treatment technologies not widely employed in community water systems also have been employed, including various filters, adsorbents, ion exchange resins and softeners (Geldreich and Reasoner, 1990). Key differences in the application of these technologies in developing countries compared to developed countries are in the availability and affordability of the materials and the need to adapt the technologies to local conditions and personal or community preferences. Furthermore, point-of-use or point-of-entry treatment devices or systems in developed countries are often being applied to waters already subjected to extensive treatment, including disinfection, or withdrawn from high quality water sources. Hence, such waters are already likely to be relatively safe or low risk with respect to microbial quality and waterborne disease risks without point-of-use or point-of-entry treatment. In many developing countries as well as in many settings in developed countries, point-of-use, point-of-entry and household treatment often must be applied to water that is microbiologically contaminated. Therefore, the treatment requirements to achieve acceptable microbiological quality can be substantial and only some technologies or unit process will be capable of meeting this objective.

Table 3. Physical Methods for Water Treatment at the Household Level

Method	**Availability and Practicality**	**Technical Difficulty**	**Cost**[a]	**Microbial Efficacy**[b]
Boiling or heating with fuels	Varies[c]	Low-Moderate	Varies[c]	High
Exposure to Sunlight	High	Low-Moderate	Low	Moderate

UV Irradiation (lamps)	Varies[d]	Low-moderate	Moderate-high[d]	High
Plain Sedimentation	High	Low	Low	Low
Filtration[e]	Varies[e]	Low-Moderate	Varies[e]	Varies[f]
Aeration	Moderate	Low	Low	Low[g]

[a] Categories for annual household cost estimates in US dollars are less than \$10 for low, >\$10-100 for moderate and >\$100 for high.

[b] Categories for microbial efficacy are based on estimated order-of-magnitude or $\log_{10}$ reductions of waterborne microbes by the treatment technology. The categories are <1 $\log_{10}$ (<90%) is low, 1 to 2 $\log_{10}$ (90-99%) is moderate and >2 $\log_{10}$ (>99% is high).

[c] Depends on heating method as well as availability and cost of fuels, which range from low to high.

[d] Depends on availability of and type of lamps, housings, availability and cost of electricity, as well as operation and maintenance needs (pumps and system cleaning methods).

[e] Different filtration technologies are available. Some (e.g., membrane filtration) are recommended for emergency water treatment. Practicality, availability, cost and microbial efficacy depend on the filter medium and its availability: granular, ceramic, fabric, etc.

[f] Depends on pore size and other properties of the filter medium, which vary widely. Some are highly efficient (>>99% or >>2 $\log_{10}$) for microbial removals.

[g] Aeration (oxygenation) may have synergistic effects with other water treatments, such as solar disinfection with sunlight or with other processes that may oxidize molecular oxygen.

Table 4. Chemical or Physical-Chemical Methods for Water Treatment at the Household Level

Method	**Availability and Practicality**	**Technical Difficulty**	**Cost[a]**	**Microbial Efficacy[b]**
Coagulation-Flocculation or Precipitation	Moderate	Moderate	Varies	Varies[c]
Adsorption (charcoal, carbon, clay, etc.)	High to moderate	Low to moderate	Varies	Varies with adsorbent[d]
Ion exchange	Low to Moderate	Moderate to high	Usually High	Low or moderate
Chlorination	High to Moderate	Low to Moderate	Moderate	High
Ozonation	Low	High	High	High
Chlorine Dioxide	Low	Varies[e]	High	High

Iodination (elemental, salt or resin)	Low	Moderate to High	High	High
Acid or base treatment with citrus juice, hydroxide salts, etc.	High	Low	Varies	Varies
Silver or Copper	High	Low	Low	Low
Combined systems: chemical coagulation-flocculation, filtration, chemical disinfection	Low to Moderate	Moderate to High	High	High

[a] See footnote to Table 3.

[b] See footnote to Table 3

[c] Varies with coagulant, dose, mixing and settling conditions and pH range.

[d] Microbial adsorption efficiency is low for charcoal and carbon and high for some clays.

[e] On-site generation of gas is difficult but chemical production by acidifying chlorate or chlorite is simple if measuring devices and instructions are provided.

3. Heat and UV Radiation

Overall, the results of both microbiological and epidemiological indicate that solar disinfection of household water has the ability to appreciably improve its microbial quality and to reduce household diarrheal disease of consumers. Additional epidemiological studies to better document the extent of diarrheal disease reduction are recommended because available studies are limited to only one geographic region, Kenya, and study population, Maasai children. Apparently, additional epidemiological studies are now in progress (Mintz et al., 2001). Because of its simplicity, low cost, and the need for only beverage bottles and sunlight, solar disinfection is an appropriate technology for disinfection of household water in the developing world.

The UV radiation technology is simple to use and highly effective for inactivating microbes in drinking water, and it does not introduce chemicals or cause the production of harmful disinfection by-products in the water. While UV lamp disinfection systems have been widely used to disinfect drinking water at the community and household levels, no epidemiological studies of intervention type that document health impacts at the household level have been reported for this technology. There are no reasons to doubt the efficacy of sound UV lamp disinfection technology to adequately disinfect either household or community drinking water when properly applied. However, field studies documenting the ability of this technology to disinfect household drinking water and reduce diarrhea and other waterborne diseases are recommended. Such studies would validate the expected performance of this technology and provide further evidence that the technology is reliable and capable of being used successfully by individuals and communities. Such documentation is needed because UV lamp disinfection has some disadvantages for use as a drinking water disinfectant at the household level. It does not provide a chemical disinfectant residual to protect the water from recontamination or microbial regrowth after treatment. Particulates, turbidity and certain dissolved constituents can interfere with or reduce microbial inactivation efficiency. A reliable and affordable source of electricity is required to power the UV lamps. The UV lamps require periodic cleaning, especially for systems using submerged lamps, and they have a finite lifespan and must be periodically replaced. The technology is of moderate to high cost when used at the household level. Despite these drawback and limitations, UV irradiation with lamps is a recommended technology for disinfection of household and community water.

3.1. Boiling or heating with fuel

Boiling or heating of water with fuel has been used to disinfect household water since ancient times. It is effective in destroying all classes of waterborne pathogens (viruses, bacteria and bacterial spores, fungi and protozoans and helminth ova) and can be effectively applied to all waters, including those high in turbidity or dissolved constituents. Although some authorities recommend that water be brought to a rolling boil for to 1 to 5 minutes, the WHO GDWQ recommend bringing the water to a rolling boil as an indication that a high temperature has been achieved. These boiling requirements are likely to be well in excess of the heating conditions needed to dramatically reduce most waterborne pathogens, but observing a rolling boil assures that sufficiently high temperatures have been reached to achieve pathogen destruction.

Although boiling is the preferred thermal treatment for contaminated water, heating to pasteurization temperatures (generally ≥60°C) for periods of minutes to tens of minutes will destroy most waterborne pathogens of concern. Even heating to as little as 55°C for several hours has been shown to dramatically reduce non-sporeforming bacterial pathogens as well as many viruses and parasites, including the waterborne protozoans *Cryptosporidium parvum, Giardia lamblia* and *Entamoeba histolytica* (Feachem et al., 1983; Sobsey and Leland, 2001). In many situations, however, it is not possible to monitor the temperature of the water with a thermometer or other temperature sensor such as a melting wax visual indicator system. Unless such temperature monitoring is possible, caution is recommended in attempting to pasteurize waters at non-boiling temperatures.

It is also recommended that the water is stored in the same container in which it has been boiled or heated, preferably one with a lid or other protected opening, in order to reduce opportunities for recontamination. It is further recommended that boiled or heat-treated water be consumed soon after it has cooled and preferably within the same day. This is because of the potential for microbial recontamination during prolonged storage. Introduction of microbes from hands, utensils and other sources is a major concern. A major disadvantage of boiling is its consumption of energy in relation to the availability, cost and sustainability of fuel. It is estimated that 1 kilogram of wood is needed to boil 1 liter of water. In areas of the world where wood, other biomass fuels or fossil fuels are in limited supply and must be purchased, the costs of boiling water are prohibitive. Therefore, boiling household water is unrealistic and inaccessible for many of the world's poorest people due to the scarcity and high cost of fuels and the lack of sustainability of biomass or fossil fuels in the community or region. In some areas of the world the use of wood and wood-derived fuels is also a concern because it contributes to the loss of woodlands and the accompanying ecological damage caused by deforestation. However, where affordable and sustainable sources of fuel are available without causing environmental degradation, heating household water to a rolling boil is an effective and accessible method of treatment for collected household water.

3.2. Thermal Treatment with Solar Radiation and Solar Cooking

Although boiling with fuel may be a prohibitive option for household treatment of water, heating water, other liquids and other foods to lower temperatures using solar radiation is a more accessible, economical and technologically feasible option than heating with fuel. Treatment of water with solar radiation was practiced in ancient India more than 2000 B.C.E. The ability of solar radiation to disinfect has been recognized in modern times at least since studies at by Acra at al. (1984) at The American University of Beirut, Lebanon. Since then, it has been shown that water can be heated to temperatures of ≥55°C in transparent bottles (e.g., clear plastic beverage bottles) exposed to sunlight for several hours, especially if the bottle is painted black on one side or is lying on a dark surface that collects and radiates heat (Wegelin et al., 1994; Joyce et al., 1996). This method of treatment utilizes both the UV radiation in sunlight as well as the thermal effects of sunlight to inactivate waterborne microbes, and will be discussed in detail in the next section of this report. Alternatively, if the exterior of the vessel is completely black or similarly capable of absorbing heat (e.g., most metal containers), only thermal effects occur and temperatures can reach >60°C. At these temperatures, water and other liquids can be pasteurized because most enteric viruses, bacteria and parasites are rapidly inactivated (Ciochetti and Metcalf, 1984). Furthermore, if a dark, opaque container is more highly exposed to solar radiation using a solar reflector or solar cooker, the water temperature can reach ≥65°C, a pasteurization temperature capable of inactivating nearly all enteric pathogens within several tens of minutes to hours (Safapour and Metcalf, 1999).

In those parts of the world where solar cooking already is available and widely practiced, solar pasteurization of water, other beverages and weanling foods is a practical, accessible and affordable option for household water treatment. Low cost solar reflectors or cookers can be made from materials as simple and economical as cardboard and aluminum foil. This technology for water treatment and food preparation has been field tested in many parts of the world, including Kenya, Tanzania, Ethiopia, Vietnam and some countries in the Americas. A major limitation of solar heating is that only small volumes (≤ 10 liters) of water can be exposed conveniently at one time per water container and solar reflector. However, using multiple water containers and alternative solar collectors (e.g., metal roofing material), the volume of water treatable with solar heat at one time can be substantially increased. Another important limitation of solar heating is the availability of sunlight, which varies greatly with season, daily weather (meteorological) conditions and geographic location. However, in many regions of the developing world, sunlight conditions are suitable for solar heating of water and for cooking nearly all year long on full sun or part sun days (approximately 200-300 days per year). A third potential limitation of solar heating to disinfect water is the determination of water temperature. Thermometers are relatively expensive and may not be available or affordable in many regions of the developing world. However, several simple, low cost temperature indicators have been devised. One of the simplest and most effective is a reusable water pasteurization indicator (WAPI) based on the melting temperature of soybean wax. The WAPI consists of a clear plastic tube partially filled with a soybean wax that melts at about 70°C and a piece of nylon (e.g., fish) line attached on each end to stainless steel washers. The WAPI is placed in the water to be heated with the wax at the top of the tube. When the wax reaches 70°C, it melts and falls to the bottom of the tube, thereby giving a simple visual indication of when pasteurization conditions have been achieved. Similar wax indicators have been devised for other target melting temperatures, depending on the type of wax.

3.3. Solar treatment by combined UV and thermal effects

Treatment to control waterborne microbial contaminants by exposure to sunlight in clear vessels that allows the combined germicidal effects of both UV radiation and heat also has been developed, evaluated and put into field practice (Acra et al., 1984; Conroy et al., 1996; 1996; 1999; Joyce et al., 1996; McGuigugan et al., 1998; 1999; Sommer et al., 1997; Wegelin and Sommer, 1998; Wegelin et al., 1994). A number of different solar treatment systems have been described, but one of the technically simplest and most practical and economical is the SODIS system developed by scientists at the Swiss Federal Agency for Environmental Science and Technology (EAWAG) and its many collaborators and partners. The SODIS system consists of three basic steps: (1) removing solids from highly turbid (>30 NTU) water by settling or filtration, if necessary, (2) placing low turbidity (<30 NTU) water in clear plastic bottles of 1-2 liter volume (usually discarded beverage bottles and preferably painted black on one side), and (3) aerating (oxygenating) the water by vigorous shaking in contact with air, and (4) exposing the filled, aerated bottles to full sunlight for about 5 hours (or longer if only part sunlight). The water is exposed to UV radiation in sunlight, primarily UV-A and it becomes heated; both effects contribute to the inactivation of waterborne microbes. The system is suitable for treating small volumes of water (<10L), especially if the water has relatively low turbidity (<30 NTU). Clear plastic bottles are considered preferable by some workers over glass because they are lighter, less likely to break, and less costly. Bottles made of polyethylene terephthlate (PET) are preferred to those made of polyvinylchloride (PVC), other plastics and most types of glass because they are less likely to leach harmful constituents into the water. In addition, they are lightweight, relatively unbreakable, chemically stable and not likely to impart tastes and odors to the water. PET bottles require period replacement because they can be scratched and they become deformed if temperatures exceed 65°C. The use of an internal temperature sensor is encouraged as an aid to determining if a minimum target temperature of 50°C and preferably 55°C or higher is reached. The reusable sensor contains paraffin wax attached to a screw weight. When the paraffin melts, the weight drops to indicate that the target temperature has been attained.

The effects of several factors influencing microbial inactivation by solar disinfection are summarized in Table 5 below. Microbial inactivation by the SODIS system is attributed to the combined effects of UV radiation in the UV-A range (320 to 400 nm), which is somewhat germicidal, and heating to temperatures of 50-60°C, which are high enough to extensively (≥99.9%) inactivate many enteric viruses, bacteria and parasites in about 1 hour to several hours. It has been reported that the combined exposure to UV plus heat in the SODIS process has a synergistic effect on microbial inactivation, producing greater inactivation than predicted by comparable levels of exposure to either one of the two agents alone. During the exposure period, UV dose increases to ≥100 Wh/m^2 and the water temperature reaches 55°C or even higher. However, others report that even non-UV transmissible sunlight when used to heat water to 60°C in a commercial solar panel system, will inactivate enteric bacteria, spores and viruses (Rijal and Fujioka, 2001). When treated with heat and no UV or heat with UV for 2-5 hours, fecal coliforms, *E. coli,* enterococci, HPC bacteria and coliphage MS2 were reduced by >3 log_{10} and *Clostridium perfringens* spores were 1-2 and nearly 3 log_{10}, respectively. Under cloudy conditions bacterial and spore reductions were much lower, they were lower with heat-no UV than with heat plus UV and temperatures did not reach 50°C. Therefore, achieving a sufficiently high temperature (preferably 55°C or higher for several hours) is an important factor for microbial inactivation by solar disinfection systems. Overall, studies have shown that various bacteria, such as fecal coliforms, *E. coli* and enterococci, and viruses, such as coliphage f2, rotavirus and encephalomyocarditis (EMC) virus, in water bottles are reduced extensively (by several orders of magnitude) when exposed to sunlight for periods of several hours and sufficiently high temperatures are achieved.

Studies also show that dissolved oxygen in the water contributes to bacterial inactivation, with much greater reductions of *E. coli* and enterococci after 3 hours in oxygenated water (~6 log_{10}) than in anaerobic water (<2 and <1 log_{10}, respectively) (Reed, 1996). In subsequent studies total and fecal coliforms were inactivated by >3 log_{10} in 6 and 4 hours, respectively, in aerated water and by ≤1.5 log_{10} in anoxic water or water kept from sunlight (indoors) (Meyer and Reed, 2001). Therefore, aeration of the water by mechanical mixing or agitation is recommended before solar treatment in bottles. The combined process of oxygenation (aeration) by mixing, followed by solar radiation exposure for several hours in a clear plastic bottle is also referred to as solar photooxidative disinfection of SOLAR. Enteric bacteria inactivated by the SOLAR or SODIS process do not appear to regrow or recover their infectivity.

Table 5. Factors Influencing Microbial Inactivation by Solar Disinfection of Water

Factor	**Influences on Microbial Inactivation**
Type of microbe	Microbes differ in sensitivity to inactivation be heat and by UV radiation. Heat is more effective against vegetative bacteria, viruses and protozoans than against bacteria spores and helminth ova. UV radiation is more effective against vegetative bacteria and protozoans than against viruses and bacteria spores.
Water Vessel	Type, composition, volume, and depth influence water temperature, UV penetration of water, cleanability and portability; PET or other UV-penetrating bottles for SODIS system; black or opaque bottles for solar cooker of reflector system
Sunlight; ambient temperature	Sunlight intensity, duration, and cloudiness influence water temperature and UV penetration; ambient temperature influences internal temperature within water vessel. Achieving water temperatures of 55°C or higher for periods of several hours is recommended for inactivation of most enteric pathogens
Vessel placement and orientation	Exposure to full sun without shade (from trees and other objects); influences water temperature and UV exposure; horizontal instead of vertical placement of cylindrical bottles to imp rove UV penetration
Mixing or movement of vessel	To provide more uniform water exposure to sunlight and minimize differences in sunlight (UV) dosimetry
Solar collection or reflection	Solar collection (on dark surfaces) or reflection (by shiny surfaces of reflector panels or cookers) influence water temperature and UV exposure
Water quality	UV exposure (UV scattering by particles and absorption by solutes and particles); microbial protection by solids-association
Water Aeration (oxygenation)	Increased oxygen content of the water by agitating (shaking) for several minutes in contact with air prior to sunlight exposure increases microbial inactivation when sunlight is allowed to

	penetrate water in clear bottles (SOLAIR or SODIS processes)
Exposure time	Water temperature and duration of exposure to elevated temperature; cumulative UV dose. Typically several hours with full sunlight and as long as two days with partial sunlight

3.4. Advantages, disadvantages and limitations of solar treatment systems

The advantages of disadvantages of solar treatment systems are summarized in Table 6 below. Potential limitations of this and perhaps other solar disinfection systems are: the availability of suitable water containers and other needed materials, lack of sunlight for disinfection, potential difficulties in treating highly turbid water and the availability of simple methods for reducing the turbidity of water before solar treatment, lack of a residual disinfectant to protect water during handling and storage, potential user objections to the technology due to the length of time to treat the water (several hours or longer) and possible objectionable tastes and odors leached into the water from the plastic bottles. Despite these limitations, solar disinfection in clear plastic bottles is one of the most promising and extensively tested methods for disinfection of household water stored in a container.

Table 6. Advantages and Disadvantages of Solar Treatment Systems

Advantages	**Disadvantages**	**Comments**
Microbial inactivation by pasteurization (temperatures of 55°C or higher for several hours are recommended).	Often requires several hours to disinfect and even longer (2 days) if cloudy weather; more heat-resistant pathogens inactivated only slowly (rotavirus) or not at all (e.g., hepatitis A virus and bacterial spores).	Time to inactivate varies with system (UV+heat) or (heat only) and sunlight conditions; requires a system to indicate that target temperature has been reached (thermometer, melting wax indicator or other thermal indicator).
Simple, low cost use of small vessels (PET plastic for SODIS and black or opaque bottles for solar reflection or cooking system); maybe other bottles or vessels, too.	Limited to volumes of 1 - several liters per bottle; using 1.5-L bottles (optimum size), several bottles are needed per household per day.	Availability of sufficient number of suitable bottles, depending on type of solar treatment (simple sunlight exposure vs. solar collectors or cookers) and geographic location.
Does not change the chemical quality of the water.	Provides no chemical disinfectant residual; water must be consumed within a day or so, or else microbial regrowth can occur.	Leaching of chemicals possible from some plastic bottles, causing objectionable tastes and odors; periodic bottle replacement needed; periodic bottle cleaning to avoid development of biofilms.
SODIS (heat + UV) system effective in water with low to moderate turbidity (<30 NTU).	High turbidity interferes with microbial inactivation; requires turbidity reduction by sedimentation, filtration	Requires clear bottles allowing penetration of UV radiation (preferred plastic is polyethylene terephtalate or

	or other methods.	PET); some bottles do not allow UV to penetrate.
Apparent synergistic effects of heat and UV in the SODIS (UV+heat) system	Requires low (<30 NTU) turbidity water; requires at least several clear plastic bottles and an opaque or black surface on a side of the bottle or on surface on which bottle rests to expose to sunlight	Evidence of synergistic effects documented for vegetative bacteria but it has not been studied for viruses or parasites
Improved bacterial inactivation in aerobic water by SODIS system	Requires pre-aeration (e.g., mechanical mixing) to create aerobic conditions; effect may not occur in water with reducing agents (e.g., sulfides)	Inactivation of *E. coli* >10,000-fold higher in aerobic water (99.9999% reduction) than in anaerobic water (90-99%); effect has not been studied for viruses or parasites
Opaque or black bottle system achieves temperatures high enough to inactivate viruses and is less affected by turbidity or UV-absorbing solutes	System requires solar collector or cooker to deliver sufficient solar energy; small volume of water vessels; poor inactivation on cloudy days	Solar cooker system gives virus inactivation of 99.99% in 1.5 hours in a 1.4-L black bottle and 99% inactivation in 3 hours in a 3.8-L black bottle. Virus inactivation only 90% in 3 hours using a simple 2-sided solar reflector and <30% using no solar reflector.

In addition to the essential technical components, the SODIS system for drinking water disinfection also includes important educational, socio-cultural, behavioral and motivational components, such as education and training, behavior modification and motivational training. SODIS has been field-tested in many different parts of the world and in many countries, including South America (Colombia and Bolivia), Africa (Burkino Faso and Togo), Asia (China) and Southeast Asia (Indonesia and Thailand). It has been introduced and disseminated by both governments and NGOs and subjected to economic analysis based on actual costs (estimated at 3 US$ per year for a household of 5 people) for willingness to pay. Acceptance rates, based on willingness to continue use after its introduction as a demonstration project, is reported at to be >80%. However, when introduction was not adequately supported by community involvement activities to address educational, socio-cultural, behavioral and motivational issues, community support for continued use was lower.

3.5. Epidemiological Studies of Solar Disinfection of Household Water

The SODIS system has not been extensively tested for reduction in waterborne disease in epidemiological studies of the intervention type. However, as shown in Table 7, three reported studies found measurable reductions in diarrheal disease and cholera in Maasai (Kenyan) children drinking solar disinfected water (several hours of full sunlight) compared to children drinking undisinfected water (kept indoors) in the same plastic bottles (Conroy et al., 1996; 1999; 2001). While it is clear from these intervention studies that reductions in diarrheal disease and cholera by solar disinfection in bottles are achieved in children under 6 years of age, more studies of this type are needed. This is because it is important to determine the extent of reduction of diarrheal and other waterborne disease by this system in different geographic locations having different water quality conditions and different populations at risk. The measurement of the microbial quality of the water used by intervention and control groups also would be desirable to further document the efficacy of the solar disinfection system. While there are reliable laboratory and field data from studies documenting the inactivation of waterborne microbes by solar disinfection systems, such documentation has not been included in the epidemiological studies reported to date. Therefore, the extent of pathogen or microbial indicator reduction in waters used by those consuming the water and being monitored for diarrheal and other enteric disease is not known.

Table 7. Epidemiological Studies on Diarrheal Disease Reduction by the SODIS Solar Disinfection System of Household Water

Location	Water	Treatment	% Reduction in Disease	Significant Microbial Reduction?	Reference
Kenya	Household	Solar Disinfection	86%	Not Reported	Conroy et al., 2001
Kenya	Household	Solar Disinfection	16%, diarrhea	Not Reported	Conroy et al., 1999
Kenya	Household	Solar Disinfection	9[a]/26[b], diarrhea	Not Reported	Conroy et al., 1996

[a] Total diarrheal disease
[b] Severe diarrheal disease

3.6. UV Irradiation with Lamp Systems

The germicidal activity of ultraviolet radiation from lamps was recognized in the late 1800s and disinfection of drinking water and other media with UV lamps has been practiced since the early part of the 20th century (Baker 1948, Blatchley and Peel, 2001; 1948; Sobsey, 1989; Ward, 1893). This method of drinking water disinfection has received renewed interest in recent years because of its well-documented ability to extensively (>99.9%) inactivate two waterborne, chlorine-resistant protozoans, *Cryptosporidium parvum* oocysts and *Giardia lamblia* cysts, at relatively low doses (<10 mJ/cm^2).

UV disinfection is usually accomplished with mercury arc lamps containing elemental mercury and an inert gas, such as argon, in a UV-transmitting tube, usually quartz. Traditionally, most mercury arc UV lamps have been the so-called "low pressure" type, because they operate at relatively low partial pressure of mercury, low overall vapor pressure (about 2 mbar), low external temperature (50-100°C) and low power. These lamps omit nearly monochromatic UV radiation at a wavelength of 254 run, which is in the optimum range for UV energy absorption by nucleic acids (about 240-280 nm). In recent years medium pressure UV lamps that operate at much higher pressures, temperatures and power levels and emit a broad spectrum of higher UV energy between 200 and 320 nm have become commercially available. However, for UV disinfection of drinking water at the household level, the low-pressure lamps and systems are entirely adequate and even preferred to medium pressure lamps and systems. This is because they operate at lower power, lower temperature, and lower cost while being highly effective in disinfecting more than enough water for daily household use. An essential requirement for UV disinfection with lamp systems is an available and reliable source of electricity. While the power requirements of low-pressure mercury UV lamp disinfection systems are modest, they are essential for lamp operation to disinfect water.

3.7. UV Inactivation of microbes in water

At sufficiently high doses, all waterborne enteric pathogens are inactivated by UV radiation. The general order of microbial resistance (from least to most) and corresponding UV doses for extensive (>99.9%) inactivation are: vegetative bacteria and the protozoan parasites *Cryptosporidium parvum* and *Giardia lamblia* at low doses (1-10 mJ/cm^2) and enteric viruses and bacterial spores at high doses (30-150 mJ/cm^2). Most low-pressure mercury lamp UV disinfection systems can readily achieve UV radiation doses of 50-150 mJ/cm^2 in high quality water, and therefore efficiently disinfect essentially all waterborne pathogens. However, dissolved organic matter, such as natural organic matter, certain inorganic solutes, such as iron, sulfites and nitrites, and suspended matter (particulates or turbidity) will absorb UV radiation or shield microbes from UV radiation, resulting in lower delivered UV doses and reduced microbial disinfection. Another concern about disinfecting microbes with lower doses of UV radiation is the ability of bacteria and other cellular microbes to repair UV-induced damage and restore infectivity, a phenomenon known as reactivation. UV inactivates microbes primarily by chemically altering nucleic acids (pyrimidine dimers and other alterations). However, the UV-induced chemical lesions can be repaired by cellular enzymatic mechanisms, some of which are independent of light (dark repair) and others of which require visible light (photorepair or photoreactivation). Therefore, achieving optimum UV disinfection of water requires delivering a sufficient UV dose to induce greater levels of nucleic acid damage and thereby overcome or overwhelm DNA repair mechanisms.

3.8. UV disinfection systems using lamps

Two alternative configurations or physical systems are used for UV disinfection of small or household water supplies, submerged lamps or lamps in air and mounted above a thin layer of the water to be irradiated. In the units with submerged lamps, the lamps are covered with a protective, UV-penetrable as protection from the electrical hazards associated with water. Water can be treated on a batch basis by placing the lamp in a container of water for several minutes or longer, or on a flow-through basis in a housing or channel, with the water flowing parallel or perpendicular to the lamp(s). In units having the lamps mounted in the air, the UV lamps are in a metal housing with reflective surfaces that direct the UV radiation downward onto a thin layer of water flowing through a channel or tray below the lamps. The advantage of the submerged systems is intimate lamp contact with the water, water-mediated cooling of the lamps, and the use of housing designs that maximize UV exposure of the water. However, the protective sleeves over the lamps must be mechanically or chemically cleaned on a regular basis to overcome fouling by a physical, chemical or biological film that can forms on the sleeve surface, reducing UV passage into the water. The non-submerged, in-air lamp units have the advantage of no need for lamp cleaning due to lamp fouling, but there is some loss of UV radiation due atmospheric and surface absorption. However, both types of UV disinfection system designs are available for disinfection of household water at point-of-use, point-of-entry or at the community level.

UV disinfection with lamps has the advantages of being effective for inactivating waterborne pathogens, simple to apply at the household and community levels, and relatively low cost, while not requiring the use of chemicals or creating tastes, odors or toxic chemical by-products. The disadvantages of UV disinfection with lamps are the need for a source of lamps, which have to be replaced periodically (typically every year or two), the need for a reliable source of electricity to power the lamps, the need for period cleaning of the lamp sleeve surface to remove deposits and maintain UV transmission, especially for the submerged lamps, and the uncertainty of the magnitude of UV dose delivered to the water, unless a UV sensor is used to monitor the process. In addition, UV provides no residual chemical disinfectant in the water to protect against post-treatment contamination, and therefore care must be taken to protect UV-disinfected water from post-treatment contamination, including bacterial regrowth or reactivation.

3.9. Costs of UV disinfection for household water

Because the energy requirements are relatively low (several tens of watts per unit or about the same as an incandescent lamp), UV disinfection units for water treatment can be powered at relatively low cost using solar panels, wind power generators as well as conventional energy sources. The energy costs of UV disinfection are considerably less than the costs of disinfecting water by boiling it with fuels such as wood or charcoal.

UV units to treat small batches (1 to several liters) or low flows (1 to several liters per minute) of water at the community level are estimated to have costs of 0.02 US$ per 1000 liters of water, including the cost of electricity and consumables and the annualized capital cost of the unit. On this basis, the annual costs of community UV treatment would be less than US$1.00 per household. However, if UV lamp disinfection units were used at the household level, and therefore by far fewer people per unit, annual costs would be considerably higher, probably in the range of $US10-100 per year. Despite the higher costs, UV irradiation with lamps is considered a feasible technology for household water treatment.

4. Physical Removal Processes: Sedimentation and Filtration

4.1. Microbe size and physical removal from water

Microbes and other colloidal particles can be physically removed from water by various processes. The sizes of the microbes are especially important for their removal by sedimentation and filtration. Viruses are the smallest waterborne microbes (20 to about 100 nanometers in size) and the most difficult to remove by filtration and other size exclusion methods. Bacteria are somewhat larger than viruses (about 0.5 to 3 micrometers) but too small to be readily removed by plain sedimentation or settling. Protozoan parasites are the next largest in size (most are about 3 to 30 micrometers) and only the largest ones are likely to gravity settle at appreciable rates. Protozoan removal efficiency by filtration varies with parasite size and the effective pore size of the filter medium. Helminths are multicellular animals, but some are important waterborne pathogens because their eggs (ova) and waterborne larval stages can be waterborne. Most helminths of concern in water are large enough to gravity settle at appreciable rates; they are readily removable by settling and various filtration processes.

Although viruses, bacteria and the smaller protozoans are too small to gravity settle, these waterborne pathogens are often associated with larger particles or they are aggregated (clumped). Aggregated or particle-associated microbes are easier to remove by physical processes than the free or dispersed microbes. Consequently, observed reductions of waterborne microbes by physical removal processes are sometimes greater than expected or anticipated based strictly on their individual sizes. In some situations, efforts are made to promote the association of pathogens with larger particles, such as by coagulation-flocculation, to promote their physical removal. Such methods will be described in later sections of this report.

4.2. Plain sedimentation or settling

The microbial quality of water sometimes can be improved by holding or storing it undisturbed and without mixing long enough for larger particles to settle out or sediment by gravity. The settled water can then be carefully removed and recovered by decanting, ladling or other gentle methods that do not disturb the sedimented particles. Sedimentation has been practiced since ancient times using small water storage vessels or larger settling basins, reservoirs and storage tanks. The advantages and disadvantages of plain sedimentation for household treatment of water are summarized in Table 8.

Table 8. Advantages and Disadvantages of Plain Sedimentation for Household Water Treatment

Advantages	**Disadvantages**	**Comments**
Simple, low cost technology to reduce settable solids and perhaps some microbes for water	Only settable solids, such as sands, silts and larger microbes settle efficiently; clays and smaller microbes do not settle; only moderate to low microbe reductions	Can be applied to large and small volumes of water using commonly available water collection and storage vessels; settled material must be removed and vessels cleaned regularly
Removal of settable solids can reduce turbidities and make the water more amenable to other treatment methods to reduce microbes	In some waters solids are not efficiently removed by settling and alternative methods of removing solids are required	Reduced levels of solids (turbidity) improves penetration of UV radiation (from sunlight), decreases oxidant (e.g., chlorine) demand, decreases solids-associated pathogens
Recommended as a simple pre-treatment of household water prior to application of other treatments to reduce microbes	Unreliable method to reduce pathogens; solids are not efficiently removed by settling from some waters; can be labor-intensive	Pre-treatment to remove solids (turbidity) is recommended for turbid waters prior to solar or chemical disinfection

Storing water for as little as a few hours will sediment the large, dense particles, such as inorganic sands and silts, large microbes and any other microbes associated with larger, denser particles. However, clay particles and smaller microbes not associated with large or dense particles will not settle under these conditions. Longer settling times, such as overnight or for 1-2 days, will remove larger microbes, including helminth ova and some parasites, some nuisance microbes, such as certain algae, and the larger clay particles. Most viruses and bacteria and fine clay particles are too small to be settled out by simple gravity sedimentation. Therefore, microbial reductions by plain sedimentation or gravity settling are often low and inconsistent. Overall reductions of viruses and bacteria by sedimentation rarely exceed 90%, but reductions of helminth ova and some protozoans can exceed 90%, especially with longer storage times of 1-2 days.

Sedimentation of household water can be done in simple storage vessels, such as pots and buckets. Care must be taken to avoid disturbing the sedimented particles when recovering the supernatant water by decanting or other methods. Typically, at least two containers are needed to settle water: one to act as the settling vessel and another to be the recipient of the supernatant water after the settling period. Water also can be settled in larger bulk storage systems, such as cisterns, basins and tanks. Regardless of the sedimentation vessel, it is essential that solids are removed and the vessel cleaned on a regular basis. When water is sedimented in small collection or storage vessels, the sediment should be removed and the vessel cleaned after each use. At minimum, cleaning should be by rinsing with freshly collected source water. More rigorous physical or chemical cleaning is recommended to avoid the microbial colonization of the vessel surfaces and the resulting accumulation of a biofilm. For sedimentation in larger, stationary vessels and basins, such as cisterns and sedimentation tanks (some of which are designed to collect and store water for individual or small groups of households), protection of the water during storage, sanitary collection of the supernatant water after settling, and systems and procedures to clean the storage vessel also are critical.

Sedimentation often is effective in reducing water turbidity, but it is not consistently effective in reducing microbial contamination. However, turbidity reductions often improve microbial reductions by physical and chemical disinfection processes, such as solar treatment and chlorination, respectively. Hence, plain sedimentation or gravity settling of highly turbid water for household use is recommended as a pre-treatment for systems that disinfect water with solar radiation, chlorine or other chemical disinfectants. Furthermore, sedimentation of particles improves the aesthetic qualities of the water and thereby increases its acceptance by consumers. Pre-treatment of turbid household water by sedimentation is recommended because is easy to perform and requires a minimum of materials or skill. It can be done with as little as two or more vessels by manually transferring (e.g., pouring and decanting) the water. For turbid waters containing non-settable solids, sedimentation will be ineffective and alternative methods of particle removal, such a filtration, are needed.

4.3. Filtration

Filtration is another ancient and widely used technology that removes particles and at least some microbes from water. As shown in Table 9, a variety of filter media and filtration processes are available for household or point-of-use treatment of water. The practicality, ease of use, availability, accessibility and affordability of these filtration media and methods vary widely and often depend on local factors. The effectiveness of these filtration methods in reducing microbes also varies widely, depending on the type of microbe and the type and quality of the filtration medium or system.

Table 9. Filters and Filtration Media for Treatment of Household Water: Characteristics, Advantages and Disadvantage

Type Of Filtration	Media	Availability	Ease of Use	Effectiveness (comments)	Cost
Granular media, rapid rate depth filter	Sand, gravel, diatomaceous earth, coal, other minerals	High	Easy to Moderate	Moderate* (depends on microbe size and pre-treatment)	Low to moderate
Slow sand filter	Sand	High	Easy to moderate (community use)	High** in principle but often low in practice	Low to moderate
Vegetable and animal derived depth filters	Coal, sponge, charcoal, cotton, etc.	Medium to high	Moderate to Difficult	Moderate*	Low to moderate
Fabric, paper, membrane, canvas, etc. filter	Cloth, other woven fabric, synthetic polymers, wick siphons	Varies: some low; others high	Easy to moderate	Varies from high to low (with pore size and composition)	Varies: low for natural; high for synthetics
Ceramic and other porous cast filters	Clay, other minerals	Varies: high-low, with materials availability and fabrication skill	Moderate. Must be physically cleaned on a regular basis to prevent clogging and biofilm growth	Varies from high to low (with pore size and ceramic filter quality)	Moderate to high
Septum and body feed filters	Diatomaceous earth, other fine media	Varies	Moderate to difficult; dry media a respiratory hazard	Moderate	Varies

* Moderate typically means 90-99% reductions of larger pathogens (helminth ova and larger protozoans) and solids-associated pathogens, but low (<90%) reductions of viruses and free bacteria, assuming no pre-treatment. With pre-treatment (typically coagulation), pathogen reductions are typically >99% (high).

**High pathogen reduction means >99%.

4.4. Granular media, rapid rate filters and filter media

Filtration through porous granular media, typically sand or successive layers of anthracite coal and sand, is the most widely used physical method for water treatment at the community level, and it has been used extensively for on-site treatment of both community and household water since ancient times (Oza and Chaudhuri, 1975; Chaudhuri and Sattar, 1990; Logsdon, 1990; LeChevallier and Au, 2002). A number of different granular media filters for household and other small-scale uses have been described, including so-called bucket filters, drum or barrel filters, roughing filters in the form of one or more basins, and above or below grade cistern filters. Granular media used for water filtration include sand, anthracite, crushed sandstone or other soft rock and charcoal. In recent years, efforts have been made to improve the performance of granular filter media for removing microbial contaminants by coating or co-mingling sand, coal and other common negatively charged granular media with metal oxides and hydroxides of iron, aluminum, calcium or magnesium (Chaudhuri and Sattar, 1990; Chaudhuri and Sattar, 1986; Prasad and Chaudhuri, 1989). Such modified media are positively charged and therefore, more effective for removing and retaining the negatively charged viruses and bacteria by electrostatic adsorption (Chaudhuri and Sattar, 1986). Some improved granular media filter-adsorbers have incorporated bacteriostatic agents, such as silver, in order to prevent the development of undesirable biofilms that release excessive levels of bacteria into the product water (Ahammed and Chaudhuri, 1999). The production of these more advanced filter media containing charge-modified materials and bacteriostatic agents requires specialized skills and facilities, which are beyond the capabilities of most household users. Such media would have to be prepared and distributed to communities and households from specialized facilities. However, naturally occurring, positively charged granular media, such as naturally occurring iron oxide-coated sands or deposits of iron, aluminum, calcium or magnesium minerals, may be no more difficult or costly to obtain and prepare for household water filtration than otherwise similar negatively charged granular media.

A number of different designs and scales (sizes) of rapid, granular media filters are available for household and community water treatment. For household use bucket filters, barrel filters and small roughing filters are the main choices. The advantages and disadvantages of these filter designs are summarized in Table 10.

Table 10. Advantages and Disadvantages of Different Granular Medium Filters for Household Use

Filter Design or Type	**Advantages**	**Disadvantages**
Bucket filter	Useable on a small scale at household level; simple; can use local, low cost media and buckets; simple to operate manually; low (<90%) to moderate (90-99%) turbidity reduction	May require fabrication by user; initial education and training in fabrication and use needed; requires user maintenance and operation (labor and time). Commercial ones are relatively expensive. Low (<90%) pathogen reduction.
Barrel or drum filter	Useable on a small scale at household or community level; relatively simple; can use local, low cost media and barrels or drums; relatively easy to operate manually; low to moderate turbidity reduction.	Requires some technical know-how for fabrication and use; initial education and training needed; requires user maintenance and operation (some skill, labor and time). Low (<90%) pathogen reduction.
Roughing filter	Useable on a small scale at community level; relatively	Less amenable to individual household use because of scale; requires some

	simple; can use local, low cost construction material and media; relatively easy to operate manually; low to moderate turbidity reduction	technical know-how for construction and use; initial education and training needed; requires user maintenance and operation (skill, labor and time). Low (<90%) pathogen reductions

4.4.1. Bucket filters

Bucket filter systems of granular media for household use usually require two or three buckets, one of which has a perforated bottom to serve as the filter vessel. The bucket with the perforated bottom is filled with a layer of sand, layers of both sand and gravel, or other media. Gravel and sand media of specified sizes often can be purchased locally. Alternatively, these media can be prepared locally by passing sand and gravel through metal sieves of decreasing mesh size and retaining the material in the appropriate size ranges (between 0.1 and 1 mm for sand and about 1-10 mm for gravel). Sand or other local granular media are placed in plastic or metal buckets approximately 2.5-gallon (10-liter) to 10-gallon (40-liter) capacity and having bottoms with perforations (punched with small holes and fitted with a mesh strainer, such as window screen or piece of cloth) to allow water to drain out. Buckets are filled with several cm of gravel on the bottom and then a deeper layer of sand (about 40 to 75 cm) on top of the gravel. The granular medium bucket filter is suspended above a similar size empty bucket with a solid bottom to collect the water that drains from the filter as water is poured through it. The media of newly prepared bucket filters, as well as that of larger drum and roughing filters, must be cleaned initially with water to remove fine material and other impurities. So, the dirty water draining from new filters is discarded until the filtrate water has a low turbidity. The media of bucket filters must be cleaned or replaced on a regular basis to remove accumulated particles and to prevent the development of excessive microbial growths that will degrade water quality. The frequency of filter media replacement and cleaning depends on local conditions, but typically it is after a use period of perhaps several weeks.

A number of commercial sources of bucket filters are available and some have been used in both developing countries for small community and household water treatment. On of the better known and more widely distributed of these is the so-called commercial, two-bucket, point-of-use, media filter system. It consists of two 5-gallon plastic buckets with lids, filters and accompanying assembly fittings and contains both a particulate and a carbon filter. It is recommended that water be chlorinated before filtration. Use of chlorination adds complexity to the operation of the filter system and make its use more difficult, less practical and more costly, especially for the developing world. The system sells for about $US 50.00 and is designed to provide drinking water for up to 10 people per day. Replacement filter units are about $US 20.00 plus shipping. These costs are beyond the means of the world's poorest people in developing countries. However, the commercial, two-bucket, point-of-use, media filter system has been subsidized and distributed in developing countries by NGOs and is used in small communities, primarily in disaster relief settings.

4.4.2. Drum or barrel filters

A number of different designs for drum or barrel filters having either up-flow or down-flow of water have been described for use as rapid granular medium filters. These filters are usually 55-gallon (about 200-liter) capacity steel drums and contain sand and gravel media similar to that used for bucket filters (Cairncross and Feachem, 1986; IDRC, 1980; Schiller and Droste, 1982). The filters generally have a cover to prevent the introduction of airborne and other contaminants. Down-flow filters have a perforated pipe at the bottom to collect the water passing through the medium and discharge it from the side of the drum. The outlet pipe for filtered water may discharge the water at the bottom of the drum or it may be configured with an upward bend or loop to discharge the water at the same level as the top of the media in the filter. Upward flow filters have a bottom inlet and a rigid perforated or porous plate to support the filter media, which is usually coarse sand. Water flows in an upward direction and discharged through a side opening near the top of the drum. As with other granular media filters, the media of drum filters must be cleaned initially and on a regular basis. Cleaning down-flow filters tends to be technically more difficult and inconvenient. Water either has to be forced through the filter media in an up-flow direction in place, so-called backwashing, and the backwash water discarded, or the media has to be physically removed and replaced with cleaned or fresh media. Stopping the upward flow of product water and opening a bottom drain plug to discharge down-flowing dirty water that passes through the filter medium more easily cleans up-flow filters. An upward flow granular medium filter consisting of two tanks in a vertical series, with the lower tank containing a layer of charcoal sandwiched between two layers of fine sand and the upper tank the collector of the filtrate has been designed by UNICEF to treat 40 L of water per day (Childers and Claasen, 1987). The extent to which this filter reduces microbial contaminants in water has not been reported. However, if it is anticipated these filters function as typical rapid granular media filters, pathogen reductions are likely to be no more than 90% and even less (~50%) for the smallest pathogens, the enteric viruses.

4.4.3. Roughing filters

Simple, low cost, low-maintenance, multi-stage roughing filters for household and community use have been described and characterized (Galvis et al., 2000; Wegelin and Schertenlieb, 1987; Wegelin et al., 1991). Typically, these filters are rectangular, multi-compartment basins constructed of concrete or other materials. They require modest skills for operation and maintenance, and therefore, are best suited for use by communities or at least multiple households. However, it is possible for these multi-compartment tanks to be centrally fabricated and distributed at low cost for placement and final installation at their locations of use. Many of these filters are designed to use two different sizes of low cost, coarse granular media in two or three compartments or stages, and such media are generally locally available. In a typical, design water flows horizontally (or vertically in either an upflow or downflow mode) into an initial chamber containing fine gravel or coarse sand and then into another chamber or (two successive chambers) containing coarse or medium sand having smaller particle sizes than the initial chambers and from which is then discharged as product water. For highly turbid water containing settleable solids, a horizontal or vertical sedimentation basin to remove this coarse material prior to filtration precedes the filter. The filter has provision for backwashing the medium from a valved inlet (at the bottom of the filter medium chamber in the horizontal and downflow filter designs). Roughing filters usually consist of differently sized filter material decreasing successively in size in the direction of flow. Most of the solids are separated by the coarse filter medium near the filter inlet, with additional removal by the subsequent medium and fine granular media in subsequent compartments. Roughing filters are operated at relatively low hydraulic loads or flow rates. Regular backwashing is required to main flow rates and achieve efficient particulate removals, and therefore, some skill and knowledge is required to properly operate and maintain a roughing filter. Removal of indicator bacteria by roughing filters has been reported to be 90-99%. Although not reported, it is expected that compared to bacteria removals, virus removals would be lower and parasite removals would be similar to or higher.

4.4.4. Filter-cisterns

Filter-cisterns have been in use since ancient times in areas heavily supplied with rainwater or other water sources but lacking land area for reservoir or basin storage (Baker, 1948). In this filtration system cisterns or large diameter well casings, partially below grade, are surrounded by sand filters, such that water flows through the sand and into the casing or cistern either from the bottom or though side of the casing near the bottom. Such filter-cisterns function as infiltration basins to remove turbidity and other particulates. Among the best known of these filter-cistern systems were those of the city of Venice, which date back at least several hundred years (to the mid-15th century). The sand filter rings were several meters deep and in the shape of an inverted cone or pyramid in the center of, which was a cylindrical cistern or well casing that, collected the filtered water. The Venetian filter-cisterns were recognized for their ability to provide "clear and pure" water free "bad qualities". Today, filter-cisterns are being used in Sri Lanka to treat and store rainwater from roof catchment systems (Stockholm Water Symposium, 2000).

4.4.5. Biomass and fossil fuel granular media filters

Historically, depth filters composed of filter media derived from vegetable and animal matter have been employed for water treatment. Coal-based and charcoal filter media have been used since ancient times and carbon filter media are widely used today for both point-of-use and community water filtration systems (Argawal and Kimondo, 1981; Baker, 1948; Chaudhuri and Sattar, 1990). Filters containing sponges were widely used for on-site or point-of-use household and military water treatment in 18th century France. Water vessels had holes in their sides into which sponges were pressed, and water was filtered as it passed through the compressed sponges. Other filter designs consisted of sponges compressed into a perforated plate through which water was poured. Sponge filters imparted objectionable tastes and odors to the water unless they were cleaned regularly, indicating that microbial growths and biofilms probably were a major problem with these filters. Other media also employed in these point-of-use filters included sand, cotton, wool, linen, charcoal and pulverized glass, either individually or in various combinations as successive layers. These media also were used in larger scale filters for community water supply. Other examples of vegetable matter depth filters are those containing burnt rice hulls (as ash) or those consisting of vessels or chambers containing fresh coconut fibers and burnt rice husks in series (Argawal and Kimondo, 1981; Barnes and Mampitiyarachichi, 1983).

4.4.6. Microbial reductions by rapid granular media filters and recommended uses

Rapid granular media filters of the types described above are capable of reducing turbidities and enteric bacteria by as much as 90% and reducing larger parasites such as helminth ova by >99%. Because of their small size (typically <0.1 micrometer), enteric viruses are not appreciably removed by rapid granular media, with typical removals of only 50%-90%. These filters remove only viruses associated with other, larger particles or aggregated in larger particles. When roughing filters have been applied to highly turbid surface waters, removals have ranged from about 50 to 85% for bacteria and yeast's, with microbial removal efficiency depending on the type of filter medium (El-Taweel and Ali, 2000). The reduction of viruses and bacteria in rapid granular medium filters can be greatly increased (to >99%) if the filter medium is positively charged. This is accomplished by combining granular media such as coal (lignite, anthracite, etc.) with positively charged salts, such as alum, iron, lime or manganese. In positively charged filter media virus and bacteria reductions of 90->99% have been reported (Gupta and Chaudhuri, 1995; Chaudhuri and Sattar, 1990; Chaudhuri and Sattar, 1986; Prasad and Malay, 1989). Coal treated with alum or a combination of alum and silver was most effective for microbial reductions. Vegetable matter filters, such as those composed of burnt rice hull ash, have been reported to dramatically reduce turbidity, reduce bacteria by about 90% and require media replacement only every 2-4 months in southeast Asia (Argawal et al., 1981). Rice hull ash filters operated at a flow rate of 1 $m^3/m^2/hr$ reduced *E. coli* by 90 to 99%, which was higher than the *E. coli* removal by a sand filter tested under similar conditions (Barnes and Mampitiyarachichi, 1983). However, such vegetable matter filters, as well as many of the other designs of low cost granular media filters, have not been adequately evaluated for their ability to reduce a wide range of enteric pathogens, including enteric viruses, or their susceptibility to microbial growths and biofilms that can degrade the quality of the filtered water. Technological methods to modify granular media, such as chemical modification to impart positive surface charges, can improve microbial removals by filtration. However, such modifications are to technically demanding to be applied at the household level and therefore, are recommended primarily for piped community water supply systems.

Overall, simple granular media filters, including bucket, barrel or drum and roughing filters, are appropriate technologies for water treatment in at the community and perhaps the household level. They are effective in reducing turbidity but achieve only low to moderate microbe reductions, unless modified to make the media positively charged. Of these filter designs, the bucket filter is probably the most appropriate for household use because of its small scale, simplicity and manual application to quantities of water collected and used by individual households. Barrel or drum filters and roughing filters are more appropriate for community use or for sharing among several households within a community. However, none of these filtration methods achieve consistently high reductions of pathogens, unless chemically modified filter media are employed or the filtration process is combined with chemical disinfection such as chlorination. Therefore, granular media filters are best used at pre-treatment processes to reduce turbidity and provide product water that is more amenable to pathogen reductions by disinfection processes, such as solar radiation or chlorination. Due to their variable and potentially low microbe reductions, typical granular medium filters (not containing chemically modified media) are not recommended a standalone treatment for household water supplies.

4.5. Slow sand filters

Slow sand filtration of drinking water has been practiced since the early 19th century and various scales of slow sand filters have been widely used to treat water at the community and sometimes local or household level (Cairncross and Feachem, 1986; Chaudhuri and Sattar, 1990; Droste and McJunken, 1982; Logsdon, 1990). Most are designed as either barrel filters, basins or galleries containing a bed of about 1-1.25 meter of medium sand (0.2 to 0.5 mm) supported by a gravel layer incorporating an underdrain system. The filters operate with a constant head of overlying water and a flow rate of about 0.1 m/hour. Slow sand filtration is a biological process whereby particulate and microbial removal occurs due the slime layer ("schmutzdecke") that develops within the top few centimeters of sand. Reductions of enteric pathogens and microbial indicators are relatively efficient and generally in the range of 99% or more, depending on the type of microbe. Therefore, microbial reductions by slow sand filtration can be high, if the filters are properly constructed, operated and maintained. However, slow sand filters often do not achieve high microbial removals in practice, especially when used at the household level. This is because of inadequacies in constriction, operation and maintenance and the lack of institutional support for these activities.

Because of the development of the schmutzdecke and its accumulation of particles removed from treated water, the top layer (5-10 cm) of sand must be manually removed and replaced on a regular but usually infrequent basis. The removed sand is generally cleaned hydraulically for later reuse. Labor to clean larger scale community sand filters has been estimated at 1 to 5 hours per 100 m^2 of filter surface area. Freshly serviced slow sand filters require time for reestablishment of the schmutzdecke or "ripening" to achieve optimum performance, and therefore, multiple filter units are recommended. The performance and operation cycles of slow sand filters is influenced by raw water quality. Highly turbid waters are difficult to filter directly and may require a pre-treatment procedure, such as sedimentation or roughing filtration, to reduce turbidity. Slow sand filters are an appropriate, simple and low cost technology for community water treatment in developing countries. However, they are not recommended for individual household use because of their relatively large size (surface area), and the needs for proper construction and operation, including regular maintenance (especially sand scraping, replacement and cleaning) by trained individuals. Such demands for achieving good performance are unrealistic because they are beyond the capacities and capabilities of most households.

4.6. Fiber, fabric and membrane filters

Filters composed of compressed or cast fibers (e.g., cellulose paper), spun threads (cotton) or woven fabrics (cotton, linen and other cloths) have been used to filter water and other beverages (e.g., wine) since ancient times. The use of wick siphons made of wool thread and perhaps other yarns to filter water was well known in the days of Socrates and Plato (about 350 to 425 BCE) (Baker, 1948). Various compositions, grades and configurations of natural fiber and synthetic polymer filter media materials continue to be widely used today for point-of-use and small community water supply systems. In their simplest applications these filters are simply placed over the opening of a water vessel through which particulate-laden water is poured. Another simple application is to place a cone shaped filter in a funnel through which water is poured and collected in a receiver vessel. The particles are removed and collected on the filter media as the water is poured into the vessel. Other paper and fibrous media filters are in the form of porous cartridges or thimbles through which water is poured to exit from the bottom, or alternatively, which are partially submerged in are water so that filtered water passes to the inside and accumulates within. More advanced applications employ filter holders in the form of porous plates and other supports to retain the filter medium as water flows through it.

Paper and other fibrous filter media retain waterborne particles, including microbes, by straining them out based on size exclusion, sedimenting them within the depth of the filter matrix or by adsorbing them to the filter medium surface. Therefore, removal is dependent on the size, shape and surface chemistry of the particle relative to the effective pore size, depth and surface physical-chemical properties of the filter medium. Most fabric (cloth) and paper filters have pore sizes greater than the diameters of viruses and bacteria, so removal of these microbes is low, unless the microbes are associated with larger particles. However, some membrane and fiber filters have pore sizes small enough to efficiently remove parasites (one to several micrometers pore size), bacteria (0.1-1 micrometer pore size) and viruses (0.01 to 0.001 micrometer pore size or ultrafilters). Typically, such filters require advanced fabrication methods, special filter holders and the use of pressure to force the water through the filter media. For these reasons, such filters and their associated hardware are not readily available and their costs generally are too high for widespread use to treat household water in many regions and countries. However, simple fiber, fabric, paper and other filters and filter holders for them are available for widespread, practical and affordable household treatment of collected and stored water throughout much of the world.

Some waterborne and water-associated pathogens are relatively large, such as the free-swimming larval forms (cercariae) of schistosomes and *Faciola* species, guinea worm larvae within their intermediate crustacean host (*Cyclops*), and bacterial pathogens associated with relatively large copepods and other zooplankters in water, such as the bacterium *Vibrio cholerae.* Various types of filters, including fabric and paper filters can physically remove these larger, free-living pathogens as well as the smaller ones associated with larger planktonic organisms. Paper filters have been recommended for the removal of schistosomes and polyester or monofilament nylon cloth filters have been recommended for the removal of the *Cyclops* vector of guinea worm (Imtiaz et al., 1990). Such filters have been used successfully at both the household and community levels (Aikhomu et al., 2000). Colwell and colleagues have shown that various types of sari cloth (fine mesh, woven cotton fabric) and nylon mesh can be used in single or multiple layers to remove from water the zooplankton and phytoplankton harboring *V. cholerae,* thereby reducing the *V. cholerae* concentrations by >95 to >99% (Huq et al., 1996). Where waterborne schistosomes, guinea worms, *Faciola* species and zooplanton-associated *V. cholerae* are a problem, use of these simple, point-of-use filter methods are recommended and encouraged, especially if other control measures are not available or difficult to implement.

However, typical fabric, paper, monofilament nylon and similar filters are not recommended for general treatment of household water. This is because the pore sizes of these filters are too large to appreciably retain viruses, bacteria and smaller protozoan parasites, especially if such microbes are free and not associated with large particles or organisms. Therefore, other types of physical or chemical water treatment processes are usually needed to effectively control a wider range of waterborne or water-associated microbial pathogens in household drinking water supplies. However, fabric, paper and similar filters can be used in conjunction with coagulation processes or disinfection processes to achieve improved reductions of particles (turbidity) and microbes in water. Such combined or multi-step systems are described elsewhere in this report. Furthermore, the World Health Organization and the international health community strongly support the use of filtration with fabric, paper and other mesh filter media as an essential intervention to eradicate guinea worm (dracunculiasis).

4.7. Porous ceramic filters

Porous ceramic filters made of clay, carved porous stone and other media have been used to filter water since ancient times and were cited by Aristotle (322-354 BCE). Modern accounts of ceramic filters for household use date back to at least the 18^{th} century (Baker, 1948). Most modern ceramic filters are in the form of vessels or hollow cylindrical "candles". Water generally passes from the exterior of the candle to the inside, although some porous clay filters are designed to filter water from the inside to the outside. Many commercially produced ceramic filters are impregnated with silver to act as a bacteriostatic agent and prevent biofilm formation on the filter surface and excessive microbial levels in the product water. However, all porous ceramic media filters require regular cleaning to remove accumulated material and restore normal flow rate. Porous ceramic filters can be made in various pore sizes and most modern ceramic filters produced in the developed countries of the world are rated to have micron or sub-micron pore sizes that efficiently remove bacteria as well as parasites. Many ceramic filters are composed of media capable of adsorbing viruses and in principle can achieve high virus removal efficiencies. However, because adsorption sites for viruses often become occupied by competing adsorbents, virus adsorption efficiency decreases with increased use and may become inefficient, unless physical or chemical cleaning procedures can restore the virus adsorption sites.

Porous ceramic filters are made of various mineral media, including various types of clays, diatomaceous earth, glass and other fine particles. The media are blended, shaped by manual or mechanical methods, dried and then fired at various temperatures to achieve different pore sizes and filtration properties. Some are unfired to maintain an open pore structure for filtration. Most ceramic filters are easy to use and are a potentially sustainable technology. The availability of suitable raw materials and the appropriate technology to blend these raw materials, shape the filter units and then perhaps fire them in a kiln are the main technical and accessibility barriers to their availability in developing countries. The need for inspection and other quality control measures, as well as appropriate testing for proper pore size are also important requirements for their production. Some units are brittle and fragile and therefore, can break during use. Broken filters, even if only slightly cracked, are unsuitable for removal of particles and microbial contaminants from water.

Ceramic filters for point-of-use water treatment are being produced and have come into widespread use in many parts of the world. Ceramic filters containing fired clay, limestone, lime and calcium sulfate have been produced for water filtration in Pakistan (Jaffar et al., 1990). These filters were found to reduce turbidity by 90% and bacteria by 60%. Ceramic filter candles that are 6 cm diameter and 11 cm long have been produced commercially in Cote d'Ivoire for less than US$10 (Céramiques d'Afrique) and other low cost ceramic filters are being produced in different parts of the developing world with the assistance of the organization Potters for Peace. The extent to which ceramic filters being produced in the developing world have been or are being tested for reductions of waterborne microbes such as viruses, bacteria and parasites and their waterborne diseases in uncertain at this time. Such performance evaluation for microbial reductions would be valuable information and provide a basis verifying the quality of the filters. Ceramic filters manufactured commercially in various countries of the developed world, such as the United Kingdom and the United States of America, have been extensively tested for efficacy in reducing various waterborne microbial contaminants and many are certified for their performance microbial characteristics. Some of these are rated to remove at least 99.9999% of bacteria, such as *Klebsiella terrigena,* 99.99% of viruses, such as polioviruses and rotaviruses, and 99.9% of *Giardia* cysts and *Cryptosporidium* oocysts as required for Point-of-Use Microbiological Water Purifiers in the United States (USEPA, 1987). These filters tend to be more costly than most of those produced in developing countries, and therefore, their accessibility, affordability and sustainability for household water treatment by the poorest people in developing countries is uncertain at this time.

Overall, ceramic filters are recommended for use in water treatment at the household level. The main barriers to the production, distribution and use of fired or unfired ceramic filter-adsorbers are the availability of trained workers, fabrication and distribution facilities and cost. Further efforts are needed to define and implement appropriate manufacturing procedures and product performance characteristics of these filters in order to achieve products of acceptable quality that are capable of adequate microbe reductions from water. A simple and affordable method to test the quality and integrity of these filters also is recommended for use in situations where more technically demanding and costly testing is not available.. Quality and performance criteria and data for ceramic filters made in the developing world would provide a basis to judge quality and verify acceptable performance. However, the use of any intact ceramic filter to treat household water is likely to provide some improvement in water quality and therefore is preferable to no water treatment at all.

4.8. Diatomaceous earth filters

Diatomaceous earth (DE) and other fine granular media also can be used to remove particulates and microbial contaminants from water by so-called precoat and body feed filtration. Such filters have achieved high removal efficiencies of a wide range of waterborne microbial contaminants without chemical pre-treatment of the water (Cleasby, 1990; Logsdon, 1990). A thin layer or cake of the fine granular or powdery filter medium is precoated or deposited by filtration onto a permeable material held by a porous, rigid support to comprise a filter element. The water to be filtered often is supplemented with more filter medium as so-called body feed. As water passes through the filter, particulates are removed along with the body feed filter medium. This system maintains target flow rates while achieving high efficient particulate removal. DE filters also are capable of moderate to high pathogen removals (Logsdon, 1990). Eventually, the accumulation of impurities requires the removal of accumulated filter medium, cleaning of the filter medium support and reapplication of filter medium precoat to start the process over again. Although such DE and other precoat-body feed filter systems are used for small scale and point-of-use water treatment, they require a reliable, affordable source of filtration medium, regular care and maintenance, and they produce a spent, contaminated filter medium that may be difficult to dispose of properly. In addition, the filter media are difficult to handle when dry because as fine particles they pose a respiratory hazard. Because of these drawbacks, DE filters are not likely to be widely use for household water treatment in many parts of the world and in many settings, and therefore, they are not recommended for this purpose.

Table 11 Types, Performance Characteristics, Advantages and Disadvantages and Costs of Alternative Filters for Household Water Treatment

Filter Type	Advantages	Disadvantages	Comments
Rapid. Granular Media	See Table 8 above for details on these filters		
Slow Sand Filters	Useable on a small scale at community and maybe household level; relatively simple; can use local, low	Requires some technical know-how for fabrication and use; initial education and training needed; requires user	Simple, affordable and appropriate technology at the community level; less appropriate for treating individual household water, unless

	cost construction materials and filter media; relatively easy to operate manually; high turbidity and microbe reductions.	maintenance to clean and operate (materials, skill, labor and time).	by a collection of households.
Fiber, fabric and membrane filters	Usable at household level if filter media is available, easy to use and affordable	Wide range of filter media, pore sizes and formats; microbe removal varies with filter media; best used to remove large and particle-associated microbes; not practical, available or affordable for efficient removal of all waterborne pathogens	Has been effective in reducing guinea worm, *Fasciola* and schistosomiasis; can be coupled with other treatment methods (coagulation and disinfection) to improve overall microbe reductions
Porous ceramic filters	Simple and effective technology for use at the household level; extensive microbe reductions by quality filters; filters can be locally made from local materials, if education and training provided	Quality ceramic filters may not be available or affordable in some Quality of local made filters may be difficult to document unless testing is available to verify microbe reductions; need criteria and systems to assure quality and performance of filters	Greater efforts are needed to promote the development of effective ceramic filters for household water treatment in developing countries by adapting the local production of clay and other ceramic ware now used for other purposes to water treatment
Diatomaceous earth filters	Efficient (moderate to high) removals of waterborne pathogens	Not practical for household use; need specialized materials, construction and operations including regular maintenance; dry media a respiratory hazard	Pre-fabricated, commercial DE filters and media are available in some countries but high costs and low availability may limit household use in other places

4.9. Aeration

Aeration of water alone is simple, practical, and affordable, especially if done manually in a bottle or other vessel. Aeration of water as been practiced since ancient times and was believed to improve water quality by "sweetening" and "softening" it (Baker, 1948). It was later discovered that aeration indeed oxygenated anaerobic waters and that such a process would oxidize and precipitate reduced iron, manganese and sulfur, as well as strip volatile organic compounds, some taste and odor compounds, and radon. However, there is no evidence that aeration for brief time periods (minutes) has a direct microbiocidal effect. However, aeration of water introduces oxygen, which can cause chemical reactions, such as precipitation in anaerobic water containing certain dissolved solutes, and which can contribute indirectly to other process that may lead to microbial reductions. In addition, studies suggest that aeration has a synergistic effect with sunlight and heat on disinfection by solar radiation of water held in clear bottles. The mechanisms of this effect are not fully understood. However, they may involve conversion of molecular oxygen to more microbiocial chemical species by photooxidation reactions with microbial components or other constituents in the water, leading to photodynamic inactivation. Further studies of the ability of aeration to inactivate microbes in water either alone or in combination with other agents needs further study. Currently, there is no clear evidence that aeration alone is capable of appreciably and consistently reducing microbes in water.

5. Chemical Methods of Water Treatment

A number of chemical methods are used for water treatment at point-of-use or entry and for community water systems. These methods can be grouped into several main categories with respect to their purpose and the nature of the technology. The main categories to consider here are: (1) chemical pre-treatments by coagulation-flocculation or precipitation prior to sedimentation or filtration, (2) adsorption process, (3) ion exchange processes and (4) chemical disinfection processes. All of these processes can contribute to microbial reductions from water, but the chemical disinfection processes are specifically intended to inactivate pathogens and other microbes in water. Therefore, chemical disinfection processes appropriate for household water treatment in the developing world will be the focus of attention in this section of the report. Other chemical methods for water treatment will be examined for their efficacy in microbial reductions and their applicability to household water treatment.

5.1. Chemical coagulation, flocculation and precipitation

5.1.1. Introduction

Chemical precipitation or coagulation and flocculation with various salts of aluminum (e.g., alum), iron, lime and other inorganic or organic chemicals are widely used processes to treat water for the removal of colloidal particles (turbidity) and microbes. Treatment of water by the addition of chemical coagulants and precipitants has been practiced since ancient times, even though the principles and physico-chemical mechanisms may not have been understood. Sanskrit writings refer to the use of vegetable substances, such as the seed contents of *Strychnos potatorum* and *Moringa oleifera,* which are still in use today for household water treatment (Gupta and Chaudhuri, 1992). Judeo-Christian, Greek and Roman records document adding "salt", lime, "aluminous earth", pulverized barley, polenta as precipitants to purify water. Although alum and iron salts are the most widely used chemical coagulants for community drinking water treatment, other coagulants have been and are being used to coagulate household water at point of use, including alum potash, crushed almonds or beans and the contents of *Moringa* and *Strychnos* seeds. Table 12 lists some the coagulants that have been and are being used for water treatment at the community and household level, their advantages and disadvantages and their costs.

Table 12. Chemical Coagulants for Water Treatment and their Advantages, Disadvantage and Costs for Household Use

Coagulant	Community/ Household Use	Advantages	Disadvantages	Cost*	Comments
Alum (aluminum sulfate, etc.), alum potash	Yes/rare-moderate	Community use common; simple technology	Difficult to optimize without training and equipment	Moderate?	Proper use requires skill
Iron salts (ferric chloride or sulfate)	Yes/rare	Same as Alum	Same as Alum	Moderate?	Proper use requires skill
Lime ($Ca(OH_2)$), lime+soda ash (Na_2CO_3), caustic soda (NaOH)	Yes/rare-moderate	Same as Alum	Same as Alum; pH control and neutralization a problem; hazardous chemicals	Moderate to high?	Softeners; not applicable to many waters
Soluble synthetic organic polymers	Yes/no-rare	Improve coagulation with alum and iron salts	Same as Alum; hard to dose; need training & equipment; hazardous chemicals	High	Use with other coagulants; limited availability
Natural polymers (carbohydrates) from seeds, nuts, beans, etc.	Rare/Yes (in some developing countries)	Effective, available and culturally accepted in some places	Source plant required; training and skill required; cultural acceptability; may be toxic	Low	Traditional use based on historical practices

*Estimated Annual Cost: low is <US$0.001 per liter, moderate is 0.001-0.01$ per liter and high is >0.01 per liter (corresponds to about <US$10, $10-100 and >$100, respectively, assuming household use of about 25 liter per day)

Chemical coagulation-flocculation enhances the removal of colloidal particles by destabilizing them, chemically precipitating them and accumulating the precipitated material into larger "floc" particles that can be removed by gravity settling or filtering. Flocculation causes aggregation into even larger floc particles that enhances removal by gravity settling or filtration. Coagulation with aluminum or iron salts results in the formation of insoluble, positively charged aluminum or iron hydroxide (or polymeric aluminum- or iron-hydroxo complexes) that efficiently attracts negatively charged colloidal particles, including microbes. Coagulation-flocculation or precipitation using lime, lime soda ash and caustic soda is used to "soften" water, usually ground water, by removing (precipitating) calcium, magnesium, iron, manganese and other polyvalent, metallic cations that contribute to hardness. However, reductions in microbial contaminants as well as turbidity, and dissolved and colloidal organic matter are also achieved in this process.

5.1.2. Microbial reductions by coagulation-flocculation

Optimum coagulation to achieve maximum reductions of turbidity and microbes requires careful control of coagulant dose, pH and consideration of the quality of the water being treated, as well as appropriate mixing conditions for optimum flocculation. Lack of attention to these details can result in poor coagulation-flocculation and inefficient removal of particles and microbes. Under optimum conditions, coagulation-flocculation and sedimentation with alum and iron can achieve microbial reductions of >90 to >99% for all classes of waterborne pathogens (Sproul, 1974, Leong, 1982, Payment and Armon, 1989). However, poor microbial reductions occur (<90%) when coagulation-flocculation or precipitation conditions are sub-optimal (Ongerth, 1990). Even greater microbial reductions (>99.99%) can be achieved with lime coagulation-flocculation or precipitation if high pH levels are achieved in the process (pH >11) to cause microbial inactivation as well as physical removal.

5.1.3. Alum and iron coagulation

Because coagulation-flocculation treatment with alum, iron and other coagulants requires knowledge, skills to optimize treatment conditions, it is generally considered to be beyond the reach of most consumers. Most authorities consider such treatment to be best performed in specialized central facilities by trained personnel. This type of treatment is less likely to be performed reliably at point-of-use for household water treatment. Furthermore, the limited availability and relatively high costs of alum and ferric salts in some places present additional obstacles to widespread implementation of this technology at the household level.

Despite the caveats and limitations, alum coagulation and precipitation to remove turbidity and other visible contaminants from water at the household level has been traditionally practiced for centuries in many parts of the world (Jahn and Dirar, 1979; Gupta and Chaudhuri, 1992). When potash alum was evaluated for household water treatment in a suburban community in Myanmar by adding it to water in traditional storage vessels (160L capacity) at 500 mg/L, fecal coliform contamination was reduced by 90-98% and consumer acceptance of the treated water was high (Oo et al., 1993). The ability of the intervention to reduce diarrheal disease was not reported. In another study, alum potash was added to household water stored in pitchers of families with an index case of cholera and intervention and control (no alum potash) households were visited to 10 successive days to track cases of enteric illness (Khan et al., 1984). Illness among family members was significantly lower ($p < 0.05$) in intervention households (9.6%) than in control households (17.7%). The authors concluded that household water treatment by adding a pinch of alum potash was effective in reducing cholera transmission during outbreaks and was an appropriate and low cost (1 cent per 20 liters) intervention.

5.1.4. Seed extract coagulation-flocculation

Coagulation-flocculation with extracts from natural and renewable vegetation has been widely practiced since recorded time, and appears to be an effective and accepted physical-chemical treatment for household water in some parts of the world. In particular, extracts from the seeds of *Moringa* species, the trees of which are widely present in Africa, the Middle East and the Indian subcontinent, have the potential to be an effective, simple and low-cost coagulant-flocculent of turbid surface water than can be implemented for household water treatment (Jahn and Dirar, 1979; Jahn, 1981; Jahn, 1988; Olsen, 1987). The effectiveness of another traditional seed or nut extract, from the *nirmali* plant or *Strychnos potatorum* (also called the clearing nut) to coagulate-flocculate or precipitate microbes and turbidity in water also has been determined (Tripathi et al., 1976; Able et al, 1984). Microbial reductions of about 50% and 95% have been reported for plate count bacteria and turbidity, respectively. Despite the potential usefulness of *Moringa oleifera, Strychnos potatorum* and other seed extracts for treatment of turbid water, there has been little effort to characterize the active agents in these seed extracts or evaluate the efficacy as coagulants in reducing microbes from waters having different turbidities. The chemical composition of the coagulant in *Strychnos potatorum* has been identified as a polysaccharide consisting of a 1:7 mixture of galactomannan and galactan. These findings suggest that such seed extracts may function as a particulate, colloidal and soluble polymeric coagulant as well as a coagulant aid. The presence of other constituents in these seed extracts are uncertain, and there is concern that they may contain toxicants, because the portions of the plant also are used for medicinal purposes. Also, little has been done define, optimize and standardize conditions for their use. Furthermore, there appears to be little current effort to encourage or disseminate such treatment for household water or determine its acceptability, sustainability, costs and effectiveness in reducing waterborne infectious disease.

5.1.5. Summary

The results of several studies suggest that alum and other coagulation-flocculation or chemical precipitation methods can be applied at the household level to improve the microbiological quality of water and reduce waterborne transmission of diarrheal disease in developing countries. However, further studies are needed to determine if this type of treatment can be effectively, safely, and affordably applied for household water at point of use by the diverse populations living in a variety of settings. Furthermore, it is uncertain if household use of coagulation-flocculation can be optimized to provide efficient and consistent microbial reductions on a sustainable basis. Therefore, household water treatment by coagulation-flocculation and precipitation is not be widely recommended at this time. More information is needed on the effectiveness, reliability, availability, sustainability and affordability of these processes when applied at the household level. However, newer approaches to treatment of collected and stored household water have combined chemical coagulation-flocculation with chemical disinfection to achieve both efficient physical removal as well as inactivation of waterborne microbes. These systems offer great promise as effective, simple and affordable household water treatment technologies. These systems and their performance are described in a later section of this report.

5.2. Adsorption processes

5.2.1. Introduction

Adsorption processes and adsorbents such as charcoal, clay, glass and various types of organic matter have been used for water treatment since ancient times. Some of these adsorption processes tend to overlap with either filtration processes, because the media are often used in the form of a filter through which water is passed, or coagulation processes, because they may be combined with chemical coagulants. Therefore, adsorption processes can be carried out concurrently with filtration or coagulation. The candidate media potentially used for adsorption treatment of household water are shown in Table 13.

Table 13. Adsorbents for Water Treatment and their Advantages, Disadvantages and Costs for Household Use

Adsorbent	Community/ Household Use	Advantages	Disadvantages	Cost*	Comments
Clays	Rare/rare-moderate	Some efficiently adsorb microbes; adaptable to many treatment formats	Some adsorb microbes poorly; availability limited	Low to moderate	Use as an adsorbent or coagulant
Charcoal (C), Activated Carbon (AC)	Moderate/Moderate; (AC more in developed world; C more in developing world)	Adaptable to many treatment formats; charcoal often readily available	Poor microbe adsorption; can degrade microbial quality	Moderate (C) to high (AC)	Used as adsorbents or coagulants; use varies regionally; C use based on traditional practice
Crushed organic matter: seeds, rice, etc.	No-very rare/Rare-moderate in some countries	Ditto charcoal and carbon	Poor microbe adsorption; can degrade microbial quality	Low	Used as adsorbent or coagulant

*See footnote to Table 11 for explanation of cost basis.

5.2.2. Clay adsorption

Clay continues to be used as an adsorption medium for household water treatment in some regions and countries, with applications as clay particles in suspension, as filters (usually fired ceramic) or in conjunction with a chemical coagulant. Porous, fired ceramic clay filters (and adsorbers), typically as candles or other vessels have been described in a previous section of this report. The use of clay in conjunction with chemical coagulants also has been described elsewhere (Lund and Nissen, 1986; Olsen, 1987). When used alone, clays can decrease turbidity and microbes in water by about 90-95%. However, some microbes may not efficiently or consistently adsorb to certain, which reduces the overall efficiency of clay adsorption as a household water treatment process. Furthermore, the use of clay particles as suspensions in water is limited by the availability of the material and by the need to control the process so that the particles will settle, either alone or in the presence of a coagulant or coagulant aid. The use of such technology for clay adsorption requires training and is best supported by specialized equipment to carry out and monitor treatment effectiveness. Therefore, clay adsorption is not well suited for household water treatment.

5.2.3. Charcoal and activated carbon adsorption

Charcoal and activated carbon have been used extensively as adsorbents for water treatment in the developed and developing world. The main application is the reduction of toxic organic compounds as well as objectionable taste and odor compounds in the water. In developed countries granular or powdered activated carbon are used in community water treatment and granular or pressed carbon block is typically used for point-of-use or household water treatment (AWWA, 1999; LeChevallier and McFeters, 1990). Although fresh or virgin charcoal or activated carbon will adsorb microbes, including pathogens, from water, dissolved organic matter in the water rapidly takes up adsorption sites and the carbon rapidly develops a biofilm. Therefore, carbon is not likely to appreciably reduce pathogenic enteric microbes in water over an extended period of time. If anything, carbon particles are prone to shedding heterotrophic plate count bacteria and other colonizing microbes into the product water, thereby reducing the microbial quality. In many point-of-use devices the carbon is impregnated or commingled with silver that serves as a bacteriostatic agent to reduce microbial colonization and control microbial proliferation in the product water. Fecal indicator bacteria, such as total and fecal coliforms, and opportunistic bacterial pathogens, such as *Aeromonas* species are capable of colonizing carbon particles and appearing in product water. For these reasons, activated carbon is not recommended as a treatment method to reduce pathogenic microbes in drinking water. Additional treatment, such as chemical disinfection, often is needed to reduce microbe levels in carbon-treated water. Mixed media containing carbon along with chemical agents effective in microbial retention have been developed and evaluated. For example, carbon filters containing aluminum or iron precipitates have been described, and these filters have achieved appreciable microbial reduction in laboratory scale tests (Farrah et al., 2000). Therefore, it is possible that granular activated carbon filter media prepared with chemical agents more effective in retaining microbes may eventually become more widely available for point-of-use treatment of household water. However, the conventional charcoal and activated carbon media currently available for water treatment are not recommended for use at the household level to reduce microbial contaminants. Only charcoal or activated carbon media that been combined with other materials to improve microbial reductions should be considered for household treatment of collected and stores water and then only if there are performance data or certifications to verify effective microbial reductions.

5.2.4. Vegetative matter adsorbents

Historically, other vegetative matter has been used as an adsorbent for water treatment, as has been previously noted (Baker, 1948). Of these other plant media, burnt rice hulls seems to have been the most widely used in recent times (Argawal and Kimondo, 1981; Barnes and Mampitiyarachichi, 1983). The application of this material has been in the form of a granular medium filter, either alone or in conjunction with another filter medium, such as sand or activated (burnt) coconut shell. Use of this water treatment medium is still limited, primarily to those parts of the world where rice agriculture is widely practiced and where other filter media are not readily available at low cost. However, these adsorbent materials and their technologies require further development, evaluation and dissemination before they can be recommended for household water treatment in other parts of the world.

5.3. Ion exchange processes

5.3.1. Introduction

Ion exchange processes in water treatment have been used primarily for softening (hardness removal) in both community and point-of-use treatment and for disinfection in point-of-use treatment. Some ion exchange resins are used to deionize, disinfect or scavenge macromolecules from water. The main classes of ion exchangers used in water treatment and their advantages, disadvantages and costs are summarized in Table 14.

Table 14. Ion Exchangers and their Advantages, Disadvantages and their Advantages and Disadvantages for Household Use

Exchange Resin	Community/Household Use	Advantages	Disadvantages	Cost*	Comments
Softening resins	Yes/Yes	Easy to use	Do not inactivate microbes; spent resin replacement and disposal required; unavailable in some parts of the world	High	Lack of microbial reduction makes them unsuitable for microbial reductions in household water treatment
Deionizing Resins	Yes/Yes	Inactivate microbes; easy to use	Not recommended for drinking water; spent resin replacement and disposal required; unavailable in some parts of the world	High	The effects on long-term consumption of deionised water on health are not fully understood.
Iodine Disinfection (tri-iodide and pentaiodide)	No/Yes	Inactivates microbes; easy to use	Risk of soluble iodine leaching into water; spent resin replacement and disposal required; unavailable in some parts of the world	High	Difficult to determine useable life without added technology; impractical and limited availability in developing world
Adsorbent and scavenging resins	No/Yes	Easy to use	Not likely to inactivate microbes; microbial colonization and release a	High	Difficult to determine useable life without added technology;

			concern; not available in some parts of the world		impractical and limited availability in many parts of the world

*See Table 11 footnote for explanation of cost basis

5.3.2. Softening, deionizing and scavenging resins

Ion exchange typically employs synthetic polymeric resins that must be centrally manufactured in specialized production facilities. The costs of these synthetic resins are relatively high and their availability in developing countries is limited. Ion exchange using natural zeolites has been applied to softening, chemical adsorption and other purposes in water treatment. However, natural zeolites have only limited availability worldwide, they require mining and processing systems that may be beyond the capacity of developing countries, and they have not been widely evaluated or used for microbial reductions in drinking water. The effects on long-term consumption of deionised water on health are not fully understood.

Water softening resins are intended to remove hardness and they do not remove or inactivate waterborne microbes on a sustained basis. Furthermore, softening resins often become colonized with bacteria, resulting in excessive bacterial levels in product water, and they also increase the levels of sodium in the product water. In developed countries, point-of-use water treatment systems employing softening or scavenging resins often include addition treatment methods to reduce microbial loads in product water. Softening resins are relatively expensive, require regular monitoring and frequent replacement or recharging (regeneration of exchange capacity of spent resin); therefore, they are not practical for widespread household use to treated collected stored water. Because of their inability to reduce microbes, their complexities and other limitations, as described in Table 14, softening and scavenging resins are not recommended for household water treatment.

5.3.3. Ion exchange disinfection

Ion exchange disinfection is primarily with iodine in the form of tri-iodide or penta-iodide exchange resins. Portable and point-of-use iodine exchange resins have been developed and extensively evaluated for inactivation of waterborne pathogens, primarily in developed countries. Most of these are in the form of pour through cups, pitchers, columns or other configurations through which water is passed so that microbes come in contact with the iodine on the resin. Point-of-use iodine resins have been found to extensively inactivate viruses, bacteria and protozoan parasites (Marchin et al., 1983; 1985; Naranjo et al, 1997; Upton et al., 1988). While such iodine exchange disinfection resins are both effective and convenient, they are too expensive to be used by the world's poorest people and the production and availability of these resins is limited primarily to some developed countries. As described in the next section of this report, other chemical disinfection methods besides ion exchange halogen resins are available and preferred for household treatment to inactivate microbes in collected and stored drinking water.

5.4. Chemical Disinfection Processes

5.4.1. Chemical disinfectants for drinking water

Chemical disinfection is considered the essential and most direct treatment to inactivate or destroy pathogenic and other microbes in drinking water. The abilities of chemical disinfectants to inactivate waterborne microbes and reduce waterborne infectious disease transmission have been well known since the germ theory was validated in the mid-19th century. However, it was not until the late 19th and early 20 centuries that chlorine became widely recognized as an effective, practical and affordable disinfectant of drinking water. Subsequently, ozone and chlorine dioxide were developed as drinking water disinfectants and their ability inactivate waterborne pathogens was determined.

Today, chemical disinfection of drinking water is widely recognized as safe and effective and is promoted and practiced at the community level as well as at point-of-use. The preferred and most widely used chemical disinfectants of drinking water are all relatively strong oxidants, namely free chlorine, ozone, chlorine dioxide, chloramines (primarily monochloramine), and oxidants generated by electrolysis of sodium chloride solution (primarily or exclusively free chlorine). Additional chemical disinfectants sometimes used for drinking water are acids and bases; these agents inactivate microbes by creating either low or high pH levels in the water, respectively. The combined use of multiple treatment processes or "barriers" is a widely embraced principle in drinking water science and technology that is widely applied in community drinking water supplies, especially for surface waters. This approach also has been adapted to water treatment at the household level by the use of combined chemical treatments that are designed to chemically coagulate, flocculate, filter and disinfect the water. The advantages, disadvantages, costs and practicalities of these disinfectants for household treatment at the household levels are summarized in Table 15.

Table 15. Chemical Disinfectants for Drinking Water Supplies: Advantages, Disadvantages and Costs for Household Use

Disinfectant	**Community/ Household Use**	**Advantages**	**Disadvantages**	**Cost***	**Comments**
Free chlorine ($NaOCl$, $Ca(OCl)_2$)	Yes/Yes (worldwide, but not in some regions)	Easy to use; effective against most pathogens; stable residual	Not available worldwide; some users object to taste and odor	Low	The most widely used drinking water disinfectant; proven technology
Electro-chemically generated oxidant from NaCl	Yes/Yes (limited distribution)	Easy to use; effective against most pathogens; stable residual	Not available worldwide; some users object to taste and odor (mostly chlorine)	Low	Practical for worldwide use; can generate on site by electrolysis of NaCl; proven technology
Chloramines	Yes/Rare (less	Stable	Less effective	Moderate	More

(monochloramine)	widely used than free chlorine; must react free chlorine with ammonia)	residual	microbiocide than free chlorine; requires skill and equipment to generate on-site; household use impractical		difficult to use than free chlorine; potentially available where free chlorine is used but requires ammonia source
Ozone	Yes/Rare (less widely than free chlorine; mostly in Europe)	Highly micro-biocidal;	No residual; Generate onsite; hard to use; need special facilities and trained personnel; hazardous	High	Not practical for household use in many regions and countries
Chlorine Dioxide	Yes/Rare (much less use than free chlorine; for individual use by acidifying chlorite or chlorate)	Highly micro-biocidal	Poor residual; generate on-site; some technologies require special facilities, trained personnel and are hazardous; toxicologic concerns	High	Can be generated on-site by reacting chlorate or chlorite salts with acids; reactants may not be available and some are hazardous
Acids (especially lime juice and mineral acids) and hydroxide (caustic)	Limited/Limited (in community systems mineral acid and base for pH control; lime (CaO) and soda ash for chemical softening; in household Treatment lime juice for inactivation of *V. Cholerae*)	Acids inactivate *V. cholerae* & some other bacteria; limes and chemicals widely available	Limited microbiocidal activity; CaO use requires special facilities and trained personnel and is hazardous; CaO process difficult to control	High for CaO; low-moderate for lime juice	Lime juice has been reported to be effective for cholera control at the household level; Chemical acids and lime precipitation not practical for household use

Combined chlorination, coagulation-flocculation-filtration systems	Yes/Yes As sequential processes in community systems and as combined processes in household systems	Highly effective for microbe reductions	Availability now limited; requires some training and skill; efficacy varies with water quality;	High	Limited availability and higher cost (compared to chlorine) are barriers to household use in some countries and regions

*See Table 11 footnote for explanation of cost basis.

Iodine, silver, copper, quaternary ammonium compounds and some other chemical agents have been proposed and are sometimes used to inactivate waterborne pathogens. However, none of them are considered suitable for long-term use to disinfect drinking water for various important and valid reasons. Iodine is difficult to deliver to water and can cause adverse health effects, silver and copper are difficult to deliver to water and primarily only bacteriostatic, and quaternary ammonium compounds are limited in availability, costly and not effective against viruses and parasites. However, iodine, either dissolved in water or in the form of an iodinated exchange resin, has been used for short-term water treatment by outdoor recreationists (campers, hikers, etc), field military personnel, and persons displaced by natural disasters and human conflicts (wars and other societal disruptions). Silver is used as a bacteriostatic agent for point-of-use or household water treatment by storing water in vessels composed of silver or passing water through porous or granular filter media impregnated with silver. However, the extent to which silver alone inactivates microbes in water is limited, bacteria may develop silver resistance and many microbes, such as viruses, protozoan cysts and oocysts and bacterial spores, are not inactivated at silver concentrations employed for point-of-use drinking water treatment. Therefore, these agents are not recommended for routine disinfection of household water.

5.4.2. Factors influencing disinfection efficacy

The ability to inactivate waterborne microbes differs among the commonly used disinfectants as follows (from most to least potent): ozone > chlorine dioxide ≥ electrochemically generated oxidant ≥ free chlorine > chloramines. It is also noteworthy that these disinfectants differ in their stability and ability to persist in water to maintain a disinfectant residual. Ozone is a gas and the least stable in water; it is unable to provide a stable disinfectant residual. Chlorine dioxide is a dissolved gas in water and capable of persisting typically for periods of hours. Free chlorine is stable in water and can persist for days if there is no appreciable chlorine demanding material in the water. Because electrochemically generated oxidant from NaCl is primarily free chlorine (about 80 to nearly 100%, depending on the electrolysis conditions), it is relatively stable in water. Chloramines (primarily monochloramine) are the most stable of the listed disinfectants in water and can persist for many days.

Waterborne microbes also differ in their resistance to the chemical disinfectants used for drinking water as follows (from greatest to least resistant): parasites (protozoan cysts and oocysts and helminth ova) ≥ bacterial spores ≥ acid-fast bacteria (notably the

Mycobacteria) > enteric viruses > vegetative bacteria. Within each of these major microbe groups there are differences in the resistance of different sub-groups and specific species or strains of microbes. In addition, the resistance of waterborne microbes to inactivation by chemical disinfectants is influenced by their physical and physiological states. Microbes in the form of aggregates (clumps) or embedded within other matrices (membrane, biofilm, another cell, or fecal matter, for example) are protected from being reached by chemical disinfectants and by the oxidant demand of the material in which they are present. This makes the microbes more resistant to inactivation.

The quality of the water to be disinfected also influences microbial inactivation by chemical disinfectants. Particulate, colloidal and dissolved constituents in water can protect microbes from inactivation by reacting with and consuming the chemical disinfectant. The microbiocidal activity of some chemical disinfectants is influenced by the pH of the water, with generally better inactivation at low pH than at high pH for free chlorine, for example. Further details of the water quality factors influencing microbial inactivation are presented in detail elsewhere (Sobsey, 1989).

5.4.3. Free chlorine treatment

Of the drinking water disinfectants, free chlorine is the most widely used, the most easily used and the most affordable. It is also highly effective against nearly all waterborne pathogens, with notable exceptions being *Cryptosporidium parvum* oocysts and *Mycobacteria* species (Sobsey, 1989). At doses of a few mg/l and contact times of about 30 minutes, free chlorine generally inactivates >4 $\log_{10}$ (>99.99%) of enteric bacteria and viruses. For point-of-use or household water treatment, the most practical forms of free chlorine are liquid sodium hypochlorite, solid calcium hypochlorite and bleaching powder (chloride of lime; a mixture of calcium hydroxide, calcium chloride and calcium hypochlorite). Bleaching powder is less desirable as a drinking water disinfectant because it may contain other additives that are undesirable in drinking water (detergents, fragrances, abrasives, etc), and because it is somewhat unstable, especially if exposed to the atmosphere or to water.

In addition to the well-documented evidence that free chlorine effectively inactivates waterborne microbes and greatly reduces the risks of waterborne disease in community water supplies, there is considerable evidence of the same beneficial effects in point-of-use and household water supplies. Table 16 summarizes the results of carefully designed intervention studies documenting the ability of free chlorine to reduce microbes and to reduce household diarrheal disease when used to disinfect household drinking water in developing countries. The results of these studies show conclusively that chlorination and storage of water in either a "safe" (specially designed) vessel or even a traditional vessel reduces diarrheal disease by about 20-48% and significantly improves the microbial quality of water (by reducing thermotolerant (or fecal) coliforms, *E. coli, V. cholerae* and other microbial contaminants). Most of the recent studies on chlorination of household water have been done by the US Centers for Disease Control and Prevention (CDC) and its many partners and collaborators around the world (CDC, 2001). The CDC intervention includes a hygiene education component and the use of a plastic, narrow-mouth water storage vessel with a spigot designed to minimize post-treatment contamination. Therefore, the beneficial effects of this chlorination system in the form of improved microbial quality and reduced diarrheal and other infectious diseases may also include the positive effects of the improved storage vessel as well has improved hygienic practices. However, some water chlorination studies listed in Table 16 tested only the effect of chlorination or chlorination plus the use of an improved water storage vessel for better protection of the chlorinated water during storage. These studies of the water intervention only also demonstrate improved microbiological quality of chlorinated water and reduced diarrheal and other infectious diseases.

Table 16. Efficacy of Chlorination and Storage in a Specialized Container (Safewater System) to Disinfect Household Water: Disease Reduction and Improvement in Microbial Quality

Location	Water and Service Level[a]	Treatment	Storage Vessel	Disease Reduction (%)	Significant Microbe Decrease?[b]	Intervention[c]	Refer
Saudi Arabia	Household/ On, G	Free Chlorine	House-hold Tanks Outside	48%, diarrhea	Yes, *E. coli* +ive ⇓ from 100 to 3%	W	Mhafc al, 19
India	Household;	Free Chlorine	Earthenware	17-7.3%, cholera	Not Measured	W	Deb e 1986
Bolivia	Household/On, G	Electro-chemical Oxidant (Mostly Free Chlorine)	Special Vessel[d]	44%, diarrhea	Yes, *E. coli* +ive ⇓ from 94 to 22%; Median *E. coli* ⇓ from >20,000 to 0	W + SH	Quick al., 19
Bangladesh	Household/Off, M	Free Chlorine	Improved Vessel[e]	20.8%, diarrhea	Yes,	W	Handz 1998
Guinea-Bisseau	ORS'/Off/G or S not reported	Free Chlorine	Special Vessel[d]	No Data	Yes, mean *E. coli* ⇓ from 6200 to 0/100 ml	W + SH	Danie al., 19
Guatemala	Street-vended Water/Off. M	Free Chlorine	Special Vessel[d]	No Data	Yes, *E. coli* +ive ⇓ from >40 to<10%	W + SH	Sobel al., 19
Zambia	Household/Off or On not reported/G	Free Chlorine	Special[d] or Local Vessel	48%, diarrhea	Yes, *E. coli* +ive ⇓ from 95+ to 31%	W + SH	Quick al., in press
Mada-Gascar	Household	Free Chlorine; (traditional vessel)/Off, G or S not reported	Special[d] and Traditional Vessels	90%, cholera, (during outbreak)	Yes, Median *E. coli* ⇓ from 13 to 0/100 ml	W + SH	Mong 2001 Quick pers. comm
Uzbekistan	Household/On and Off/M	Free Chlorine	Special[g] Vessel	85%, diarrhea	No (but based on small number of samples)	W	Seme et al., 1998

Pakistan	Household/On and Off/ municipal	Free Chlorine	Special[d] Vessel	No Data	Yes, Thermotol. Colif. ⇓ by 99.8%	W + SH	Luby et al., 20

[a] Water storage and source:

[b] Significant difference in disease burden in intervention household members than in control household members. In some cases only certain age groups were studied or scored for an effect.

[c] W = Water intervention only. SH = Sanitation and health intervention.

[c] Water and Service Level: Household stored water or other water; water service levels: on-plot (On) or off-plot (Off), communal (C), yard (Y), surface water (S), ground water (G), other water (O), mixed sources (M)

[d] CDC vessel: Plastic (high-density polyethylene), about 20-L capacity, valved spigot to dispense water, 6-9 cm opening to fill and clean, handle to carry and re-position.

[e] 12-L jerry can: plastic, 12-L capacity, medium opening for filling, cleaning and dispensing water.

[f] ORS = Oral rehydration solution.

[g] Narrow-necked vessel with a spout

Only a few studies have not demonstrated the ability of household water chlorination to reduce diarrheal illness. One such study compared microbial water quality and diarrheal illness in households chlorinating drinking water stored in clay pots at a dose of 6.3 mg/l versus matched control households not chlorinating in rural village in Northeastern Brazil (Kirchhoff et al., 1984). Bacterial contamination of water in households chlorinating was significantly lower than in non-intervention households (70 versus 16,000 colonies per 100 ml, $p < 0.001$). However, diarrhea rates were not significantly different between the intervention and control households. Several factors may account for the lack of differences in diarrheal illness rates between the two sets of households. First, it is unclear whether or not the treated water was actually used for drinking purposes and at what consumption level. Second, the drinking water for all families was heavily contaminated pond water, so it may have continued to harbor appreciable levels of pathogens despite chlorination. Third, chlorine dose was not rigorously controlled and chlorine residual in stored household water was not measured. Incorrect chlorine dosing may have resulted in either too little chlorine to reduce pathogens or too much chlorine that caused families to stop using the water or drop out of the study. Eight of 9 families who dropped out of the study reported objectionable taste as the reason for dropping out. Additionally, families were not involved in the intervention process; they were passive recipients of it and received no hygiene education. Finally, because overall sanitary conditions were poor and socio-economic status was very low, a single intervention only on drinking water may not have had sufficient impact on overall pathogen exposure to observe a significant decrease in diarrheal illness, especially in a short-term study of only 18 weeks.

As summarized in Table 16, many studies have shown that the microbiological quality of stored household water can be significantly improved and diarrheal disease can be significantly reduced by adding chlorine to water stored in a household vessel. Recent studies have attempted to overcome the limitations and uncertainties of previous efforts by employing uniform and fully articulated systems of chlorine production, distribution and dosing, an improved, standardized household water storage container, and the inclusion of participatory education, motivation and behavior modification components (Mintz et al., 2001; USA CDC, 2000). A simple and low cost system of adding chlorine to collected household water stored in a dedicated, narrow-mouth plastic container (preferably with a valved spigot) has typically reduced waterborne microbes by >99% and reduced community diarrheal disease, including cholera, by as much as 17-90% (Handzel, 1998; Mintz et al., 1995; 2001; Quick et al., 1999; Semenza et al., 1998). To make the system sustainable efforts are made to have users purchase concentrated sodium hypochlorite that is produced in the community by electrolysis of NaCl solution. The concentrated sodium hypochlorite solution is added to household water stored in a specially designed, rectangular, 20-liter plastic vessel with a moderate diameter, screw cap opening for filling and cleaning and a separate valved spigot to dispense the treated, stored water. The treatment and storage technology is accompanied and supported by an education, motivation (through social marketing) and behavior modification system to achieve community and household participation and improve hygiene behaviors related to household water use. This approach to providing microbially safe household drinking water, called the "CDC Safewater" system, has been successfully implemented in numerous communities, countries and regions in different parts of the world, including Latin America (Bolivia, Ecuador, Nicaragua and Peru), Central Asia (Uzbekistan), the Indian subcontinent (Pakistan), and Africa (Zambia and Madagascar) (Luby et al., 2001; May and Quick, 1998; Mong et al., 2001; Quick, et al. 1996; 1999; Semenza et al., 1998). In addition, similar systems have been used to disinfect water for oral rehydration therapy (ORT) solutions and for water and beverages marketed by street food vendors (Sobel et al., 1998; Daniels et al, 1999).

Consumer education, participation and social marketing are considered essential and integral to achieving acceptance and sustainability for this and other household drinking water treatment systems (Thevos et al., 2000). In addition, pilot and feasibility studies are also encouraged, as is economic, social and political support from donor agencies, NGOs, government agencies, the private sector and other sources. Such activities are recognized as essential for designing, mobilizing for, implementing and assessing this and other water quality management systems at the household level. Further considerations of the role of these factors in household water treatment systems are discussed in a later section of this report.

5.4.4. Chloramine treatment

Disinfection of water with chloramines or ammonia-chlorine is widely practiced in community water supplies in order to provide a long-lasting disinfectant residual and to reduce tastes and odors associated with the use of free chlorine in some drinking water supplies. Chloramination also reduces the formation of free chlorine by-products that are considered toxic, such as trihalomethanes. However, compared to free chlorine, ozone and chlorine dioxide, chloramines are relatively weak oxidants and germicides. Based on the product of disinfectant concentration, C, and contact time, T, (CxT) it takes about 10 to 100 times more chloramine than free chlorine to inactivate an equivalent amount of most waterborne microbes. Chloramination is also more difficult to apply to water than free chlorine because it requires the combined addition of controlled amounts of both free chlorine and ammonia. Treatment of water with chloramines is not commonly practiced at point-of-use and is not recommended for household water treatment. This is because it requires the availability of both free chlorine and ammonia, it is complicated to properly apply both free chlorine and ammonia to water at the required doses, the resultant disinfectant is weak and slow acting, and the cost of using both chlorine and ammonia is higher than the cost of using chlorine alone.

5.4.5. Ozone

Ozone has been used as a drinking water disinfectant since the early 20th century. It has gained popularity for community water supplies in developed countries because it is a strong oxidant capable of rapidly and extensively inactivating a variety of waterborne pathogens, including chlorine-resistant *Cryptosporidium parvum* oocysts. Ozone is a highly reactive gas that must be generated on site using electricity. It requires specialized equipment to deliver to water at required doses, and care must be taken to prevent safety hazards from the release of ozone gas by the treated water. Because ozone is rapidly consumed by dissolved and particulate constituents in water, achieving appropriate ozone doses in actual practice requires careful attention to water quality as well as the ability to monitor both ozone dose and ozone residual in the treated water. Therefore, this method of drinking water disinfection is suitable primarily for community or other centralized water systems where the specialized equipment and delivery systems required for its use can be properly applied by trained personnel. Although small, point-of-use ozone treatment systems are available for consumer use they are relatively expensive and difficult to maintain, require electricity and therefore are not recommended for household water treatment.

5.4.6. Chlorine Dioxide

Chlorine dioxide is used primarily as a bleaching agent and has gained some use for disinfection of both community and point-of-use drinking water supplies in developed countries. Chlorine dioxide is a relatively strong germicide capable of inactivating most waterborne pathogens, including *Cryptosporidium parvum* oocysts, at practical doses and contact times. For community water treatment, chlorine dioxide is generated on-site from the reaction of sodium chlorite with chlorine gas or from the reaction of sodium chlorite with acid. Producing chlorine dioxide from free chlorine and sodium chlorite is technically demanding and requires specialized equipment. For point-of-use treatment of water, chlorine dioxide is produced on site from the reaction of sodium chlorite with acid. Such use is primarily for disinfecting temporary or informal water sources used by outdoors enthusiasts and others requiring short-term applications in developed countries. The toxicity of chlorine dioxide and its by-products, such as chlorite, limits the use of this disinfectant, because the amount of toxic by-products is difficult to control or measure. In addition, the generation of chlorine dioxide from sodium chlorite and acid is relatively expensive, compared to free chlorine. For these reasons, chlorine dioxide is not widely used and is not recommended for long-term disinfection of household drinking water.

5.4.7. Combined point-of-use treatment systems

The combined application of chemical coagulation-flocculation, filtration and chlorine disinfection is widely practiced for community water treatment in developed countries, especially for surface sources of drinking water. In combination, these processes have been shown to dramatically reduce microbial contaminants in drinking water, produce product water that meets international guidelines and national standards for microbial quality and embody the principles of a multiple barrier approach to drinking water quality (LeChevallier and Au, 2000). Because of the relative complexity of these processes, they are more difficult to implement at point-of-use for household drinking water supplies in developed countries. However, purification of water at point-of-use using tablets or powders that combine a coagulant-flocculent and a chemical disinfectant have been described (Kfir et al., 1989; Rodda et al., 1993; Powers, 1993; Procter & Gamble Company, 2001). In South Africa commercial tablets containing chlorine in the form of Halazone p-triazine-trione or dichloro-S-triazine-trione and either aluminum sulfate or proprietary flocculating agents have been developed, evaluated and promoted for community and household water treatment, as well as emergency water treatment. For household use on non-piped, household water supplies it is recommended that the tablets be added to water in a 20-liter bucket. The mixture is stirred to dissolve the tablet and flocculate, then allowed to stand unmixed to settle the floc and then supernatant water is poured through a cloth filter into another bucket. When these tablets were tested for efficacy in reducing bacteria, viruses and parasites, they were found to achieve extensive reductions and meet US EPA requirements for a microbiological water purifier. According to the manufacturer, the cost of treatment with these tablets is low. Epidemiological studies of the effectiveness of these systems to reduce waterborne diarrheal and other diseases have not been reported.

The Procter and Gamble Company in cooperation with the USA CDC and other collaborators reports the development and evaluation of a combined flocculent-disinfectant powder supplied in a small packet that is added to a 10-liter volume of household water by consumers. The powder contains both coagulants and a timed-release form of chlorine. After stirring briefly, contaminants settle to the bottom of the container and the supernatant water is poured through a cloth filter into another container for safe storage and use. Initial studies document dramatic reductions of microbial as well as some chemical contaminants in water, and field epidemiological studies to determine reductions in household diarrheal disease are under way in Guatemala villages. The cost of the treatment is estimated at US$0.01 per liter.

Overall, combined coagulation-flocculation and chlorine disinfection systems have shown considerable promise as microbiological purifiers of household water. Currently, they have not come into widespread use and their worldwide availability is limited at the present time. However, further studies that document efficacy in reducing diarrheal disease and improving microbial quality are apparently forthcoming for some of these systems. Such data documenting performance and the commercial availability of the materials through widespread marketing and distribution create the potential for this technology to be not only scientifically supportable but also widely available in many parts of the world. The relatively high costs of these combined systems may limit their use by some of the world's poorest people, but market studies also are under way to determine consumers' willingness to pay. Therefore, these combined systems may prove to be appropriate technologies for household water treatment in many settings for the large segment of the world's population now collecting and storing water for household use.

5.4.8. Lime juice disinfection of V. cholerae

Drinking water disinfection by lowering water pH with lime juice is effective in inactivating *V. cholerae* and in reducing cholera risks (Dalsgaard et al., 1997; Mata et al., 1994; Rodrigues et al., 1997; 2000). Adding lime juice to water (1-5% final concentration) to lower pH levels below 4.5 reduced *V. cholerae* by >99.999% in 120 minutes (Dalsgaard et al., 1997). Lime juice also killed >99.9% of *V. cholerae* on cabbage and lettuce and was recommended for prevention of cholera by addition to non-acidic foods, beverages and water (Mata, 1994). Epidemiological studies during cholera outbreaks in Guinea-Bissau showed that lime juice in rice foods was strongly protective against cholera and laboratory studies showed that the presence of lime juice inhibited V. cholera growth in rice foods. These studies indicate that adding lime juice to water, beverages and other foods (gruels, porridges, etc.) has the ability to inactivate *V. cholera* and reduce disease risks. Therefore, the use of lime juice in water and foods is a potentially promising household treatment to control cholera transmission. Further studies to better characterize the efficacy of this treatment and its ability to reduce cholera transmission are recommended.

6. Social and Economic Aspects

6.1. Educational, Behavioral and Related Socio-Cultural Considerations for Household Water Treatment Systems

A number of studies and considerable field experiences have shown that the introduction of water treatment technology without consideration of the socio-cultural aspects of the community and without behavioral, motivational, educational and participatory activities within the community is unlikely to be successful or sustainable. Therefore, initiatives in water, hygiene and sanitation must include community participation, education and behavior modification. A number of systems have been developed and successfully implemented for this purpose. One of the most widely used and successful of these is termed PHAST, which stands for Participatory Hygiene and Sanitation Transformation (WHO, 1996). It is an adaptation of the SARAR (Self-esteem, Associative strengths, Resourcefulness, Action-planning and Responsibility) method of participatory learning. PHAST promotes health awareness and understanding among all members of a community or society in order to change hygiene and sanitation behaviors. It encourages participation, recognizes and encourages self-awareness and innate abilities, encourages group participation at the grassroots level, promotes concept-based learning as a group process and attempts to link conceptual learning to group decision-making about solutions and plans of action for change and improvement of the current situation. It encourages internally derived decisions and both material and financial investment of the community to affect change.

Current approaches to participatory education and community involvement in water and sanitation interventions apply behavioral theory and other related sciences to successfully implement control measures. The use of water treatment technologies and other water quality control measures that are consistent with prevailing beliefs and cultural practices and local resources are promoted by behavioral theory. Community involvement at all levels is important in achieving community support and sustainability for the technology. Efforts to introduce improved household water treatment and storage systems have employed health education, community mobilization, social marketing, motivational interviewing, focus groups, and other educational, promotional, communication and mobilization techniques to change behaviors, facilitate learning and elicit participation.

Another example of this approach is a program to facilitate support agencies in developing community willingness and capacity to take responsibility for their own water supplies called the MANAGE Dissemination system developed by the International Water and Sanitation Centre (IRC, 1999). The goal of the system is to facilitate achievement of community management of and decision-making for rural water supply supplies. The MANAGE Dissemination program disseminates and shares findings of entities engaged in developing and implementing community participatory action through an information network intended to enhance multi-institutional learning approaches and develop training methods and tools that facilitate and support community management of water supplies. The system employs exchange visits and other communications activities among participants who are stakeholders in the community's water supply ranging from local citizens to NGOs and their national and international partners. The MANAGE Dissemination system has been implemented in many parts of the world, including Africa (Cameroon and Kenya), the Indo-Asian region (Pakistan and Nepal) and Latin America (Colombia and Guatemala).

The use of social marketing in the effort to gain acceptance and support for household water treatment and storage systems depends to some extent on the nature of the household water treatment technology and its use of marketable commodities, such as a disinfectant, other water treatment chemicals or an improved household water storage vessel. In the case of household water treatment with liquid chlorine and storage in a narrow-mouth container, social marketing of the chlorine solution became an important activity to change behavior by motivating potential users buy and use the product. (USA CDC, 2000; Thevos et al., 2000). It is likely that some previous efforts to introduce and promote similar practices of household water chlorination and safe storage in an improved vessel failed or achieved poor results because of inadequate participatory education, behavioral modification, motivational communication, social marketing and other community-based participation and responsibility.

Assessing the success of water and sanitation interventions is another important consideration. It not only provides key information about the success of the intervention but also that has been used to assess and improve water sanitation technologies and systems in developing countries is the Knowledge, Attitudes and Practices (KAP) survey. A KAP survey was used to better understand the impacts of the cholera epidemic in the Amazon region of Peru in the early 1990s and to assess the socio-cultural aspects of the cholera preventive measures that were introduced (Quick et al., 1996).

6.2. Economic Aspects of Household Water Treatment Processes and Systems

The affordability, costs and willingness to pay of household water treatment technologies are important considerations for their implementation, use and sustainability. All systems for household water treatment and storage require an approach for cost recovery in order to be sustainable. Approaches to cost recovery include providing all or some system components free of charge with funding provided by external sources (donors, governments, etc.), partial cost recovery by sales of some system components (e.g., sale of a household water disinfectant), recovery of all costs by sales of all system components. A phased approach to cost recovery also can be employed, with initial subsidies that decrease or stop later on or loans that must be repaid later on. Often, economic analyses reveal that the costs of prevailing water use, treatment and storage practices can be shifted to a new system of improved household water treatment and storage, if communities and consumers are made aware of the substitution, accept that is better than the existing system and thereby become willing to create an economic demand. Some water intervention initiatives have employed pricing schemes and short-term subsidies or price supports to obtain and increase consumer demand, including sales on credit, barter sales and in-kind payments (work in exchange for goods and services of the technology). The various approaches for cost recovery and financial management of household water supply systems are beyond the scope of this review. Many of the principles of financial management for more centralized water supply and sanitation systems have been described elsewhere (Cairncross et al., 1980; WHO, 1994). It is likely that these economic approaches to cost recovery and technology sustainability can be applied or adapted to the more decentralized systems for household treatment and storage of water described in this report.

The costs of various point-of-use or household water treatment and storage systems have been estimated previously. However, the cost estimates for specific technologies by different sources are not always in agreement and for some technologies cost estimates are lacking. Differences in local conditions and availability of materials also contribute to the variability and uncertainty of cost estimates for household water treatment and storage technologies. Table 17 lists the cost estimates of some of the most promising alternative household water treatments, adapted from estimates made by the USA CDC (2000).

Table 17. Cost Estimates per Household for Alternative Household Water Treatment and Storage Systems (US$)*

*Adapted from estimates by USA CDC (2001)

System	Imported Items	Initial cost of hardware (per capita; per household)	Annual operating cost per capita and household
Boiling	None	None (assumes use of a cook pot)	Varies with fuel price; expensive
Ceramic filter	Filter candles	$5; $25	$1, $5 for annual replacement
SODIS and SOLAIR (solar disinfection by UV radiation and heat)	None (assumes spent bottles available)	Cost of black paint for bottles or alternative dark surface (roofing)	None
Solar heating (solar disinfection by heat only)	Solar cooker or other solar reflector	Initial cost of solar cooker or reflector & water exposure and storage vessels	Replacement costs of solar reflectors and water exposure and storage vessels
UV Lamp Systems	UV lamps and housings	Initial cost of UV system: US$100-300, $20-60	Power (energy); lamp replacement ($10-100) every 1-3 years
On-site generated or other chlorine and narrow-mouth	Hypochlorite generator and associated	$1.60; $8.00	$0.60/$3.00 (estimated by USA CDC); costs may be higher for different sources

storage vessel ("USA CDC Safewater" system)	hardware for production and bulk storage		of chlorine and for different water storage vessels
Combined coagulation-filtration and chlorination systems	Chemical coagulant and chlorine mixture, as powder or tablet	Use existing storage vessel or buy a special treatment and storage vessels (US$5-10 each)	Chemical costs at about $US7-11 per capita per year $35-55 per household per year, assuming about 2 liters per capita (10 liters per household)/day

7. Monitoring and Evaluating the Effectiveness of Alternative Household Water Treatment and Storage Systems and Hazard Analysis at Critical Control Points (HACCP)

7.1. Introduction

The WHO Guidelines for Drinking-water Quality (GDWQ) are adopting the concept of Water Safety Plans and HACCP (Hazard Analysis - Critical Control Points). The WHO GDWQ have long emphasized the identification of key health-related quality constituents for which health-based guideline values are established. In addition, the GDWQ also identify and specify methods to monitor drinking water quality for constituents of health concern. However, an important development in the forthcoming revisions of the guidelines is an increased emphasis on water quality protection and control from source to consumer. Emphasis will be placed on management system to manage and monitor water quality from source to consumer according to a Water Safety Plan (WSP), to encourage stakeholder participation and mobilization, and to stress the need for communication and education about water quality and how safe water quality can be achieved. A Water Safety Plan includes: (1) risk assessment to define potential health outcomes of water supply, (2) system assessment to determine the ability of the water supply system to remove pathogens and achieve defined water quality targets, (3) process control using HACCP, and (4) process/system documentation for both steady state and incident-based (e.g., failure or fault event) management. It is recommended that HACCP for household water collection, treatment and storage be applied in the context of a Water Safety Plan that addresses source water quality, water collection, water treatment, water storage and water use.

7.2. HACCP for recommended household water storage and treatment systems

7.2.1. Household water storage

As shown in Table 18, the application of HACCP to water storage in household vessels is likely to address three hazards and their critical control points (CCPs): (1) vessel type (appropriate versus inappropriate), (1) vessel integrity (intact, damaged, parts missing, etc.), and (3) vessel sanitation (cleaned, not cleaned and a system to monitor and document cleaning frequency). For each type of storage vessel a set of specific hazards, critical control points and other criteria for a HACCP plan can be established. For example, for household storage of water according to the CDC "Safewater" system, a preferred vessel design and alternative vessel designs that are considered suitable are provided, as are vessel designs and types considered unsafe for sanitation reasons (no cover, wide opening allowing introduction of hands and dippers, etc.) (CDC

Safewater, 2000). For the solar disinfection system using sunlight for heating and UV-irradiating water (SODIS and SOLAIR), recommended or preferred vessels are identified (including vessel size and type of plastic), criteria for the integrity of the vessel are specified (e.g., absence of scratches and surface damage that would reduce light penetration), and the maximum time period of water storage is specified (to avoid degradation of the microbial quality of water and biofilm accumulation due to bacterial regrowth). These and other hazards and their critical control points can be specified for each type of water storage vessel and system.

Table 18. HACCP for Household Water Storage Vessels: Hazards and Criteria for Critical Control Points

Hazard	Vessel Type	Vessel Integrity	Vessel Sanitation
Critical Control Point(s)	Appropriate or not appropriate, based on design	Intact or not intact, based on visible damage (e.g., cracks, scratches), broken or missing parts (e.g., cap) and leaks	Sanitary or nor sanitary, based on frequency of cleaning and cleaning method

7.2.2. Household water treatment

As previously stated above, it is recommended that HACCP for household water treatment be applied in the context of a Water Safety Plan that addresses source water quality, water collection, water treatment, water storage and use. For each type of household water treatment and its application in practice, generic water safety plans can be developed and these can then be adapted to site-specific conditions and situations of their use for drinking water management. As shown in Table 19, the hazards and critical control points for household water treatment include: choice of source water and type of treatment. Also important are methods of source water collection and conditions of treated water storage and use. The HACCP program within a Water Safety Plan should identify the hazards and critical control points for all steps and activities in the overall plan from source water quality to the product at the point of consumer use. Some of the key hazards and critical control points for source water and for alternative household water treatments are summarized in Table 19. The hazards and critical control points described here are not intended to be comprehensive or complete. Instead they are intended to be representative of the important hazards (failures and deficiencies) and their critical control points for some of the key household water treatments identified and recommended in this report. Further efforts will be needed to better specify and develop HACCP plans for these water treatment technologies on both a generic (general) as well as site-specific basis. It is important to note that HACCP plans are always best articulated on a site-specific basis, even though the key elements of the plan are often common to a particular type of commodity, technology and process train.

Table 19. HACCP for Household Water Treatment: Hazards and Critical Control Points

Type of Treatment	Source Water Hazards	Source Water Critical Control Point(s)	Treatment Hazards	Treatment Critical Control Points

Heating to boiling with fuel	Contaminated or uncontaminated?	Choose best available source	Inadequate temperature achieved	Heat to a visible rolling boil
Solar Radiation in clear plastic bottles (heat + UV radiation or heat only)	Contaminated or uncontaminated? Turbid? UV-absorbing solutes?	Choose best available source, with low turbidity and low UV-absorbing solutes	Inadequate sunlight to achieve target temperature and UV dose	Target temperature sensor (thermometer or melting wax); elapsed exposure time (timer, clock, sun position, etc.); monitor/observe weather (sunny, part sun or cloudy)
Solar radiation (cooker or reflector) in opaque vessel (heat only)	Contaminated or uncontaminated? Turbid?	Choose best available source, with low turbidity	Inadequate sunlight to achieve target temperature	Target temperature sensor (thermometer or melting wax); elapsed exposure time (timer, clock, sun position, etc.); monitor/observe weather (sunny, part sun or cloudy)
UV irradiation with lamps	Contaminated or uncontaminated? Turbid? UV-absorbing solutes?	Choose best available source, with low turbidity and low UV-absorbing solutes	No electrical power to UV lamp; poor water quality	Assure a reliable source of electrical power to UV lamp; assure adequate water quality (based on turbidity and UV-absorbing materials)
Settling; plain sedimentation	Contaminated or uncontaminated? Turbid?	Choose best available source, with low turbidity	Poor settling of turbidity (suspended matter)	Observe (monitor) for adequate turbidity (cloudiness) reduction
Filtration methods	Contaminated or uncontaminated? Turbid?	Choose best available source, with low turbidity	Poor filtration and turbidity reduction	Observe (monitor) for adequate turbidity (cloudiness) reduction
Chlorination or mixed oxidants from electrolysis of brine (NaCl)	Contaminated or uncontaminated? Turbid? Chlorine-demanding solutes?	Choose best available source, with low turbidity and low chlorine demand	Poor chlorination due to inadequate dose and contact time	Observe (monitor) for chlorine residual (C) and for adequate contact time (T),i.e., adequate CT
Combined chemical coagulation +	Contaminated or uncontaminated? Turbid? Chlorine-	Choose best available source, with	Poor treatment due to inadequate	Observe (monitor) for turbidity (cloudiness) reduction and

chlorination systems	demanding solutes?	low turbidity and low chlorine demand	turbidity removal and chlorine dose	adequate CT (chlorine residual and contact time)

7.2.3. Summary of HACCP for household water systems

Consistent with the forthcoming WHO GDWQ, collection, treatment and storage of household water should be developed and managed according to a Water Safety Plan that includes HACCP as a management tool. For household water, hazards and critical control points can be identified for the management steps in a water safety plan that includes source water selection and protection, water collection, water treatment and water storage, including storage vessel type and its use. The approaches and examples provided here are intended to be only exemplary and not comprehensive

8. Summary Tables

Table 20. Comparison of Recommended Technologies for Household Water Treatment

Criterion	Boiling with Fuel	Solar Disinfection with UV + Heat (SODIS or SOLAIR)	Solar Disinfection with Heat Only (Opaque Vessels and Solar Panels)	UV Disinfection with Lamps	Free Chlorine and Storage in an Improved Vessel ("CDC Safewater")	Chemical Coagulation-Filtration + Chlorine Disinfection
Microbial Reductions	Yes, extensive	Yes, extensive for most pathogens	Yes, extensive for most pathogens	Yes, extensive for most pathogens	Yes, extensive* for most pathogens	Yes, extensive
Diarrheal Disease Reductions	Yes	Yes, 9-26%; two studies	None reported from epid. studies, but expected due to high temperature (55+°C)	None reported from epid. Studies, but expected due to germicidal effects	Yes, 15-48%; many studies	None reported from epid. Studies yet, but expected due to multiple treatments
Disinfectant Residual	No	No	No	No	Yes	Yes
Quality Requirements of Water to be Treated	No	Low turbidity (<30 NTU) for effective use; pre-treat turbid water	None	Low turbidity (<30 NTU) and low in UV-absorbing	Low turbidity (<30 NTU) and low chlorine demand for	None; applicable to poor quality source water

				solutes, such as NOM, iron and sulfites	effective use; pre-treat turbid water	
Chemical changes in water	No, usually except deoxygenating and chemical precipitation	None or not significant	None or not significant	None or very little	Yes; may cause taste and odor and disinfection by-products	Yes, may cause taste and odor and disinfection byproducts
Microbial regrowth potential in treated water	Yes, with storage beyond 1-2 days	Yes, with storage beyond 1-2 days	Yes, with storage beyond 1-2 days	Yes, with storage beyond 1-2 days	None to low if chlorine residual maintained	None to low if chlorine residual maintained
Skill level and ease of Use	Low skill, easy use	Low skill; very easy use	Low skill; easy use with training	Moderate skill, training needed for maintenance cleaning and lamp replacement	Low skill; easy use with training	Moderate, training needed in adding chemicals, mixing, decanting and filtering
Availability of Needed Materials	Requires a source of fuel	Requires plastic (PET) bottles and dark surface (on one side of vessel or on surface where vessel is placed)	Requires black bottles of cook vessels and a solar reflector or solar cooker	Requires UV units and replacement lamps and a reliable source of electricity (power)	Requires source of free chlorine or chlorine generator and source of safe storage vessels	Requires a source of the chemical mixture (coagulants and chlorine disinfectant) may limit availability
Limits to Water Volume Treated	Yes, difficult to scale up above usual cooking volumes	Yes, treats 1-1.5 liters per bottle; can simultaneously treat multiple bottles	Yes, treats 1-4 liters per container; can simultaneously treat multiple vessels with multiple solar panels or solar cookers	No, units can treat several liters per minute and much, depending on lamp size and number and reactor volume	No, easily scaled up	Yes, chemical mixture treats fixed volumes of 10-20 liters; repeated treatment of additional volumes
Performance verification requirements	Observe water for a rolling boil	Measure that target temperature is reached (thermometer or wax	Measure that target temperature is reached (thermometer or wax	Must verify lamp output; may be a limitation if unit lacks a	Measure chlorine residual or microbial quality (indicators)	Observe (measure) turbidity reduction and measure chlorine

		indicator)	indicator)	UV sensor	or both	residual
Accept-ability*	High	High to Moderate	High to Moderate	High	High to Moderate	High to moderate
Sustainability	High, unless fuel is scarce	High, probably	High, probably	High, probably	High	High, probably; limited data
Length of Treatment Time	Minutes to tens of minutes	Hours (full sun), days (clouds), not effective if no sun	Hours (full sun), days (part sun), not effective if no sun	Seconds to minutes, depending on water volume treated and reactor design	Tens of minutes	Tens of minutes

*High is >75%; moderate is 50-75%

Table 21. Comparison of Candidate Technologies to Pre-treat Turbid Household Water

Criterion	**Technologies**			
	Settling; plain sedimentation	**Fiber, cloth or membrane filter**	**Granular media filters**	**Slow sand filter**
Effected by particle size	Yes, only settable particles removed	Yes, depends on pore size of filter; micron-submicron preferred	Somewhat; depends of medium and design; 50-99% turbidity removal possible	Somewhat; large particles reduce filter runs (remove by roughing filters or settling)
Availability of equipment and/or materials	Readily available vessels	High for local materials such as fabric or paper filters; low for membranes	High for bucket filters and local media; Medium for drum or barrel filters or cisterns; Low for more advanced filter designs	Medium if construction materials and filter sand available
Skill; ease of use	Low; very easy	Low, easy	Low for buckets; medium for drum, barrel or cistern filters	Medium; requires training to operate filter and monitor
Maintenance requirements	Low; clean settling vessel	Low for disposable filters; moderate to high for reusable filters and filter housings	Low for buckets; medium for barrel, drum & cistern filters; all require media cleaning	Medium; requires periodic cleaning and replacement of upper sand layer

Applicability to water volumes of individual households	Yes	Yes	Yes for buckets; possibly for some drum, barrel and cistern filters	Possible but unlikely; most are too large for water needs of individual family households
Cost	Low	Low for local filters; high for imported filters	Low if filter media and constriction materials are local	Low if local media and construction materials available
Acceptance	High	High for some	High, probably	Moderate, probably
Sustainability	High	High for some	High, probably	Moderate, probably

*Slow sand filters are often less effective, accepted and sustainable in field practice at the household level than possible in principle.

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