Manos al Agua
Gestión Inteligente del Agua

APPROPRIATE **TECHNOLOGIES** FOR **WATER TREATMENT** ON COFFEE FARMS

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Nelson Rodríguez Valencia*

Laura Vanessa Quintero Yepes**

Andrés Felipe Osorio Ocampo**

Samuel Antonio Castañeda**

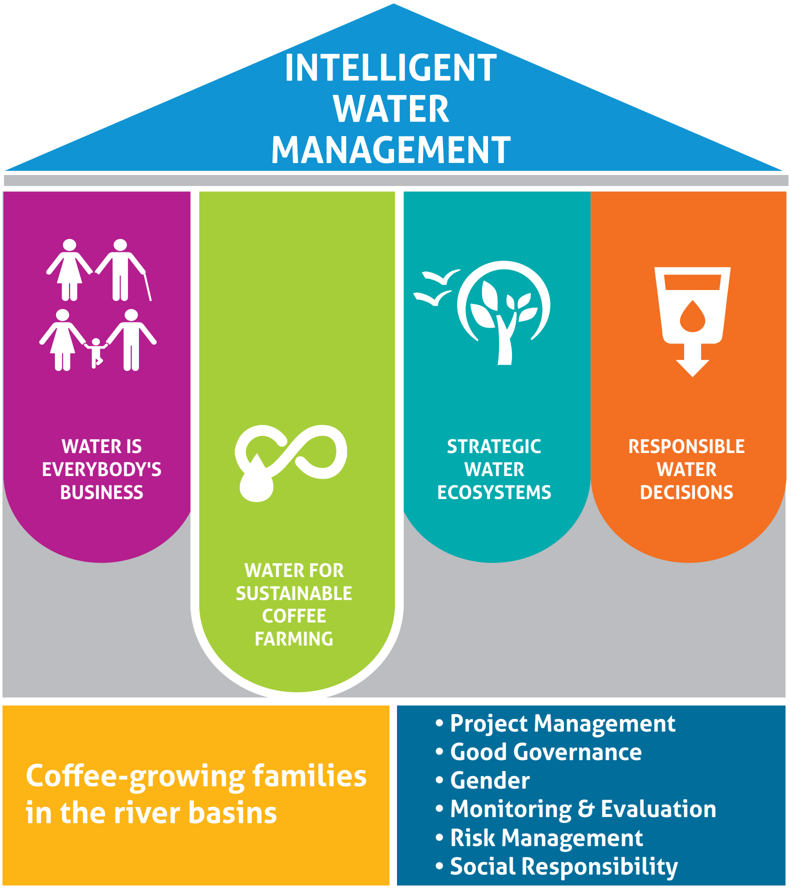
Ángel de Miguel García***

Joop Harmsen***

Iemke Bisschops***

* Scientific Researcher III
** Research Assistant
Post-harvest Discipline
National Coffee Research Center
(Cenicafé)

*** Wageningen University and Research. Environmental Research



Intelligent Water Management (IWM)-Manos al Agua is a Public-Private Partnership that developed a model to implement and improve systems for intersectoral cooperation, sustainable coffee farming, environmental protection and decision-making that help face water imbalance challenges in the coffee sector and its value chain, creating environmental, social and production conditions for: alleviating poverty, improving rural welfare, contributing to peace, and achieving sustainable development in the Colombian countryside.

APPROPRIATE TECHNOLOGIES FOR WATER TREATMENT ON COFFEE FARMS

WATER FOR SUSTAINABLE COFFEE FARMING

IWM is a 5-year project implemented in the departments of Antioquia, Caldas, Cauca, Nariño, and Valle del Cauca, focused on integrated water resource management in 25 river basins, involving over 11,630 coffee-growing families, in an intervention area of 148,754 hectares.

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CEO
Colombian Coffee Growers Federation (FNC)

Jean-Marc Duvoisin
CEO, Nespresso

Mark Schneider
CEO, Nestlé

Alejandro Gamboa Castilla
General Director, Colombia's Agency for International Cooperation (APC Colombia)

Wageningen University and Research

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Ministry of Foreign Affairs of the Netherlands and Netherlands Enterprise Agency

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Nestlé Colombia

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Green Coffe Project Manager
Nespresso Colombia

Nelson Rodríguez
Ph.D. in Hydraulic Engineering and the Environment, Scientific researcher
Cenicafé, FNC

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SUMMARY

Coffee farms require drinking water for human consumption and good-quality water for wet coffee processing. The farms produce mainly two types of wastewater that impact natural resources such as water, soil, air, and biodiversity: wastewater from household activities (domestic wastewater) and wastewater from wet coffee processing (coffee wastewater).

The Intelligent Water Management (IWM)-Manos al Agua Project implemented activities to obtain drinking water and treat coffee wastewater from farms based on appropriate technologies (efficiency and cost) for rural areas; new technologies were also researched to offer coffee growers a greater diversity of options for farm wastewater management and treatment.

For water purification, processes such as slow filtration, nanofiltration and distillation were evaluated with good results; for domestic wastewater treatment, the Project evaluated septic systems consisting of a grease trap, a polyethylene septic tank, an upflow anaerobic filter filled with corncobs, pieces of nonreturnable bottles or bamboo to enable colonization and adherence of a microbial biofilm, and further treatment in an artificial wetland (a waterproof pond with a length/width ratio lower than 4, containing plants), one of the most appropriate solutions to comply with Colombian regulations on discharges to soil (Decree 1594 of 1984) and to surface water bodies (Resolution 631 of 2015). It is of vital importance that capacities of the septic system units be designed and calculated according to provisions of Colombia's Technical Regulations on Drinking Water and Basic Sanitation (RAS 2000) and sludge be periodically removed; for this purpose, a pipeline device based on the inverted-siphon principle was specifically designed.

The main strategy for coffee wastewater treatment is adoption of ecological wet milling of coffee, understood as the process where less than 10 L of water are used to produce 1 kg of dry parchment coffee (dpc), and pulp and mucilage generated in the transformation of cherries into dry beans are appropriately managed.

The first step in ecological wet milling of coffee is removal and transport of pulp to a roofed pit without using water. Depending on farm production and economic capacity of the producer, coffee washing may use fermentation tanks with the technique of four rinses that consume less than 5 L of water per kilogram of dry parchment coffee, mechanical mucilage removal that consumes less than 1 L of water per kilogram of dry parchment coffee, and the Ecomill® technology (mechanical washer), which consumes less than 0.5 L of water per kilogram of dry

parchment coffee, generating in all cases volumes of water to be treated lower than those generated in conventional wet coffee processing, which consumes over 40 L of water per kilogram of dry parchment coffee.

There are several technologies for coffee wastewater treatment with different efficiencies, lifetimes, and investment and maintenance costs, and selection by producers will depend, in addition to national regulations, on requirements by local regulations, the producer's economic capacity, and wastewater volume.

The IWM Project implemented and assessed reuse pits, Modular Anaerobic Treatment Systems (SMTA in Spanish), and artificial wetlands.

Reduction of pollution in the IWM river basins was determined based on the 3,346 wastewater treatment implementations (both for coffee and domestic wastewater).

Treatment systems prevented 37% of pollution in domestic wastewater from 50% of the farms located within 200 m from water bodies, and 29.5% of pollution in coffee wastewater from 50% of the farms located within 200 m from water bodies.

The wastewater treatment implementations prevented 2,443 tons of pollution (expressed in COD) per year in the river basins, an achievement of great importance as the coffee regions are located mostly in the large Magdalena-Cauca basin, where 87% of the country's pollution load is generated.

On average, pollution prevented in the 11 river basins evaluated until the seventh water quality monitoring campaign was 19.36% thanks to the wastewater treatment systems implemented, and surface water quality improved 149.12% on average, a multiplying factor of 9.

WATER TREATMENT ON COFFEE FARMS

INTRODUCTION

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Water availability is essential for sustainable development of societies. Climate variability and air pollution directly influence availability of water, whose space-time supply is variable. Agriculture is a production activity demanding large water volumes and is one of the main economic activities in the country. According to the 2010 and 2014 National Water Studies, average rainfall has decreased from 3,000 mm/year in 2010 to 2,864 mm/year in 2014. The 136 mm of water that stopped falling as rain are equivalent to 93 km3 of surface run-off that would have supplied our country's population for 34 years.

Most of the coffee regions in Colombia are located in the large Cauca-Magdalena basin, where about 70% of the Colombian population lives and which receives only 13.5% of the national water supply. Caring for the region's water resource is therefore of vital importance, starting with rational use in production processes and water reuse as a strategy to reduce pressure on surface water, not only with regard to the amount of water in the basin that is abstracted, but also as to water quality (preventing wastewater discharges improves water quality at source).

It is estimated that the Cauca-Magdalena basin generates 90% of the country's pollution load resulting from wet coffee processing and 87% of the pollution resulting from domestic and industrial wastewater; however, only 10% to 20% of the pollution load passes though treatment systems.

43.5% of Colombia's municipalities report having domestic wastewater treatment plants, but only 26% are operating (Superintendency of Public Utilities, SSPD, 2013). Of the plants that work, some do preliminary treatment, others primary treatment, and others secondary treatment, so environmental impact on water resources is very high and is becoming the main cause of less availability of this resource.

In 2010, Colombia enacted its National Policy for Integrated Water Resources Management, which establishes eight principles: **1.** Water is a public good and its conservation is everybody's responsibility; **2.** Human consumption will have priority over other uses, and collective use takes precedence over individual use; **3.** Water is a strategic resource for social, cultural and economic development; **4.** Water management harmonizes with local, regional and national processes; **5.** The river basin is the fundamental unit for planning and management of the resource; **6.** Fresh water is a scarce resource and its use must be rational; **7.** Water management will have a participatory and multi-sectoral approach incorporating social equity; and **8.** Access to information and research are fundamental in integrated water resources management.

To achieve these principles more easily, the national water policy makes use of:

- Planning tools, including river basin management plans (Decree 1640 of 2012 by the Ministry of the Environment and Sustainable Development, MADS, the acronym in Spanish).
- Control tools, including the Program for Efficient Use and Saving of Water (PUEAA), the Sanitation and Wastewater Management Plans (PSMV), and wastewater regulations (Decree 1594 of 1984, Ministry of Agriculture; Decree 3930 of 2010, former Ministry of the Environment, Housing and Territorial Development, MAVDT; and Resolution 631 of 2015, MADS).
- Economic tools, including water use taxes (Decree 155 of 2004, MAVDT), retribution taxes (Decree 2667 of 2012, MADS), and tax incentives (Decree 3172 of 2003, Ministry of Finance).
- Information tools, such as the National Environmental System (SINA) and the Water Resource Information System (SIRH).
- Financial, conservation, and sanctioning tools (Law 1333 of 2009, MAVDT).

The National Policy for Integrated Water Resources Management and its legal tools aim at conservation of water in quantity and quality in the different river basins in the country, in order to maintain current and future water supply for the different active and passive water uses in Colombia.

According to baseline information gathered in formulation of the IWM Project in 2012, supported by data from the Coffee Information System (SICA), the National Planning Department, and the System for Selection of Potential Beneficiaries of Social Programs (SISBEN), the percentage of coffee farmers with proper aqueduct service is 31%, and with proper sewage service is only 2%.

The IWM Project, the slogan for which, "Manos al Agua," also became its brand identity, has directly benefited nearly 2,400 farmers located within 200 m from water bodies in 25 coffee river basins, providing water savers, nanofiltration systems for drinking water production, and domestic and coffee wastewater treatment systems, thus improving the quality of farmers' lives and of water ecosystems of the coffee region in the large Cauca-Magdalena basin.

WATER TREATMENT ON COFFEE FARMS

OVERVIEW

2

Uses of water resources

Coffee farms require water for domestic, agricultural and livestock activities. In domestic activities, it is required for human consumption (drinking and food preparation), personal hygiene (showering, washing, tooth-brushing, etc.), laundry, washing-up, cleaning of facilities and vehicles, and sanitation (flushing). Coffee farming requires water for irrigation of germinators, seedlings and the garden, wet coffee processing, and cleaning of mills. Livestock activities include pig, fish and poultry farming, which require water for both drinking troughs and infrastructure cleaning.

In Colombia, water is a public good; therefore, it is necessary to obtain the right to use it.

Water use rights

In Colombia there is public-domain and private-domain water.

Public-domain water: includes rivers, water running through artificial canals derived from natural ones, lakes, lagoons, marshes, wetlands, rain water.

Private-domain water: springs up naturally and disappears by infiltration or evaporation within a property (springing up and dying in the same place), which rarely happens, so most water is of public domain.

There are several ways to obtain the right to use water and water channels:

Use by operation of law

All persons may use public-domain water that runs through natural channels without authorization if it is for drinking, bathing, washing clothes and other similar purposes, in accordance with sanitary regulations on the issue and those on protection of renewable natural resources. These uses do not grant exclusive rights or priority to the first individual or person exercising the right; in addition, use is free, that is, neither the State nor individuals may charge for it.

If it is water that runs through an artificial canal, it may also be used for domestic purposes or watering as long as the intended use does not require water to be preserved pure, damages to the canal or ditch are not caused, or the water licensee is not prevented or hindered from using it.

Use of private-domain water for domestic purposes requires:

- No damages to the source farm.
- Avoiding diversions or using machines or devices or altering or contaminating water in such a way that its use by the property owner becomes impossible.
- A previous agreement with the farm owner on the access path and hours to exercise that right.

Use by concession

A water concession is one of the ways of gaining the right to use water for the activities or purposes that natural or legal, public or private persons require.

This is a way for ensuring its conservation, as well as fair distribution. So every natural or legal, public or private person requires a concession or permit for its use.

A water concession must be requested in all cases where its use is not authorized by operation of law. For example, for the following purposes:

- Domestic supply requiring diversion.
- Irrigation and forestry.
- Supply to troughs requiring diversion.
- Industrial use.
- Mining and oil industry.
- Hydroelectric generation.
- Aquaculture and fishing.
- Recreation and sports.

Use by permits

Common permits for withdrawal of materials from channels, beds or reservoirs; they are requested before the region's environmental authority.

Use by association

Associations or community companies are formed to use watercourses or channels. Water user associations are to be formed by those using water from one or more streams within the same distribution system. They must be constituted by document and have bylaws governing relations between all the users.

Priorities for water use

There is a priority order for water concessions. Household use will always have priority over the others, collective uses over individual ones, and uses by a region's inhabitants over those from outside.

Granting of water concessions is subject to availability of the resource, therefore the State, i.e. the environmental authority, is not accountable when the granted amount of water cannot be guaranteed because of natural causes. The order in which concessions are granted does not give priority, and in cases of shortage, the environmental authority will define the best procedure to distribute water.

Concessions are granted for up to 10 years, except those for provision of public services or construction of public- or social-interest works, which may be granted for up to 50 years.

Water quality according to use

By Decree 1594 of 1984, the Colombian Ministries of Agriculture and of Health set the quality standards and maximum permissible values for water intended for human and domestic consumption, flora and fauna preservation, and agricultural, livestock, recreational, industrial, and transport uses.

Of all uses described, the one intended for human consumption requires the best-quality water, requiring a purification process.

Resolution 2115 of 2007 by the Ministry of Social Protection (MPS) and the former Ministry of the Environment, Housing and Territorial Development defines purification as a set of operations and processes applied to raw water in order to modify its physical, chemical and microbiological characteristics to make it fit for human consumption.

Water supply systems

Water supply systems refer to activities and elements required for continuously having water available, both at home and in production processes.

The methods most commonly used for water supply are: transport, rainwater collection and storage, digging of wells to use groundwater that is close to the surface, and abstraction from surface sources, as well as its distribution to households or production systems with or without treatment.

In most cases where water is used directly from the source, without purification treatment, the environmental regulations regarding quality are being broken.

Water purification plants

Drinking water is water that has been treated for human consumption. This water must not contain organisms, chemicals, minerals, or impurities that may cause diseases.

In purification, water undergoes treatment processes, the most important being: clarification, filtration, and disinfection.

Clarification: a process to remove suspended matter from turbid water to make it clear, adding chemicals known as coagulants. Iron and aluminum salts are the most commonly used ones, which enable formation of settleable particles to thus remove pollution from water. The process may be accelerated by using other chemicals known as flocculants.

Filtration: a process where water is passed through several layers of porous material to remove some bacteria and suspended particles.

Disinfection: a process that removes microorganisms from water. Among the disinfectants most commonly used are chlorine and its derivatives, iodine and ozone.

A water purification plant is a sequence of processes (performed in different structures or units) to fully remove microbiological contaminants from raw water, and partially the physical and chemical ones, until reaching acceptable limits required by regulations.

There are several types of purification plants, the most common being conventional plants and compact plants.

Conventional plants: They sequentially perform the processes of coagulation, sedimentation, filtration, and chlorination in different tanks or structures.

Compact plants: In these plants, the treatment processes take place in a prefabricated module (Figure 1); they are recommended for supplying water to small communities.

Figure 1. Compact plant installed in the department of Antioquia.

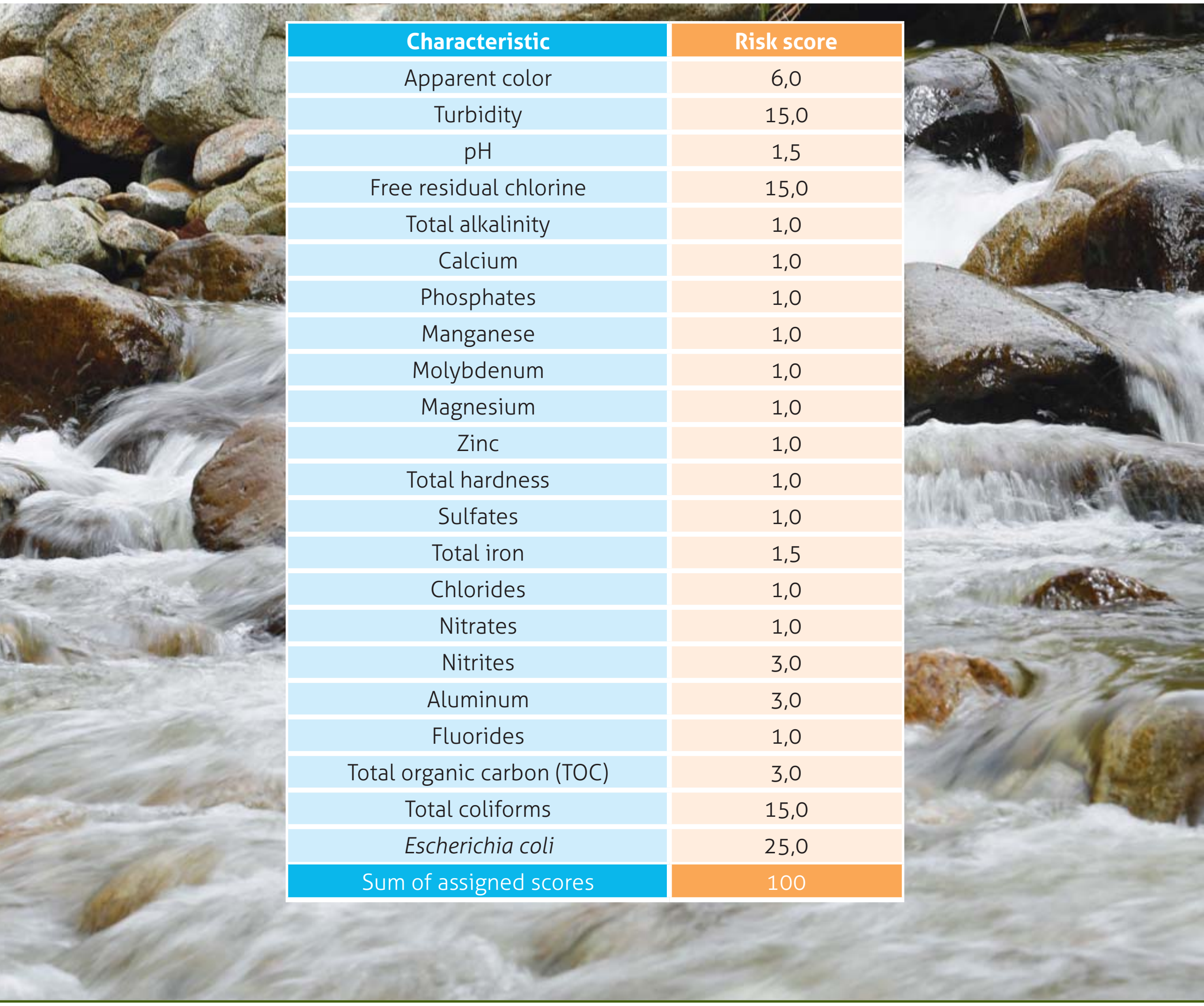
Water Quality Risk Index (IRCA)

Regarding human consumption, the Water Quality Risk Index (IRCA) is a basic tool to guarantee water quality. It is defined in Resolution 2115 of 2007, issued by the former Ministry of the Environment, Housing and Territorial Development.

For calculation of this index, risk scores are given to water characteristics or parameters not complying with limit values set in the resolution. The characteristics considered are: color, turbidity, pH, residual chlorine, alkalinity, calcium, phosphates, manganese, molybdenum, magnesium, zinc, hardness, sulfates, iron, chlorides, nitrate, nitrites, aluminum, fluorides, total organic carbon, and total and fecal coliforms.

The parameters that do not pose a risk are given a score of zero, and those exceeding limit values and therefore posing a risk are given predetermined scores, depending on their importance and impact on human health (Table 1).

Table 1. Risk parameters and scores in calculation of IRCA (Source: MAVDT, 2007).



Characteristic	Risk score
Apparent color	6,0
Turbidity	15,0
pH	1,5
Free residual chlorine	15,0
Total alkalinity	1,0
Calcium	1,0
Phosphates	1,0
Manganese	1,0
Molybdenum	1,0
Magnesium	1,0
Zinc	1,0
Total hardness	1,0
Sulfates	1,0
Total iron	1,5
Chlorides	1,0
Nitrates	1,0
Nitrites	3,0
Aluminum	3,0
Fluorides	1,0
Total organic carbon (TOC)	3,0
Total coliforms	15,0
Escherichia coli	25,0
Sum of assigned scores	100

The IRCA value is zero when all of the characteristics being assessed meet acceptable values and 100 when they are not met at all.

IRCA calculation

For calculation of the IRCA, Equation (1) is used:

$$\text{IRCA (\%)} = \frac{\sum \text{ of risk scores of unacceptable characteristics}}{\sum \text{ of risk scores of all characteristics analyzed}} \times 100 \quad (1)$$

Based on the IRCA results, the risk level of water supplied for human consumption is classified (Table 2).

Table 2. IRCA classification and risk level (Source: MAVDT, 2007).

IRCA classification (%)	Risk level	IRCA per sample (notifications to be immediately issued by health authority)	Monthly IRCA (actions)
80,1 - 100	Sanitarily unviable	Inform provider, Epidemiological Monitoring Committee (COVE), Mayor, Governor, SSPD (utilities supervisor), MPS, INS, MAVDT, Auditor General, and Inspector General.	Water unfit for human consumption, direct management, according to powers, by provider, Mayors, Governors, and national government agencies.
35,1 - 80,0	High	Inform provider, COVE, Mayor, Governor, and SSPD.	Water unfit for human consumption, direct management, according to powers, by provider, and respective Mayors and Governors.
14,1 - 35,0	Medium	Inform provider, COVE, Mayor, and Governor.	Water not fit for human consumption, direct management by provider.
5,1 - 14,0	Low	Inform provider and COVE.	Water unfit for human consumption, need for improvement.
0 - 5,0	Without risk	Control and monitoring must continue.	Water fit for human consumption. Continue monitoring.

Hierarchy of water needs

According to the Pan American Health Organization (PAHO) and the World Health Organization (WHO), the daily minimum water requirements per person are shown in Table 3.

Table 3. Domestic water requirements (Source: Adapted from PAHO/WHO, 2009)

Activity	Range (L/day)
Drinking	3-4
Cooking	2-3
Personal washing	6-7
Washing clothes	4-6
Sanitation	10-15

Figure 2 shows the hierarchy of water requirements.

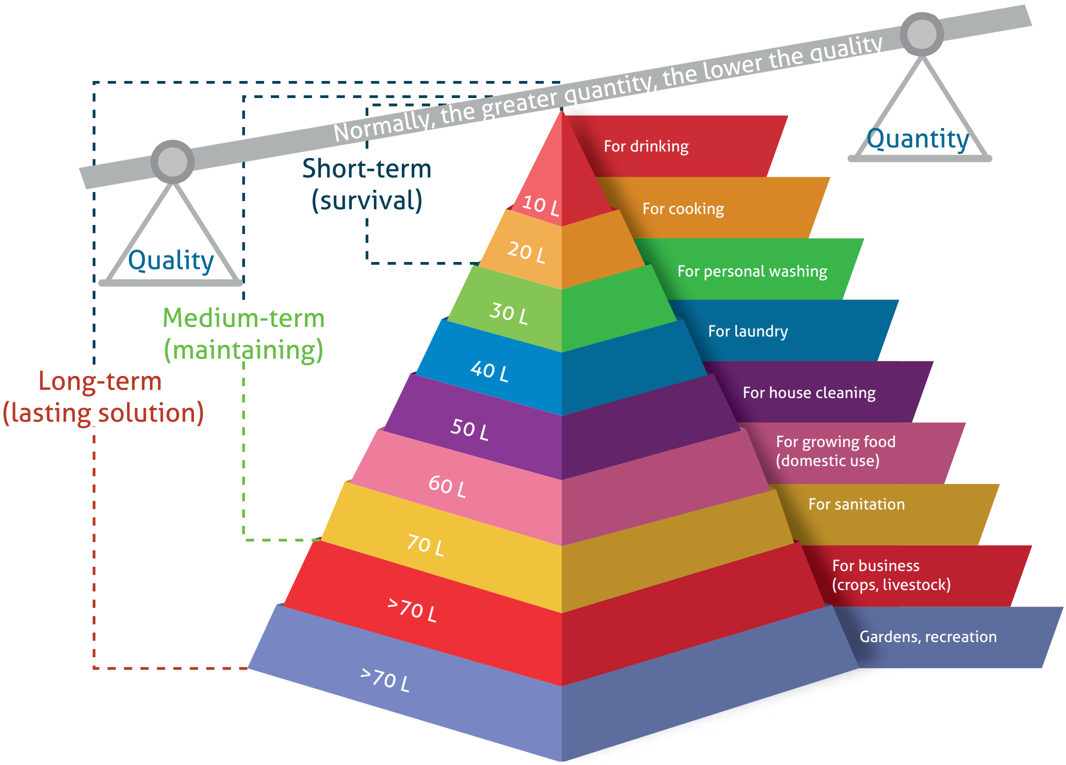


Figure 2. Hierarchy of water requirements (Source: Adapted from PAHO / WHO, 2009).

Program for efficient use and saving of water

Colombia enacted Law 373 of 1997, which established the Program for efficient use and saving of water, drafted by the Ministry of the Environment and Sustainable Development, and Resolution 726 of 2015, issued by the Drinking Water and Basic Sanitation Regulatory Commission, "by which measures are adopted to promote efficient use and saving of drinking water, and discourage excessive use," (defined as higher than 28 m3/subscriber-month in settlements from 1,000 to 2,000 masl).

Efficient water use involves technologies and improved practices to provide the same or better service with less water; these practices mean making rational and efficient use of water, in the minimal quantities according to their use. These practices may be:

Engineering practices: based on modification of operation pipes, accessories, and water use procedures:

- Reduction of losses (checking and fixing leaks).
- Reuse of water, i.e. using water resulting from a specific purpose for another different purpose.
- Water recycling, i.e. using water for the same purpose it initially served; treatment is likely to be required before using it again.

Behavior (conduct) practices: based on change of water consumption behaviors for a more efficient use; these changes save water without having to make modifications to infrastructure.

Efficient water use at home

Average water use at an average home may vary between 150 and 250 L per person a day.

A series of simple daily activities at home to save water:

- Turn off the faucet while brushing teeth; in this way, a 5-member family can save up to 40 L of water a day.
- Do not use the toilet to dispose of paper or other solid waste, as it requires flushing. This solid waste has to be disposed of in a bin.
- Take short showers, and turn off the faucet while lathering.
- Rinse the shaver in a container and not under running water.
- Use water-saving devices, such as low-flush toilets (less than 6 L) or flow restrictors in pipes, showers and faucets.
- Make sure faucets and toilet are not leaking.
- Lawns and gardens are to be watered at the end of the afternoon to reduce evaporation.
- All family members must have water saving in mind.

These practices reduce water consumption at home, also reducing costs and contributing to sustainability of water ecosystems.

Efficient water use in wet coffee processing

Ecological wet coffee processing is a process by which coffee cherries are transformed into dry parchment coffee (dpc), an ecofriendly process that produces coffee with the physical quality and sensory attributes typical of Colombian coffee (Roa *et al*., 1999).

Ecological wet mills typically have two fundamental characteristics:

1) Overall water consumption in wet coffee processing is less than 10 L/kg of dpc, and **2)** Byproducts (pulp and mucilage) generated in the process have to be partially or totally managed, following best practices (Rodríguez *et al*., 2015).

In ecological wet processing, dry or water-recirculation hoppers, natural fermentation, and coffee washing and classification in fermentation tanks, using the technique of rinses (Zambrano, 1993), are recommended for growers producing less than 1,000 kg of coffee cherries on the peak day. For medium-sized and large producers (more than 1,000 kg of coffee cherries on peak day), hydraulic separators with hopper and worm gear (Oliveros *et al*., 2007), wet hoppers with recirculation and siphon tank with recirculation are recommended for hydraulic classification of beans, and mechanical mucilage removers and washers are recommended for washing beans.

Wastewater treatment systems

According to the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM, 2015), in the 2014 National Water Study, the estimated water consumption in 2012 for domestic use was 2.96 billion cubic meters; with an estimated return coefficient of 80%, daily domestic wastewater volume would be 6.5 million cubic meters, of which only about 20% is treated. However, not all treatment systems work properly due to different causes, such as: 1. Lack of knowledge about how the system works; 2. Bad operation and poor maintenance; 3. Lack of financial sustainability; 4. Insufficient environmental awareness of populations; and 5. Low public-private participation in initiatives to promote basic sanitation projects, coupled with institutional deficiencies (MAVDT, 2010). The remaining 80% is discharged, without any treatment, to water bodies (surface, groundwater, marine) or to the ground, causing great deterioration of natural resources.

With enactment of the National Policy for Integrated Water Resources Management, planning, control, economic, sanctioning and information tools were updated with the aim of recovering and conserving the different water sources.

One of the main planning tools is Decree 1640 of 2012 on river basin management plans; control tools include Decree 3930 of 2010, with provisions on use and management of water resources, and discharges to water bodies, to soil and to drainage systems, and Resolution 631 of 2015, setting parameters and maximum permissible values for wastewater before being discharged to surface water bodies.

Among the economic tools is Decree 2667 of 2012 on payment of taxes as retribution for wastewater pollution; sanctioning tools include Law 1333 of 2009 and Decree 3678 of 2010, with environmental fine rates; and, finally, information tools include the Environmental Information System (SIA) and Water Resources Information System (RIME).

Wastewater treatment is one of the solutions for mitigating deterioration of water quality in surface, underground and sea water bodies caused by disposal of wastewater from production sectors and residential areas.

Permit for discharges

A discharge is any disposal of elements, substances or compounds in a liquid medium to a water body or public sewage system or to the ground.

Any person whose activities generate liquid discharges to water or to the ground must apply for a permit for discharges, for example, mining and industry wastewater or household wastewater when there is no sewer available.

The permit for discharges is the right granted by the environmental authority to discharge wastewater to a water body, to the ground or to any other environment with a previous treatment thereof, and complying with regulations on point source discharges. The permit for discharges is important to reduce water, soil and groundwater pollution, helping keep water resources free from pollution. Permits for discharges also help prevent sanctions.

Decree 3930 of 2010, issued by the Ministry of the Environment and Sustainable Development, states: *"Any natural or legal person whose activity or service is discharging wastewater to surface or sea water or to the ground must request and obtain from the competent environmental authority the respective permit for discharges."*

Characteristic parameters of wastewater

The parameters most frequently used to characterize and evaluate efficiency of removal of pollution from wastewater are those related to: ***presence of organic matter, presence of nitrogenous substances, presence of phosphorous substances, and presence of enterobacteria.***

Surface water and groundwater, besides minerals and dissolved substances, may have suspended organic substances coming from runoffs or metabolized by organisms living in soils. In addition, domestic or industrial wastewater can reach surface water and groundwater bodies , causing pollution at variable levels.

These organic substances are a food supply for (autotrophic and heterotrophic) organisms present in water; they tend to disappear progressively by oxidation and turn into CO2, ammonia, nitrites and nitrates, among others.

Usually uncontaminated natural water has minimal amounts of organic matter, except that coming from forests or stagnant water. Organic matter may be, in many cases, responsible for water color, smell and taste, which must be removed during treatment in order to make water fit for human consumption.

Quantification of organic matter in wastewater. Overall methods to determine the organic substances present in wastewater have been established with the following parameters:

Chemical Oxygen Demand (COD): a measure of the equivalent oxygen necessary to chemically oxidize the organic matter found in water. It is the amount of oxygen that reducing substances in wastewater, such as organic matter, need to decompose without intervention of microorganisms (Figure 3).

Biochemical Oxygen Demand (BOD5): measures the amount of oxygen (mg/L) to be provided to a natural bacterial culture to consume organic contaminants in five days (Figure 3).

Total Organic Carbon (TOC): an analysis to determine the amount of all organic carbon present in a wastewater sample, the result of all organic compounds in the sample; the higher content of TOC, the greater pollution in the wastewater sample.

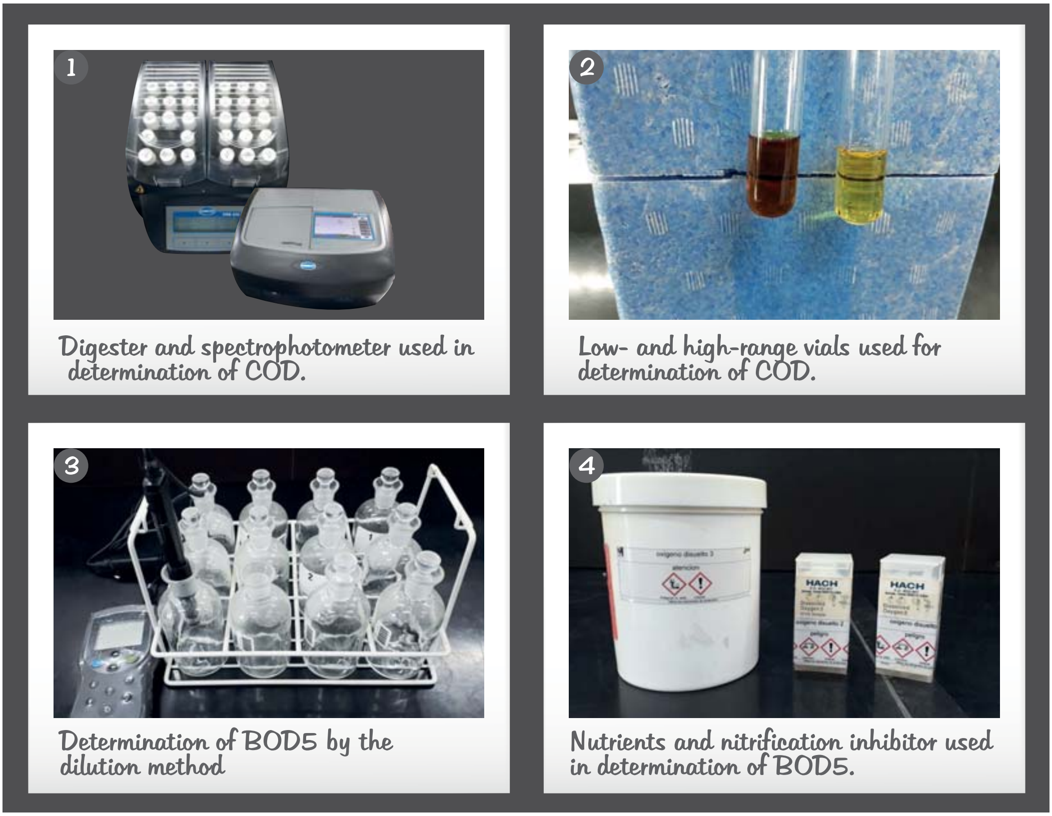
TOC may be related to COD (Hach, 2013) by Equation (2):

$$\textbf{TOC} = 0{,}2498\,(COD) + 4{,}6532 \quad (2)$$

There are rapid methods for determining COD in 2 hrs, such as the closed reflux, colorimetric method, developed by the HACH and approved by the US EPA (HACH, 1988).

Organic matter is removed through coagulation-flocculation, sedimentation and filtration; however, when the raw water source has a very large organic and bacterial load, a case in which the BOD5 may reach very high values, a pre-chlorination (as a properly controlled process) is required.

Raw water sources must not have a high organic load. Because of the nature of these parameters, water quality standards establish that causes of organic pollution must be absent in water for human consumption.



Digester and spectrophotometer used in determination of COD.

Low- and high-range vials used for determination of COD.

Determination of BOD5 by the dilution method

Nutrients and nitrification inhibitor used in determination of BOD5.

Figure 3. Physicochemical characterization of wastewater.

Quantification of solids present in wastewater. All matter, except water, found in liquid materials is classified as solid matter. In basic sanitation, it is necessary to measure the amount of solid matter present in liquid substances ranging from drinking water to polluted water (domestic and industrial wastewater). High values of solids in wastewater (higher than 500 ppm) may indicate pollution problems.

The following parameters are used for quantification of solids present in wastewater:

Total Solids (TS): Those remaining after drying a wastewater sample at 105° C (Figure 4). They consist of total suspended solids and total dissolved solids.

Figure 4. Oven used in determination of solids.

Total Suspended Solids (TSS): Non-filterable residue or undissolved material present in wastewater (Figure 5).

Figure 5. Filter paper used in determination of suspended solids.

Settleable solids: Volume of solid material that settles to the bottom of an Imhoff cone in an hour per each liter of wastewater (Figure 6).

Figure 6. Determination of settleable solids in Imhoff cones.

Quantification of nitrogen present in wastewater. The most important forms of nitrogen in wastewater are nitrate, nitrite, ammonia and organic nitrogen. Nitrogen is removed in several phases. Nitrogen is quantified according to the methodology established in the standard manual of methods (APHA, AWWA, WPCF, 1992). (Figure 7).

Figure 7. Determination of nitrogen by the Kjeldahl method.

Quantification of phosphorus present in wastewater. Phosphorus in wastewater is almost only found in the form of phosphates, classified into orthophosphates and polyphosphates (Figure 8). Phosphorus is quantified according to the methodology established in the standard manual of methods (APHA, AWWA, WPCF, 1992).

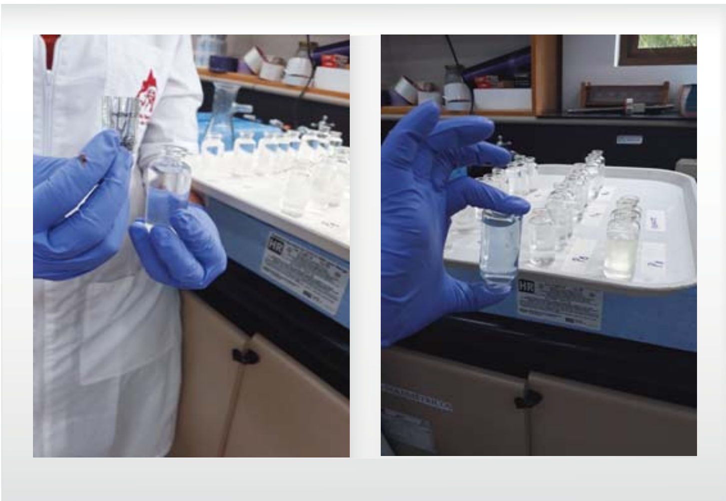


Figure 8. Determination of phosphorus in wastewater.

Other parameters of sanitary significance

pH: is a measurement of wastewater acidity or alkalinity. The measurement scale ranges from 0 to 14 (7 being the value that represents neutrality); values of this parameter above 7 show water alkalinity, and below 7, acidity conditions, in many cases indicating presence of water pollutants (Figure 9).

Figure 9. Equipment for determination of pH.

Total and fecal coliforms: Microbiological water quality is evaluated by indicators. The most commonly used are total coliforms, thermotolerant (fecal) coliforms, *Escherichia coli* and viable aerobic mesophilic heterotrophic bacteria (Aurazo, 2004).

Coliforms are bacteria that live in the intestines of mammals and also as saprophytes in the environment, except *Escherichia*, which has intestinal origin. Coliforms are counted by membrane filtration (Figure 10), according to the standard manual of methods (APHA, AWWA, WPCF, 1992).

Figure 10. Determination of total and fecal coliforms.

Wastewater treatment types

Once the physicochemical and microbiological characteristics of wastewater are determined, and keeping in mind the quality goals pursued in treated effluents (depending on regulations or intended later use), it is necessary to choose treatments that, from the technical and economic point of view, are appropriate for purification. In general, what is sought is to reduce contaminants to turn wastewater into an effluent harmless to the environment.

In wastewater treatment, it is generally necessary to combine several single operations, whose methods may be physical, chemical or biological, and whose purpose is to remove, in the first place, suspended material, then colloidal substances, and finally the dissolved ones.

Wastewater treatments may be classified according to method of removal of pollutants, purification phase and costs.

According to method of removal of pollutants, treatments may be:

Physical: Those in which the application of physical forces predominates; among them we can find coarse screening (using bars or sieves to remove large material), degreasing (using tanks for flotation of greases, detergents and foams), sedimentation (tanks that favor settlement of particulate matter), filtration (use of filters to retain suspended solids), evaporation (use of energy to change water state), and adsorption (use of materials for removal of solids).

Chemical: Contaminants are removed by adding chemical products (such as iron and aluminum salts to enable coagulation and flocculation of pollutants, or calcium compounds for removal of phosphorus compounds by precipitation).

Biological: Pollutants are removed by biological activity; the most common are: activated sludge (use of aerobic microorganisms in presence of air bubbles or water agitation), bacterial filters (use of microorganisms attached to a support, to which enough oxygen is added to ensure microbial activity), lagooning (aerated or non-aerated lagoons with microorganisms), anaerobic digestion (microorganisms that do not need oxygen for their metabolism).

According to purification phase, treatments may be:

Preliminary treatment: intended to prepare wastewater so it can be subsequently treated. It aims at removal of large objects, preventing clogging of pipes, presence of floating solids and flow rate variations, among others, through physical (manual or mechanical) processes. The most common preliminary treatment units are screens, grease traps, compensation tanks, and grit chambers. On coffee farms, domestic wastewater is pre-treated with grease traps, and coffee wastewater with pulp traps.

Primary treatment: aims to remove a portion of suspended solids and organic matter present in wastewater through physical processes (sedimentation, flotation, and filtration), in some cases with chemical processes (coagulation), and in others with biological processes (hydrolysis and acidogenesis). For this type of treatment on coffee farms, domestic wastewater is treated in septic tanks, and coffee wastewater is treated in hydrolytic-acidogenic reactors.

Secondary treatment: Compounds in the form of dissolved solids are transformed into stable compounds through physical (heat treatment), chemical (precipitation and neutralization) or biological treatments (lagooning, activated sludge, biological filters, bio discs, anaerobic sludge blanket reactors, UASB). For this treatment on coffee farms, domestic wastewater is treated through upflow anaerobic filters, and coffee wastewater is treated with methanogenic reactors.

Tertiary treatment: the last step to fully clean secondary treatment effluents, removing elements such as nitrogen, phosphorus, potassium and calcium, among others. In this stage, physical (filters), chemical (disinfection with chlorine compounds), and biological treatments (wetlands) may be used. For tertiary treatment on coffee farms, both domestic and coffee wastewater are treated in artificial wetlands.

According to costs, treatment systems may be classified into:

Low-cost technologies: They feature, among others, the following characteristics:

- Easy operation and maintenance.
- Operation does not require specialists.
- Long response times.
- Simple accessories.
- Low energy costs.
- Good integration in rural environment.
- Acceptable-to-good performance levels.
- Very suitable for agricultural sector.

These technologies include septic systems, modular anaerobic treatment systems (SMTA) for coffee wastewater, biodigesters and artificial wetlands.

Conventional technologies: They have the following characteristics:

- Instrumentation required.
- Specialized labor required.
- High investment and operation costs.
- Low integration in rural environment.
- Good purification results.

These treatment technologies include activated sludge plants and sludge blanket systems.

3

WATER TREATMENT ON COFFEE FARMS

WATER PURIFICATION

Water purification and supply systems

Water for human consumption has to meet the requirements (set out in Decree 1575 of 2007 and Resolution 2115 of 2007) that make it fit for drinking and rate it as such. According to the Technical Regulations on Drinking Water and Basic Sanitation (RAS, 2000), net water supply per person-day for low-complexity aqueduct users (< 2,500 inhabitants) is 100 to 150 L (Table 4).

Net supply is the minimum water amount required for basic needs of a person regardless of losses occurring in the aqueduct system. According to data from the World Health Organization (WHO), the amount of water necessary for cooking ranges from 2 to 3 L/person-day, and for drinking, 3-4 L/person-day.

Table 4. Water supply (Source: RAS, 2000, Title B)

System complexity level	Population (inhabitants)	Minimum net supply (L/inhab-day)	Maximum net supply (L/inhab-day)
Low	< 2.500	100	150
Medium	2.501 a 12.500	120	175
Medium-High	12.501 a 60.000	130	-
High	>60.000	150	-

According to characterization of the IWM river basins, only 31.2% of the surveyed farms have aqueduct service (drinking water supply). Depending on quality of water of the source (raw water), coffee farms can use several simple methods to produce drinking water, such as distillation and filtration.

Domestic distillation for production of drinking water (Rodríguez *et al.*, 2016)

On coffee farms, some kitchen tools can be used to distill raw water. Distilled water meets all parameters required for water fit for human consumption, as it is free from chemical and biological pollutants.

The materials and procedure for producing drinking water on coffee farms through a distillation process, in order to meet water consumption needs (5 to 7 L/person-day), are described below.

Materials needed:

- Pressure cooker or teapot
- Heat source (electricity, natural gas, propane, firewood)
- Cooling coil made of aluminum tube of ¼"
- Plastic container for storage of cooling water
- Plastic container for storage of distilled water
- Plastic container for cooling water outflow

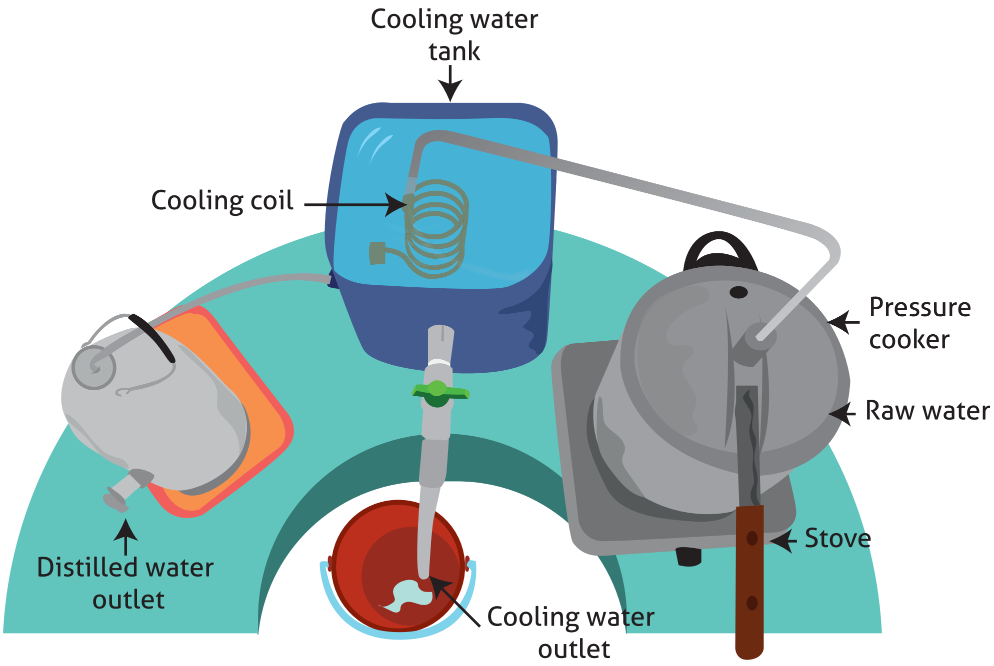


Figure 11. Distillation system with pressure cooker.

Distillation system with pressure cooker. The pressure cooker cover is fitted, at the vent pipe (once the pressure regulator is removed), with a coil made of an aluminum tube of ¼ in, which is then put into a container of water to condense the resulting water vapor. A hose is coupled to the free end of the coil to carry the distilled water to a storage container (Figure 11). The container where the coil is immersed should have a valve to discharge cooling water for refill purposes, due to presence of algae or suspended materials.

Raw water is poured into the pressure cooker, which is covered and placed on a heat source until at least 60% to 70% of initial raw water is distilled.

Distillation system with teapot. Another way of distilling water is using a teapot, which is fitted with an aluminum coil that is submerged in a tank containing water for cooling the vapor generated. A hose is coupled to the free end of the coil for carrying the distilled water to the storage container (Figure 12).

Raw water is poured into the teapot, which is covered and placed on a heat source until at least 60% to 70% of initial raw water is distilled.

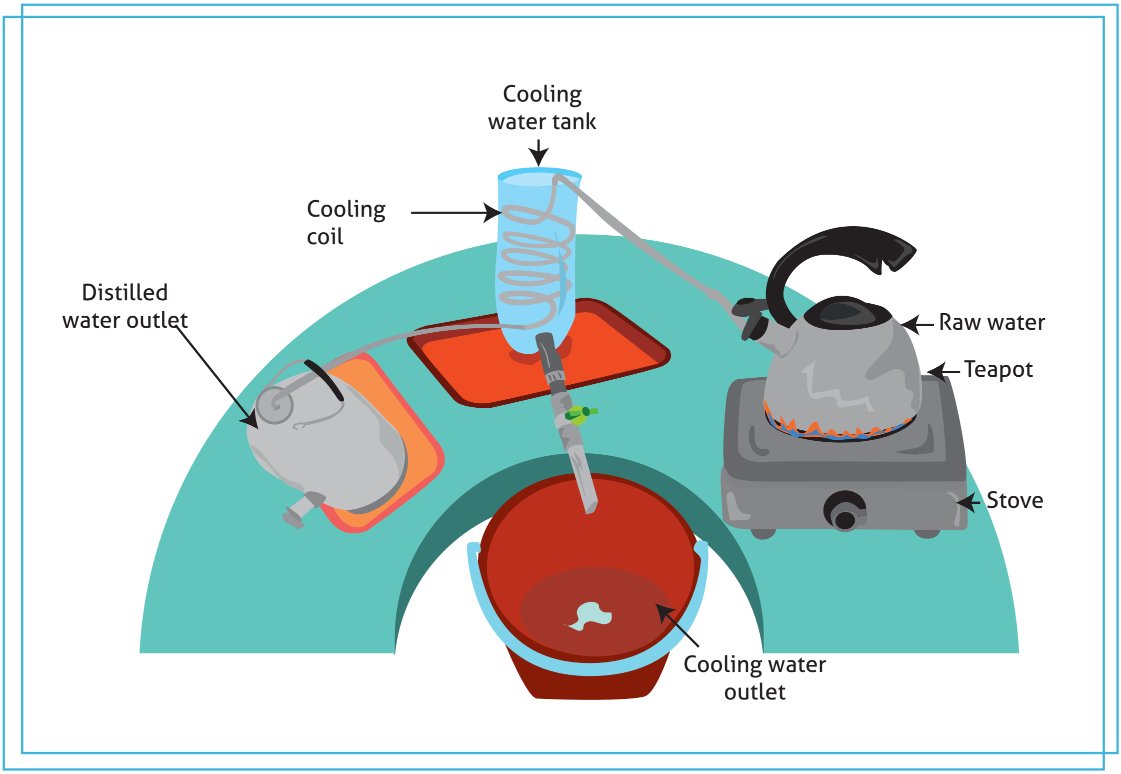


Figure 12. Distillation system with teapot.

Distillation process performance

Table 5 shows information about quantity of water poured into the teapot or pressure cooker in different tests, as well as distillation times and amount of water obtained.

Table 5. Amount of water produced and distillation time.

System type	Raw water amount (L)	Duration (h)	Distilled water amount (L)	Distilled water rate (L/h)
Teapot	2,0	1,32	1,37	1,03
Teapot	2,0	1,24	1,45	1,17
Teapot	2,5	1,41	2,00	1,42
Pressure cooker	5,0	2,27	2,28	1,00
Pressure cooker	3,0	2,18	1,79	0,82
Pressure cooker	2,0	1,39	1,31	0,94

Water characterization

Table 6 shows results of water characterizations in three tests and the values required by Resolution 2115 of 2007 (which sets out the maximum permissible limits for drinking water).

Table 6. Results of distilled water analyses vs. drinking water standards.

Parameters	Test 1		Test 2		Test 3		Max. perm. value (Resolution 2115)
	Raw water	Distilled water	Raw water	Distilled water	Raw water	Distilled water	
pH (units)	6,97	7,07	6,85	7,02	7,01	7,04	6,5-9,0
Apparent color (Pt-Co Un)	14	0	15	0	14	0	15
Turbidity (NTU)	1	0	2	0	1	0	2
Total solids (ppm)	230	12	150	10	180	8	500
TOC (ppm)	24	12	22	10	23	11	5
Total coliforms (CFU/100 mL)	Countless	0	Countless	0	Countless	0	0
Fecal coliforms (CFU/100 mL)	34	0	37	0	43	0	0

Of the variables monitored, only Total Organic Carbon (TOC) exceeded the maximum standard limit: on average, the final value was 11 ppm and the Colombian drinking water standard requires a maximum value of 5 ppm. The predetermined score given for not meeting the parameter limit is 3, so the value of the Water Quality Risk Index (IRCA) is 3%, which is within the range 0% to 5%, meaning there is no risk, water is fit for human consumption, and control and monitoring should continue.

Costs

For calculating costs, power of the stove used in the tests was considered to find the kilowatts per hour (kWh) necessary for production of 1 L of distilled water. With energy consumption per hour (in kWh), energy costs were calculated using other energy sources such as natural gas and propane. The main purpose is for coffee growers to take advantage of unused heat of their wood stoves, which burn throughout the day.

The results obtained in each case are described below:

Electricity: Taking into account the amount of distilled water and the stove power (1.15 kWh), we calculated the kW per hour per liter of water (kWh/L) required; results are shown in Table 7.

Table 7. Distilled water per hour and kilowatts per hour (kWh) required.

Amount of distilled water (L/h)	kW required per liter of distilled water (kW/L)
1,03	1,112
1,17	0,983
1,42	0,810
1,00	1,145
0,82	1,400
0,94	1,220
Average	1,11

On average, 1.11 kWh is required for producing 1 L of distilled water. The cost of 1 kWh in rural areas is COP 250. So, producing a liter of distilled water with electricity costs COP 280 (USD 0.088, 1 USD = COP 3,200).

Natural gas: Given that 1 m3 of natural gas equals 11.7 kWh, 0.0949 m3 of natural gas is required to produce 1 L of distilled water. The cost of 1 m3 of natural gas in the rural area is COP 900, so producing 1 L of distilled water using natural gas has an approximate cost of COP 85 (USD 0.027).

Propane gas: An average gas tank of 40 pounds was taken as a reference, equivalent to 18 kg of propane at a cost of COP 48,000. Approximately 1 kg of propane equals 13.39 kWh. To produce 1 L of distilled water, 0.083 kg of propane is needed, costing on average COP 220 (USD 0.069).

Firewood: Heat from rural firewood-based kitchens may also be used while it is not being used for cooking.

Table 8. Cost of purification of a liter of water.

Energy source	Cost USD/L	Complies with Colombian standard
Firewood	N/A	Yes
Electricity	0,088	Yes
Propane gas	0,069	Yes
Natural gas	0,027	Yes

Household filtration systems (Rodríguez, 2016)

When good quality raw water is available, with physical characteristics such as absence of color, turbidity, solids, smell and taste that can be evaluated through our senses, household filters may be used for producing drinking water. The best filters remove very small particles, such as nanofilters, which eliminate particles smaller than 100 nm.

Nanofilters (20 nm particle size). The nanofilter can purify up to 20,000 L of raw water, with a functional lifecycle of 3 years and a cost of USD 65, at a rate of 210 L/day, according to the manufacturer. The filter has a self-obstruction mechanism: if it does not supply water despite cleaning and washing the prefilter, it means that the useful life has ended.

The filter works by pouring raw water into the plastic container. Inside the container there is a membrane which retains coarse dirt particles. By force of gravity, water passes down through a plastic hose and through the membrane cartridge, which removes contaminants such as bacteria, viruses, parasites and fine dirt particles. The clean, safe water is then ready to be dispensed through the blue tap (Figure 13).

Dirt accumulated in the purifying cartridge can be released through a red outlet tap, by pressing the red membrane-cleaning bulb three times after use. The filter works by simple gravity and does not require spare parts or maintenance beyond simple cleaning; it also does not require batteries or electricity.

Micro-nanofilter

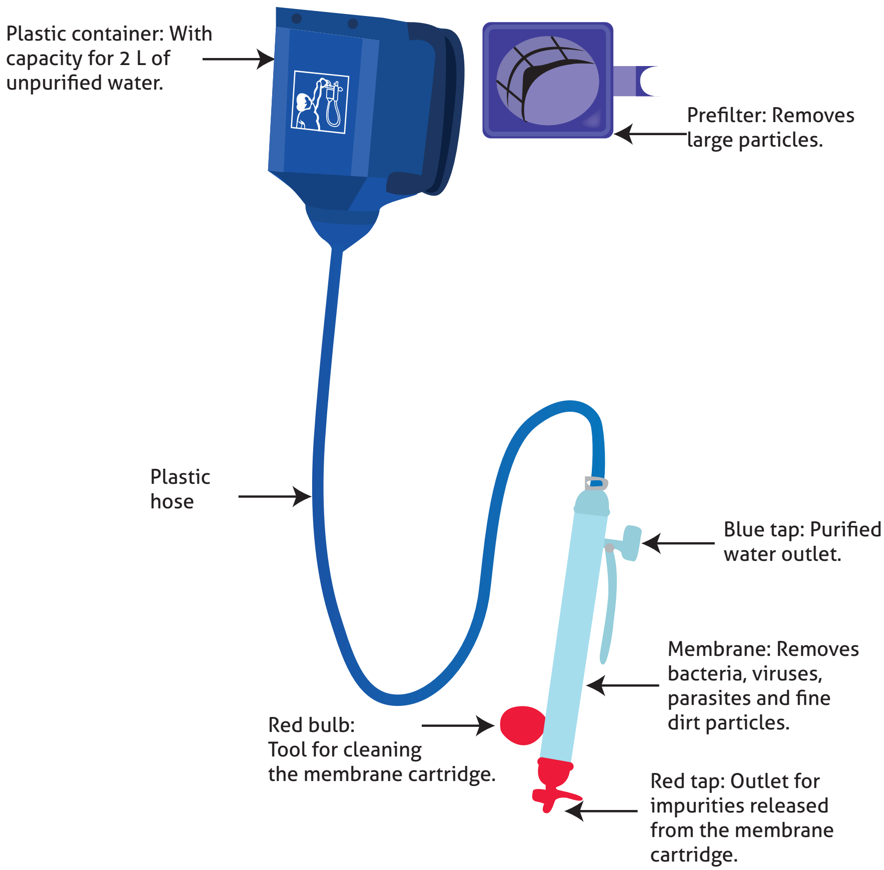


Figure 13. Nanofiltration system (Source: www.iwanagreen.com).

Microfiltration followed by nanofiltration (size particle of 1,000 nm to 20 nm). Micro-nanofilters, according to the manufacturer, can purify up to 15,000 L of raw water, with a lifecycle of 2 years, a cost of USD 45, and a rate of 33 L/day; they are made of porous clay ceramic and activated carbon, both impregnated with colloidal silver. This involves a combined process of ceramic microfiltration and drop-by-drop nanofiltration in a column of activated carbon (Figure 14). It does not require electricity or pressure for operation.

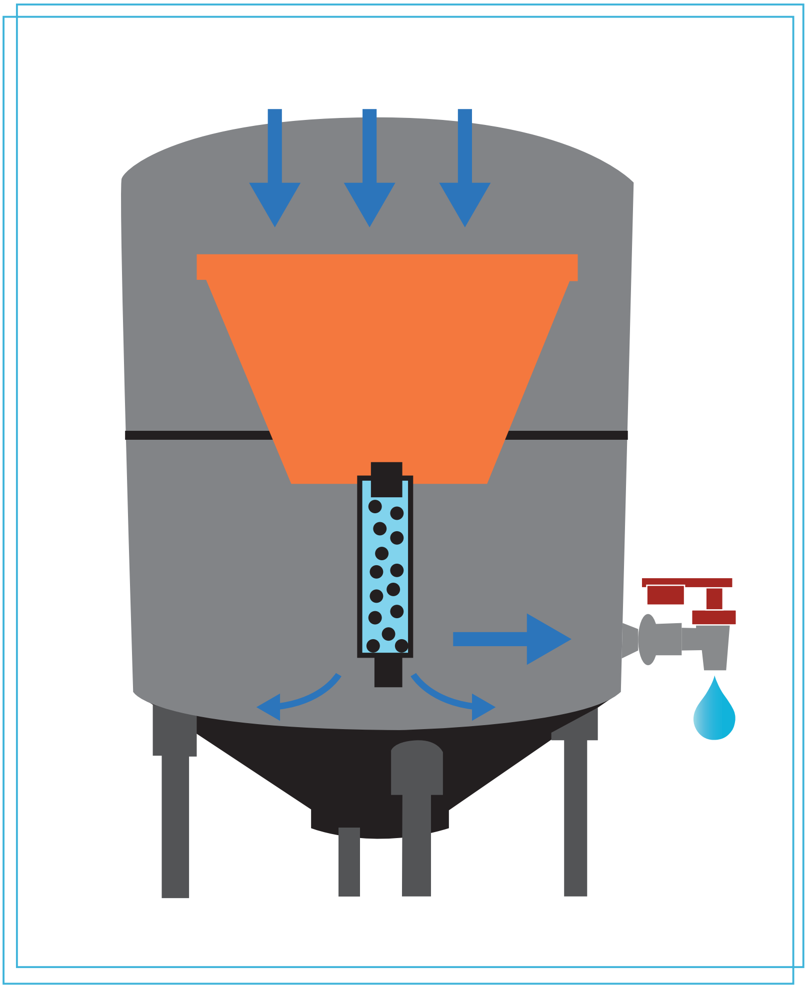


Figure 14. System of microfiltration followed by nanofiltration.

This water purification process consists basically of three stages:

- ***Microfiltration*** for removal of pathogens and contaminants. Raw water is poured into the container that is made of porous clay ceramic, with an average pore size of 1,000 nm.
- ***Removal of harmful microorganisms*** by germicidal action of colloidal silver, impregnated in both the filtering ceramic and activated carbon.
- ***Filtration in activated carbon column*** for total removal of microorganisms and toxic elements of nanometric sizes. Once water has passed through the porous clay for microfiltration, it is collected in an intermediate container that carries water so that it descends by gravity through an activated carbon column, also impregnated with colloidal silver.

The filter is maintained by washing all the filtration system components with clean water and brush at least every 15 days.

Figure 15 shows sampling of filtered water.

Figure 15. Sampling of filtered water.

Table 9 shows results of purification of raw water using the two filtration systems described.

Table 9. Results of analyses of filtered water vs. drinking water standards.

Parameters	Raw water	Water from nanofilter (20nm pore)	Water from micro-nanofilter (Pore < 1,000 nm)	Maximum permissible value (Resol. 2115 of 2007)
pH (units)	6,99	7,56	6,59	6,50 – 9,00
Apparent color (Pt-Co Un)	22	12	6	15
Turbidity (NTU)	4	2	1	2
Conductivity (µS/cm)	139	134	159	1.000
Total solids (ppm)	135	131	95	500
TOC (ppm)	45	18	7	5
Total coliforms (CFU/100 mL)	Countless	0	0	0
Fecal coliforms (CFU /100 mL)	53	0	0	0
Phosphates (ppm)	0,44	0,12	0,35	0,50
Nitrates (ppm)	1,60	0,40	1,00	10
IRCA	50,0	3	3	5

Of the variables monitored, only Total Organic Carbon exceeded the maximum standard limit. On average, the final value was 18 ppm for water coming from the nanofilter and 7 ppm for water from the micro-nanofilter, while the Colombian standard for drinking water requires a maximum value of 5 ppm. The score due to non-compliance with the parameter value is 3, so ***the value of the Water Quality Risk Index (IRCA) is 3%, which is within the range of 0% to 5%, for which there is no risk, water is fit for human consumption, and control and monitoring must continue.***

The results show that it is possible to obtain drinking water through filtration systems as long as water entering the filter is of good visual and organoleptic quality, the nanofilters being used feature a pore size equal to or less than 20 nm, and the filter is permanently maintained and backwashed in order to maintain effectiveness.

Costs of purification with the filtration systems evaluated are shown in Table 10.

Table 10. Cost of filtration systems.

Filtration system	Cost COP/L of water	Compliance with drinking water standard
Micro-nanofiltration	0,003	Yes
Nanofiltration	0,003	Yes

With a need for water for consumption (drinking and cooking) of 5 L/person-day, a 4-member family would need 20 L/day for basic needs, which can be obtained with the distillation and filtration methods.

At the end of Year 4, the IWM Project installed 712 family nanofilters and 27 community nanofilters (Figure 16), and it is estimated that upon completion, the Project will have installed 858 family nanofilters and 51 community nanofilters to provide drinking water to the beneficiaries of the project.

82% of the nanofilters evaluated maintained full efficiency in removal of fecal coliforms to obtain microbiological quality water.

Some reasons why nanofilters failed to produce drinking water were:

1. Loss of useful life because of amount of water treated; **2.** Cross pollution that contaminated treated water; **3.** Lack of filter backwashing, losing efficiency; **4.** Very bad quality of raw water reaching the nanofilter.

Figure 16. Community nanofilters.

The following recommendations for proper operation of purifiers are based on what was observed in the field:

- Placing the filter in a clean site, away from pollution sources.
- Daily backwashing and external cleaning.
- When the water to be filtered features smell, color or suspended material, a pre-treatment with a sand filter is necessary before water enters the nanofilter.
- Using the filter with clean hands.

It should be noted that filters work properly when water to be treated comes from a good quality water source. If water sources are of medium, bad or very bad quality, the filter efficiencies fall considerably.

4

WATER TREATMENT ON COFFEE FARMS

DOMESTIC WASTEWATER TREATMENT

Domestic wastewater treatment

The former Ministry of Economic Development of Colombia, by Resolution 1096 of 2000, adopted the Technical Regulations on Drinking Water and Basic Sanitation (RAS) as the document that sets the basic criteria and minimum requirements to be met by the different processes involved in conceptualization, design, construction, technical supervision, start-up, operation and maintenance of wastewater treatment, purification and sanitation systems to ensure their safety, durability, functionality, quality, efficiency, and sustainability.

On-site wastewater treatment systems (RAS, 2000)

Systems used in isolated locations, where there are no sewage networks or it is necessary to remove suspended solids before discharging wastewater into sewage.

Before designing an on-site treatment system, the following information must be gathered:

- Wastewater quantity and quality.
- Soil type and permeability.
- Temperature (monthly and annual average).
- Land use.
- Quality requirements for surface and subsurface discharges.
- Slope of the ground.

Septic systems for domestic wastewater treatment

One of the most efficient systems used for domestic wastewater treatment is the septic system, consisting of four units: grease trap, septic tank, anaerobic filter, and drain field.

Selection of an appropriate location to install the domestic wastewater treatment system is an important variable to be analyzed. Some general rules to be followed are:

- To be located on sites where it does not pollute water bodies.
- Not to be located in areas with high water-table levels (level under which soil is saturated with water) or prone to floods.
- To be installed on sites allowing by-gravity flow in household pipes.
- As far as possible, flat land requiring minor excavations is preferred.
- To be installed far from trees and bushes whose roots can move or break the system units.

Septic system components

Each of the septic system units and their design, sizing, and maintenance are described below.

Grease trap

This unit physically removes fats, oils and grease (FOG) from wastewater coming from the kitchen, shower or sink. Wastewater moves more slowly in entering the trap, allowing FOG particles, lighter than water, to cool, solidify and float, so degreased water enters the septic tank (Figures 17 and 18).

They are built with small flotation tanks, usually of stainless steel, cement or heavy-duty plastic materials, where grease floats and is retained, while clarified water goes out through a bottom outlet. It has no mechanical parts.

Location

They must be located as close as possible to the wastewater source (kitchen, sink, shower) and before the septic tank to prevent obstruction and odor problems in the subsequent units of the treatment system.

Design parameters

Design must be based on characteristics and flow rate of wastewater to be treated, taking into account that the minimum storage capacity, expressed in kilograms (kg) of grease, must be at least a quarter of the design flow rate (max flow rate) expressed in L per minute (L/min).

The tank must have 0.25 m^2 of area per liter per second, a width to length ratio of 1:4 to 1:18, and a rise rate of at least 4 mm/s. Flow rates, retention capacities and typical hydraulic retention times to be used for grease traps are shown in Tables 11 and 12.

Inlets and outlets

The diameter of the inlet pipe must be at least 2", through an elbow fitting, and the diameter of the outlet pipe of 2" to 4", through a tee fitting. The bottom end of the inlet pipe must be submerged at least 0.35 m. The outlet pipe must start at least at 0.15 m from the tank bottom and be submerged, if possible, at least 0.90 m.

The distance between the inlet and outlet pipes must be large enough to intercept grease and prevent it from being dragged with the flow (with minimal turbulence to allow grease flotation), and their difference of level must be at least 5 cm.

Table 11. Grease retention capacities (Source: RAS, 2000).

Wastewater type	Flow rate (L/min)	Grease retention capacity (kg)	Max capacity recommended (L)
Kitchen	56	14	190
Single room	72	18	190
Double room	92	23	240
Two single rooms	92	23	240
Two double bedrooms	128	32	330
Dishwasher, water volume greater than 115 L	56	14	115
Dishwasher, water volume greater than 190 L	92	23	240
Dishwasher, water volume between 190 and 378 L	144	36	378

Table 12. Hydraulic retention times (Source: RAS, 2000).

Retention time (minutes)	Inflow rate (L/min)
3	120 - 540
4	600 – 1.140
5	1,200 or more

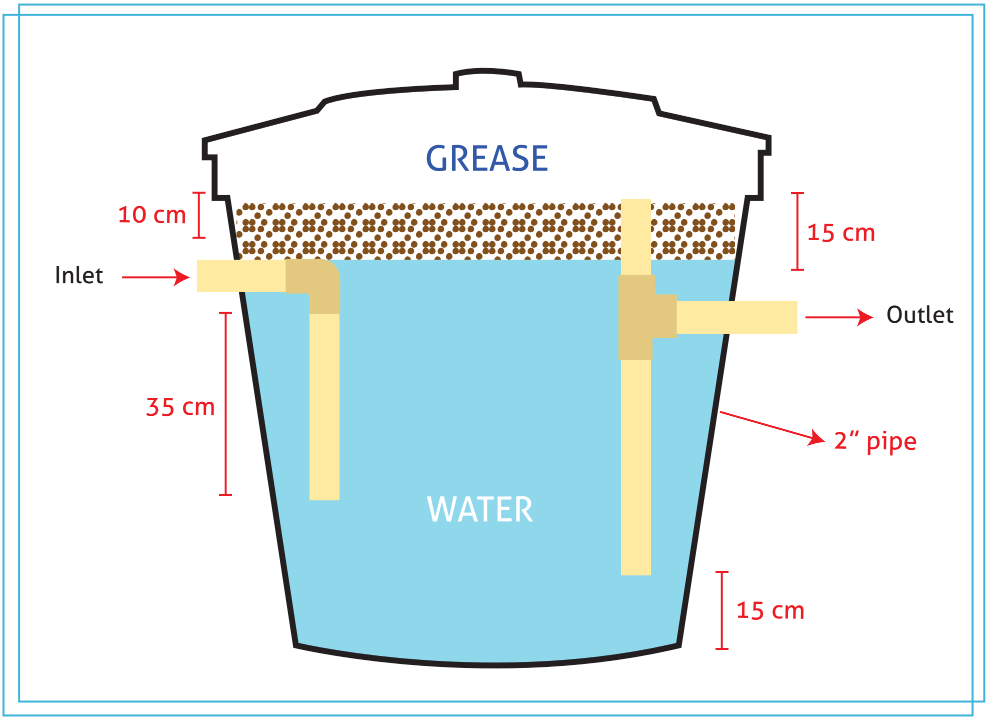


Figure 17. Grease trap.

Figure 18. Appearance of floating grease in grease trap.

Operation and maintenance

Grease traps are to be operated and cleaned regularly to prevent FOG spillage and odor problems. The cleaning frequency should be determined based on observation. Usually, cleaning must be done at least every time that 75% of the FOG retention capacity is reached.

A quarterly maintenance frequency is recommended, by applying the following protocol:

- Lift the grease trap cover with care.
- Remove FOG from the grease trap with the help of a container.
- Scrape the cover and sides of the trap with a spatula. Remove large deposits (pieces) of FOG accumulated in the trap and put them into a container.
- Reinstall the grease trap parts and close the cover.
- Mix FOG removed from the trap with slaked lime (1 to 1 ratio) and dispose of the mixture into coffee pulp processors for composting.

Septic tank (RAS, 2000)

This is a single wastewater treatment system for a household or housing complex, which combines sedimentation and digestion. The accumulated sludge is regularly removed and normally discharged to a treatment facility. Tanks are usually underground or half-buried, sealed, designed and built for rural sanitation. They must feature a post-treatment system.

They are recommended:

- For areas devoid of public sewer systems.
- As a treatment alternative in areas with local sewer systems.
- For retention of settleable solids when downstream sewerage has small diameters.

They may not be used for:

- Rainwater or waste capable of causing harmful interference in any phase of the treatment process.

Types of septic tanks

- According to material: concrete, fiberglass or polyethylene.
- According to shape: rectangular or cylindrical.

Septic tank location

The following minimum distances are to be kept:

- 1.50 m from buildings, land boundaries, drains, and septic drain fields.
- 3.0 m from trees and public water supply networks.
- 15.0 m from wells and water bodies of any nature.

Septic tank shape

Septic tanks may be cylindrical or rectangular-prismatic (Figure 19). The cylindrical ones are used to minimize the area used by increasing depth, and the rectangular-prismatic in cases requiring greater horizontal area or greater depth. Table 13 shows minimum and maximum values of the tank useful depth.

Table 13. Useful depth values (RAS, 2000).

Useful volume (m^3)	Minimum useful depth (m)	Maximum useful depth (m)
Up to 6	1,2	2,2
6 to 10	1,5	2,5
Over 10	1,8	2,8

The minimum internal diameter of tanks must be 1.10 m, the minimum internal length, 0.80 m, the minimum width-to-length ratio for rectangular-prismatic tanks 1:2, and the maximum one, 1:4.

Multiple serial chambers are recommended for small-to-medium volume tanks, serving up to 30 people. For other types of tanks, the following is recommended:

- Cylindrical tanks: three serial chambers.
- Rectangular-prismatic tanks: two serial chambers.

Figure 19. Septic tanks installed in the department of Cauca.

Septic tank sizing (RAS, 2000)

The septic tank is designed with the following parameters: **1.** Number of inhabitants or occupants; **2.** Wastewater flow rate: L/Inhab-day; **3.** Fresh sludge flow rate: L/Inhab-day; **4.** Cleaning frequency in years; **5.** Digested sludge accumulation rate, days; **6.** Retention time, days; and **7.** Useful volume.

Equation 3 is used for calculation of useful volume of the septic tank:

$$V_U = 1.000 + N_C \left(C \times T + K \times L_f \right) \quad (3)$$

Where:

Nc: Number of inhabitants or occupants.

C: Wastewater flow rate per inhabitant (L/day) (Table 14)

T: Retention time in days (Table 15)

K: Digested sludge accumulation rate (days) (Table 16)

Lf: Fresh sludge flow rate (L/Inhab-day) (Table 14)

Table 14. Wastewater and fresh sludge flow rates for permanent and temporary occupants (RAS, 2000).

Types of occupants	Property	Unit	Wastewater (C) and fresh sludge (Lf) flow rates (L/day)	
			C (L/Inhab-day)	Lf (L/day)
Permanent occupants	Upper class	Person	160	1,0
	Middle class	Person	130	1,0
	Lower class	Person	100	1,0
	Hotel (except laundry and kitchen)	Person	100	1,0
	Temporary accommodation	Person	80	1,0
Temporary occupants	Factory	Person	70	0,3
	Temporary offices	Person	50	0,2
	Public or commercial buildings	Person	50	0,2
	Schools	Person	50	0,2
	Bars	Person	6	0,1
	Restaurants	Food	25	0,01
	Cinemas, theaters or short stay establishments	establishment	2	0,02
	Public bathrooms	sanitation rate	480	4,0

Table 15. Retention times according to wastewater flow rates (RAS, 2000).

Daily volume (L)	Retention time (T)	
	Days	Hours
Up to 1,500	1,00	24
From 1,501 to 3,000	0,92	22
From 3,001 to 4,500	0,83	20
From 4,501 to 6,000	0,75	18
From 6,001 to 7,500	0,67	16
From 7,501 to 9,000	0,58	14
> 9,000	0,50	12

Table 16. Digested sludge accumulation rates according to cleaning frequency (RAS, 2000).

Cleaning frequency (years)	K values according to room temperature interval (T) in °C		
	T≤10	10≤T≤20	T > 20
1	94	65	57
2	134	105	97
3	174	145	137
4	214	185	177
5	254	225	217

Installation of septic systems

For installation of a septic tank, an excavation is made on a site of easy access if the tank is to be partially or fully buried, taking into account the positions of the inlet (higher) and outlet (lower than the tank) holes. The bottom of the excavation must be covered with a bed of sand or clean excavation material, free from angular rocks, leveled and compacted to support the tank. Then PVC fittings are coupled. To balance pressures, the tank must be filled with water up to the lower level of the outlet pipe. Between the external tank walls and the excavation, layers of compacted sand must be added one by one, with a rammer.

The inlet pipe diameter must be at least 4" (an elbow fitting), and that of the outlet pipe also at least 4" (a tee fitting). The bottom end of the inlet pipe must be submerged at least 0.35 m, and the outlet pipe at least 0.45 m. The distance between inlet and outlet pipes must be large enough for trapping the grease and preventing it from being carried with the flow (with minimum turbulence so that the grease floats), and a difference of heights of at least 5 cm.

The sizes, shapes and arrangements of the inlet and outlet pipes are designed for wastewater to remain in the tank at least 24 hours, enabling biochemical and physical processes for appropriate treatment.

For half-buried septic tanks or those installed on the ground, it is recommended that the color of the tanks be black to efficiently take advantage of the solar energy they receive (Figure 21).

Test results of black polyethylene tanks with UV additive (which protects them from UV rays), half-buried or on the ground, have shown a lifecycle of 25 years, without evidence of damage due to environmental conditions.

Septic tank operation

A septic tank has the following functions:

To separate solids from the liquid, acting as a sedimentation tank; the heavier solids precipitate as sludge to the bottom of the tank, and part of the grease, which may come from sanitation services, and particles of density lower than water ascend to the surface, forming a foam layer or scum.

To enable initial degradation of organic matter. The tank environment contains low amounts of oxygen, enabling the development of anaerobic microorganisms that break down organic matter into gas (CO2 and CH4, mainly).

Storage of sludge and scum. The tank is designed considering the frequency of cleaning and sludge removal.

To clarify wastewater that reaches the anaerobic filter (next unit of the septic system). In the middle third of the tank, wastewater is clarified, as scum floats to the top, and sludge is deposited at the bottom of the tank (Figure 20).

Because the septic tank is designed to receive only domestic wastewater, rainwater must be prevented from entering the system.

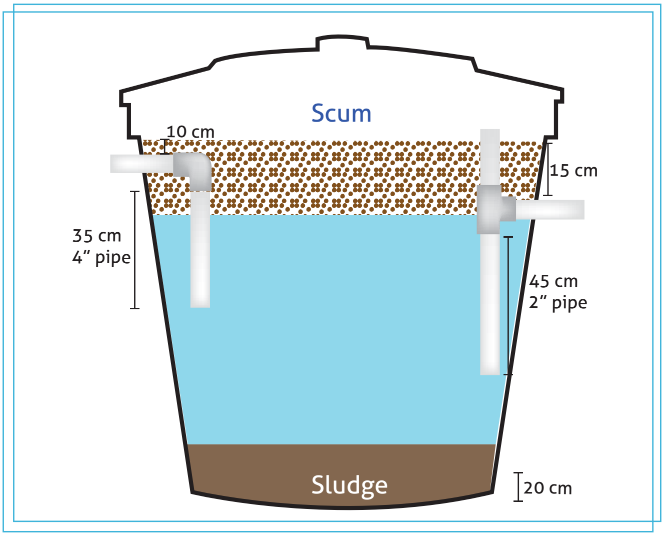


Figure 20. Details of septic tank.

Septic tanks may be completely buried (only the manhole cover is visible), half-buried or installed on the surface of the ground. Each type has advantages and disadvantages:

An advantage of fully buried tanks is lower risk of damage due to environmental conditions or impacts. As disadvantages, maintenance may be less practical, and solar energy, which favors the activity of microorganisms responsible for treatment, is not used.

Advantages of tanks installed on the ground are the use of solar energy, which favors the activity of microorganisms responsible for treatment, and more practical maintenance. Disadvantages are increased risk of damage to the tank due to environmental conditions or impacts.

Half-buried tanks (up to the middle) reduce risks of damage by impact and environmental conditions, partially use solar energy, which favors the activity of microorganisms responsible for treatment, and facilitate maintenance work.

Figure 21. Half-buried septic tanks.

Operation and maintenance (RAS, 2000)

Accumulated sludge and scum must be removed at intervals equivalent to the cleaning period, often one year. These intervals may be extended or reduced, as long as these changes are justified and do not affect operation performance, or undesirable odors occur.

Sludge must be periodically removed by trained staff, with proper equipment to prevent contact between sludge and people. Before any operation inside the tank, the manhole cover must be kept open long enough (> 15 min) for dissipation of toxic or explosive gases.

In no case may the removed sludge be disposed of in water bodies. In isolated areas, sludge may be put on drying beds (described below). The dry sludge may be disposed of in landfills or agricultural fields as long as they are not devoted to the cultivation of vegetables or fruits that are eaten raw.

Annual removal of scum and sludge built up in the septic tank is recommended; an inverted siphon device is recommended to remove sludge. The removed scum must be mixed with slaked lime at a 1:1 ratio and disposed of into coffee pulp processors for composting.

Sludge removal (Rodríguez et al., 2016)

Removal of the sludge settled in the septic tank is one of the most important maintenance tasks for good operation of the system, as its timely elimination helps reduce clogging of the anaerobic filter used after the septic tank, reduces odors, and preserves capacity of storage and time of retention of wastewater in the tank.

To make this task easier, the IWM Project assessed sludge removal with a pipeline or device built with the inverted siphon principle.

For that purpose, inside the septic tank a 1½" PVC-P pipe is placed parallel to the wall, going down from the top edge of the tank up to 20 cm before the bottom, with a 45° cut at the bottom end (Figure 22).

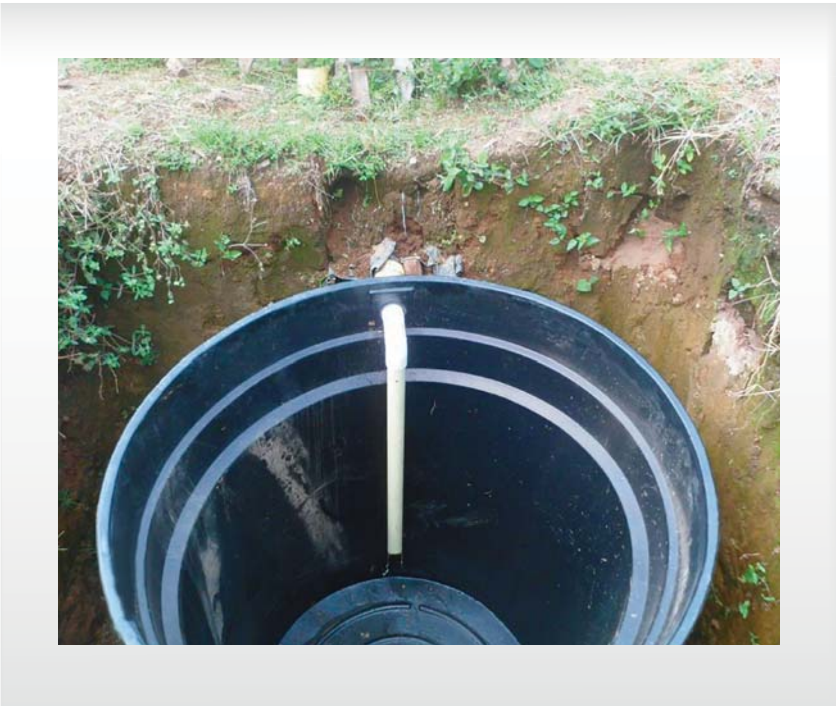


Figure 22. Pipe inside the septic tank for sludge removal.

The upper end of the parallel pipe is coupled with a PVC-P elbow, an 8cm PVC nipple of 1½", a female adapter with a neo-lite gasket against the inner wall of the tank, another neo-lite gasket against the external wall, and a male adapter. Finally, another 8cm PVC-P nipple of 1½" is coupled, followed by a male adapter (covered with Teflon tape) and a threaded cap. This device remains there until the moment of removing the sludge.

Another pipeline is built to be coupled to the male adapter located outside of the tank. It consists of a female adapter, an 8cm nipple, a tee (which holds a 15cm nipple with a smooth cap), another 8cm nipple, an elbow, a long nipple coupled downwards (up to the ground), another elbow, and finally a long pipe with a smooth stopcock to control the sludge outflow, another nipple, polyethylene adapters, and a polyethylene hose of 1½" to carry the removed sludge to the drying beds (Figure 23).

Figure 23. External pipeline or device for sludge removal.

For sludge removal, the threaded cap located outside of the septic tank is removed and the external pipeline or device is coupled, as shown in Figure 24.

Figure 24. Coupling of inverted-siphon pipeline or device for sludge removal.

Then the smooth cap on top of the tee is removed, and water is added to purge the system (Figure 25); when water fills the entire pipeline, the cap is put back, and the stopcock is opened to remove sludge (Figure 26).

Figure 25. Purging of the system for sludge removal.

Figure 26. Sludge outflow.

Septic tank effluents must not be disposed of directly to a surface water body. They are to be further treated to improve their quality.

Sludge drying beds (RAS, 2000)

These are structures that drain enough water from the sludge removed from the septic tank for it to be handled as a solid material.

A typical drying bed must be designed to retain, in one or more sections, all of the sludge removed from the septic tank. The structural elements of the bed include side walls, drainage pipes, sand and gravel layers, divisions or partitions, decanters, and sludge distribution channels.

The side walls must have a free edge of 0.5 to 0.9 m over the sand. There must be no side leaks through the walls. Table 17 shows the areas required per inhabitant according to the type of sludge to be dried.

Table 17. Area required according to sludge source and bed covering (RAS, 2000).

Sludge source	Area (m^2/Inhab) (bed without cover)	Area (m^2/Inhab) (bed with cover)
Primary	0,07 – 0,14	0,05 – 0,09
Primary + chemicals	0,14 – 0,23	0,09 – 0,173
Primary + low-rate trickling filters	0,12 – 0,17	0,086 – 0,145
Primary + activated sludge	0.16 – 0,51	0,094 – 0,156

For drainage, the use of 20-46cm-high gravel layers and 30-46cm-high sand layers is recommended.

Gravel diameter must be 3 to 25 mm. The sand must feature clean, hard, durable particles, free from clay, dust, ash, or other foreign material, of 0.30 to 0.75 mm in size.

Figure 27 shows the sequence of construction of drying beds.

Once the area necessary for drying the sludge is determined, the bed width and length is calculated (based on the area available). The excavation is made, and the vent pipe is placed; the bottom is waterproofed with plastic or geomembrane, adding the gravel and sand layers, and bricks as support.

Percolates are collected through plastic drainage pipes of 4 in, with a slope greater than 1%, located below the gravel layer.

Finally, a roof is built. The need for a roof depends on environmental conditions of the region; its use is recommended in high-precipitation areas.

Operation and maintenance of the beds must consider the following aspects:

- Control of odors.
- Control of influent sludge.
- Control of dosages.
- Operation under minimum and maximum load.
- Operation under min and max flow rate.
- Periodic inspection.
- Control of insects and plant growth.
- Dry sludge cake management.

Excavations and location of pipes

Waterproofing of drying beds

Addition of gravel layer

Addition of sand layer

Location of bricks

Roof construction for drying beds

Final appearance of drying beds

Drainage canal

Figure 27. Construction of sludge drying beds.

Up Flow Anaerobic Filter (UFAF)

Given that mainly liquid-solid separation takes place in the septic tank, its efficiency in removing organic pollution from domestic wastewater is 30%-40% (RAS, 2000), which makes necessary a post-treatment of the effluent, in order to comply with the maximum permissible values of the different parameters established by the Colombian regulations for discharges to the ground or to surface water bodies.

One technical and economical option for this post-treatment is the Upflow Anaerobic Filter, which consists of a polyethylene tank filled with filter material, where the effluent from the septic tank enters up to 10 cm from the bottom and goes up through the filter material, which hosts anaerobic microorganisms responsible for biological treatment of the effluent pre-treated in the septic tank, eliminating 60% - 80% of the organic pollution that enters the unit (RAS, 2000). The post-treated effluent exits through the upper part of the UFAF, and may be carried to an artificial wetland and then to a drain field or an absorption pit.

Location

The anaerobic filter is installed to receive the effluent from the septic tank.

Anaerobic filter design

The useful volume of the anaerobic filter is calculated through Equation (4), recommended in the RAS, 2000, Title E.

$$V_f = 1,60 * N * C * T \quad (4)$$

Where:

V_f : Useful volume of anaerobic filter, m3

N: Number of people

C: Wastewater flow rate per capita (L/day)

T: Retention time, in days

The anaerobic filter may be filled with any of the following filter media:

- Thick gravel of 2½".
- Bamboo pieces of 7.5-10 cm in diameter and 10 to 15 cm long.
- Polyethylene pipes of 2" to 3" in diameter and 10 cm long.
- Tire chips of 5x5 cm.
- Corncobs.
- Non-returnable bottle pieces.

For design, it is necessary to know the data of porosity and specific surface area of the filter media to be used in anaerobic filters, which can be found in Table 18.

Table 18. Characteristics of some filter media (RAS, 2000).

Filter material	Porosity (%)	Surface area (m2/m3)	Reference
Non-returnable bottles	98,7	52	Orozco, 2003
Pieces of bamboo	77,8	48	Zambrano, 1999
Corncobs	55,6	172	Rendón, 2014
Gravelly sand	86,0		
Rosette filters		100	

With the filter medium porosity, the anaerobic filter effective volume is calculated by dividing the useful volume (Vu) by the porosity value as a fraction (Equation 5).

$$\textbf{V}\textit{\textbf{tot anaerobic filter}} = \textbf{Vu} \, / \, \textit{\textbf{filter medium porosity}} \quad (5)$$

Installation

The anaerobic filter is installed in the same way as a septic tank (Figure 28). Once the excavation is ready, the tank is fully or partially buried, and the pipes and other accessories are coupled, bearing in mind that the 4" inlet pipe goes down up to 10 cm before the tank bottom. The filter material is deposited randomly, and the tank is filled with water up to 5 cm below the outlet pipe, also of 4".

The flow through the anaerobic filter passes through all the filter media, so the effluent is in contact with the microorganisms adhering to the filter medium (Figure 29).

Operation and maintenance

Checking the anaerobic filter every 6 months is recommended, as follows:

- Open the septic tank and observe its water level.
- If the outflow pipe of the septic tank is submerged it is because the UFAF is clogged and requires maintenance.
- Open the UFAF. Insert a metal bar in the filter media until it touches the tank bottom. Shake the filter media by making circular movements with the bar so that the bacteria biofilm snaps off and floats.
- Introduce through the anaerobic filter inlet a hose with pressurized water up to the tank bottom to produce an upflow of clean water through the tank.
- Remove the biomass layer floating on the surface and dispose of it in the pulp processor.

Figure 28. Half-buried anaerobic filters.

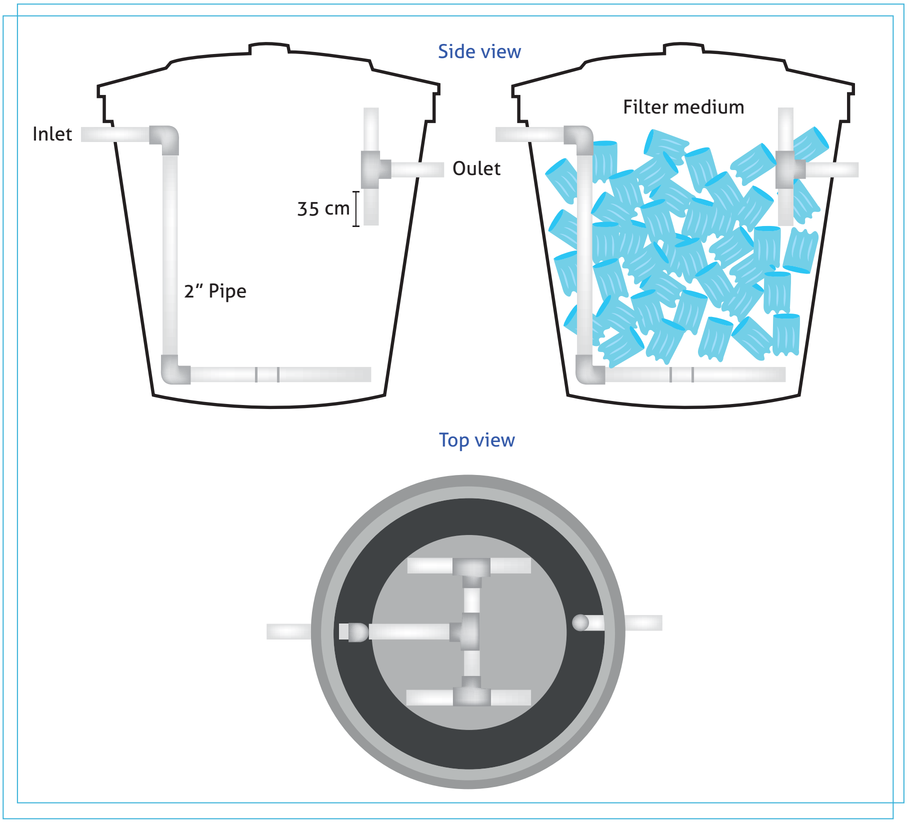


Figure 29. Characteristics of anaerobic filters.

Artificial wetlands

Artificial wetlands are manmade and simulate all the characteristics of natural wetlands and offer an alternative to conventional wastewater treatment plants, as they are relatively economical in construction and operation, easy to maintain, provide effective and reliable wastewater treatment, and are relatively tolerant to hydrological fluctuations and pollution load rates (Hammer, 1991).

Wetland systems are typically described in terms of the water surface position and/or the type of vegetation grown (US EPA, 2000). Wetlands may be classified into horizontal flow, vertical flow and combined systems.

There are two types of artificial horizontal flow wetlands developed for wastewater treatment: free water surface (FWS, or surface flow) and subsurface flow (SSF) systems (Metcalf and Eddy, 1995).

Free water surface wetlands are those systems in which water is exposed to the atmosphere (Figure 30). Most natural wetlands are FWS systems, including bogs (primary vegetation: mosses), swamps (primary vegetation: trees), and marshes (primary vegetation: grasses and tall-growing macrophytes). The observation of improved water quality in natural wetlands led to the development of artificial wetlands to try to replicate water quality and habitat benefits in constructed ecosystems. In FWS wetlands, water flows over the soil surface with vegetation from an inlet point to an outlet point. In some cases, water is completely lost to evapotranspiration and infiltration within the wetland (EPA, 2000).

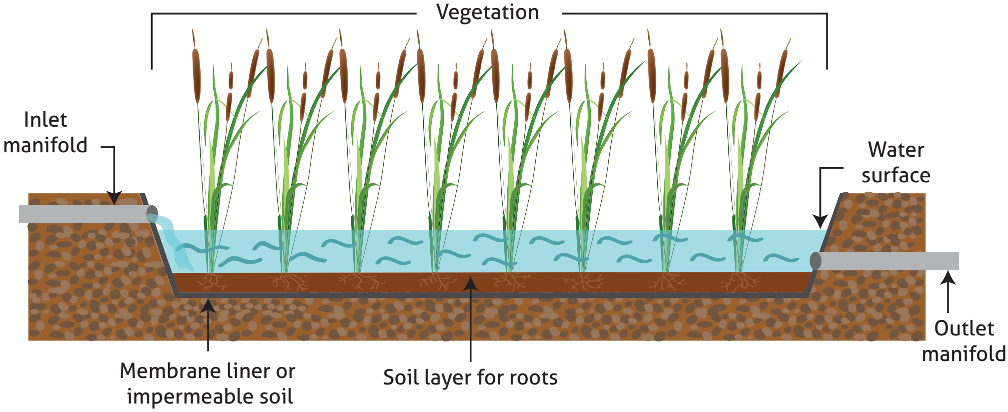


Figure 30. Free water surface wetland diagram (Source: EPA, 2000).

A subsurface flow (SSF) artificial wetland is specifically designed for treatment or polishing of some types of wastewater and is typically constructed as a bed or channel containing appropriate media such as gravel, sand or other soil materials (Figure 31). The medium is planted with tall-growing vegetation and the water surface is designed to remain below the top of the medium (EPA, 2000).

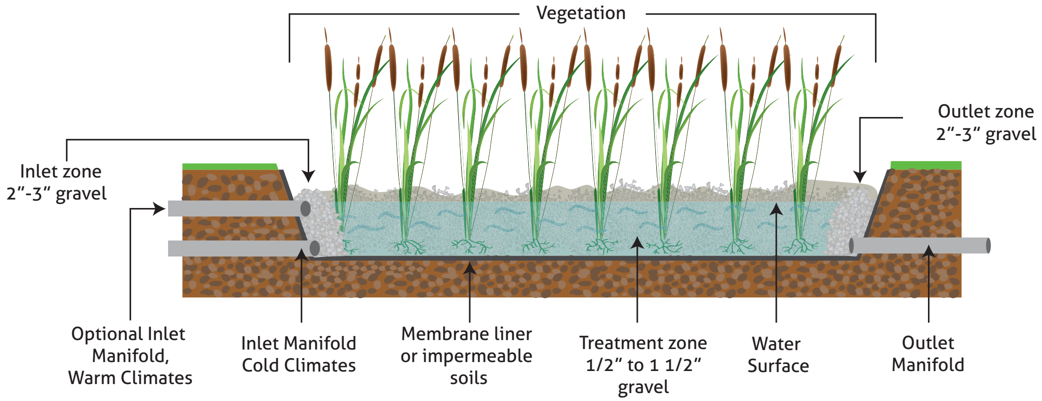


Figure 31. Constructed subsurface flow wetland diagram (Source: EPA, 2000).

Location

Wetlands must be located downstream from septic tanks or anaerobic filters. Soil characteristics, location of water bodies, topography, geographic location, property lines and existing vegetation must be assessed to properly locate the wetland (RAS, 2000).

Artificial wetland design

The method selected must ensure proper functioning of the system, taking into account the following criteria:

- Hydraulic conductivity.
- Particle size.
- Submerged flow for all flow conditions.

In addition, the following parameters are recommended in the case of subsurface flow wetlands:

Surface area: For determination of the wetland surface area, two alternatives are recommended:

a) Use the following hydraulic load values: 0.032 m^2/L-day (for cold areas or where there are space restrictions), and 0.021 m^2/L-day (for warm areas or where there are space restrictions).

b) Method including the kinetics of the process, Equation 6 :

$$A_s = l*W = \left[\frac{Q \ln \left({C_o}/{C_e} \right)}{K_t *d*n} \right] \quad (6)$$

Where:

As: Required surface area, m^2

l: Length of the bed, m

W: Width of the bed, m

n: porosity

d: water depth, m

Ce: Effluent COD, BOD concentration, mg/L

Co: Influent COD, BOD concentration, mg/L

Kt: First-order temperature-dependent rate constant, d^{-1}

Q: Average flow rate, m^3/d

The wetland depth is set at 0.5 m and the porosity of the rock used as support medium was estimated at 0.45 (crushed rock) by Rodríguez (2009).

KT = $K_{20}(1{,}06)^{(T-20)}$, T in ° C (Reed *et al.*, 1995, cited by Rodríguez, 2009).

$\mathbf{K_{20}}$ = 0,678 d^{-1} (Reed *et al.*, 1995, cited by Rodríguez, 2009), for domestic wastewater.

Cross section: It is calculated using Darcy's Law, which describes the flow regime in a porous medium and is accepted for use in designing subsurface flow wetlands that use soil or gravel in the basin (Equation 7)

$$A_c = \left[\frac{Q}{K_s *s} \right] \quad (7)$$

Where:

A_c: Cross-sectional area, m^2

Q: Average flow rate, m^3/d

K_s: Hydraulic conductivity, m^3/m^2-d

S: Bed slope, m/m (as a fraction)

For SSF wetlands, the flow velocity Ks x s must be limited to 6.8 m/d to minimize localized dragging of biofilms (Metcalf and Eddy, 1995). Conductivity used for the design may never be greater than that of the support medium; this conductivity must be reduced to take into account the clogging effects associated with retention of solids in the wetlands.

Bed width (W) (Metcalf and Eddy, 1995). The bed width is calculated with Equation 8 .

$$W = \left(\frac{A_c}{d} \right) \quad (8)$$

Where:

W: bed width, m

Ac: cross-sectional area, m^2

d: water depth, m

Hydraulic retention time: for determination of retention time in subsurface flow wetlands designed for removal of COD and BOD, a model that assumes ideal plug flow is proposed (Equation 9).

$$\frac{C_e}{C_o} = exp\left[-K_t * t' \right] \quad (9)$$

Where:

Ce: effluent COD, BOD concentration, mg/L

Co: influent COD, BOD concentration, mg/L

Kt: first-order temperature-dependent rate constant, d^{-1}

t': actual retention time, days

Table 19 shows the characteristics of media usually employed in SSF systems, according to Reed *et al.* (1995).

Table 19. Typical media characteristics for subsurface flow wetlands (Source: Reed et al., 1995).

Medium type	Effective size, D10* (mm)	Porosity, n (%)	Hydraulic conductivity, Ks (m3/m2/d)
Coarse sand	2	28 to 32	100 to 1.000
Gravelly sand	8	30 to 35	500 to 5.000
Fine gravel	16	35 to 38	1.000 to 10.000
Medium gravel	32	36 to 40	10.000 to 50.000
Coarse rock	128	38 to 45	50.000 to 250.000

Hydraulic design (Reed, Crites & Middlebrooks, 1995): Hydraulic design of an artificial wetland is critical for success of its performance. All design models used currently assume uniform plug flow conditions; in addition, there are no restrictions on contact between wastewater constituents and organisms responsible for treatment.

The length to width ratio has significant influence on the system's hydraulic regime and resistance to flow. In theory, large L to W ratios of 10:1 or greater would ensure a plug flow, but in the upper part, there would be overflow due to increased resistance to flow caused by vegetation waste accumulation, mainly in free surface flow systems. So, ratios from 1:1 up to 3:1 or 4:1 are acceptable.

Operation and maintenance

Once the required wetland area is known, the length and width are determined so that their ratio does not exceed 4:1; excavations are made with a depth of 0.5 m and a 2% slope; then it is waterproofed with a 0.7-mm geomembrane or gauge-6 black plastic, installing the inlet and outlet devices (5 to 10 cm below surface). Finally, a bamboo frame is built to hold the plastic or geomembrane (Figure 32).

Figure 32. Construction of horizontal subsurface flow wetlands (Source: Rodríguez, 2009).

Next, gravel is added for planting the vegetation, so that it covers the outlet device. Medium-sized gravel is used, of about 2-3 cm in diameter (Figure 33).

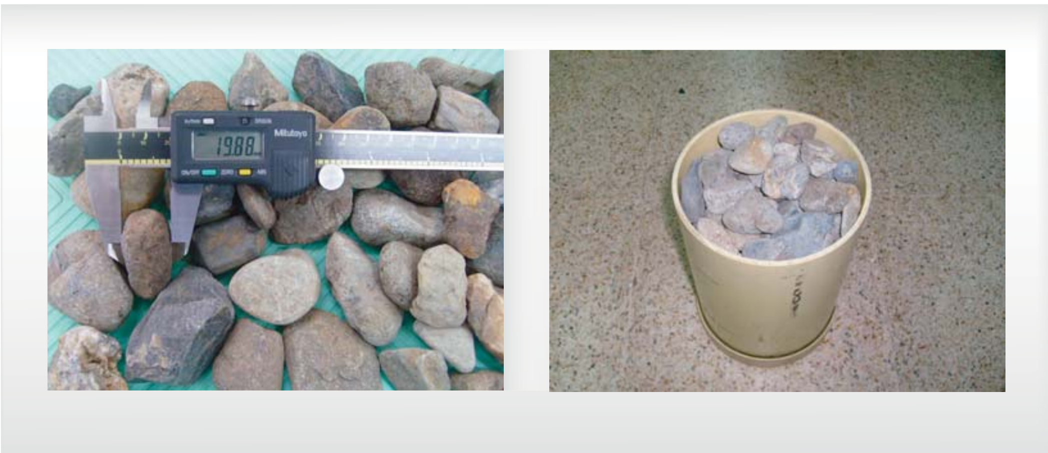


Figure 33. Particle size of gravel used in wetlands. (Source: Rodríguez, 2009).

Tall-growing plants such as cattail, vetiver grass, or scarlet banana (Figure 34) are planted in squares at a density of 30 plants/m^2.

For planting the vegetation, all foreign material adhered to roots is removed; they are planted on the same day of extraction, 5 cm from the pond bottom.

The vegetation choice depends on the type of waste, solar radiation, temperature, aesthetics, desired wildlife, native species, and wetland depth.

Figure 35 shows the wetlands built in the IWM Project.

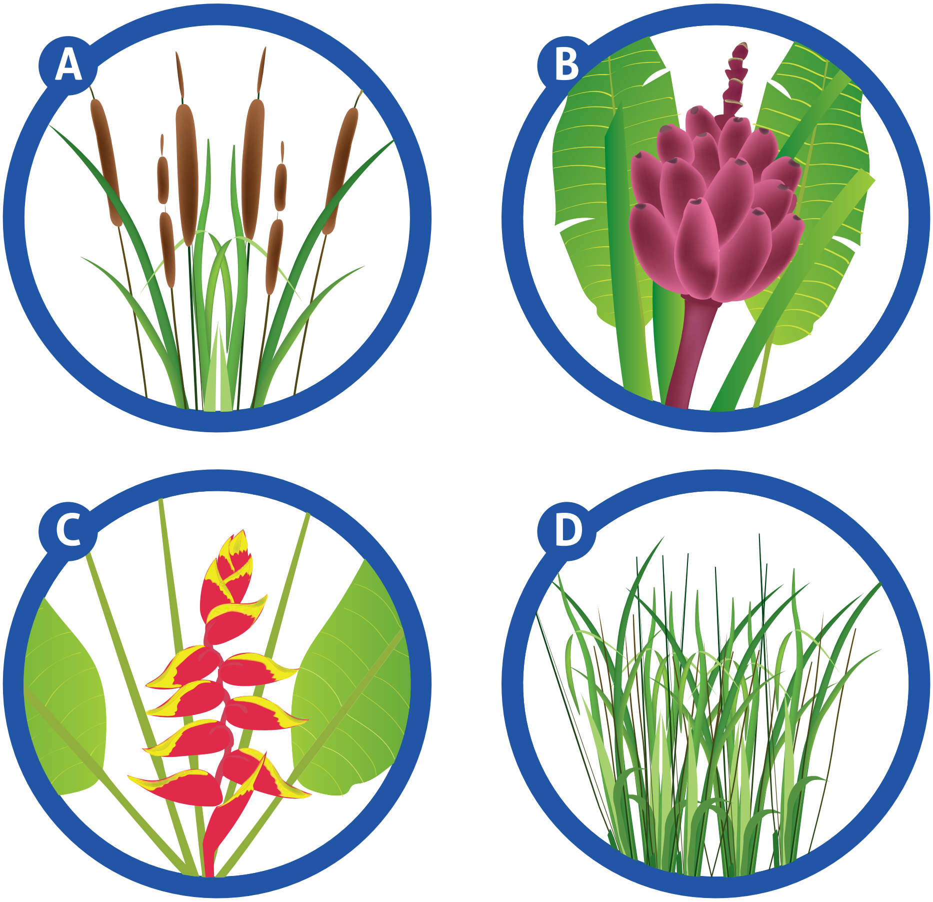


Figure 34. Plants used in the wetlands. A. Cattail (Typha spp.); B. Scarlet banana (Musa coccinea); C. Heliconia (Heliconia spp.); D. Vetiver grass (Chrysopogon zizanioides) (Source: Rodríguez, 2009).

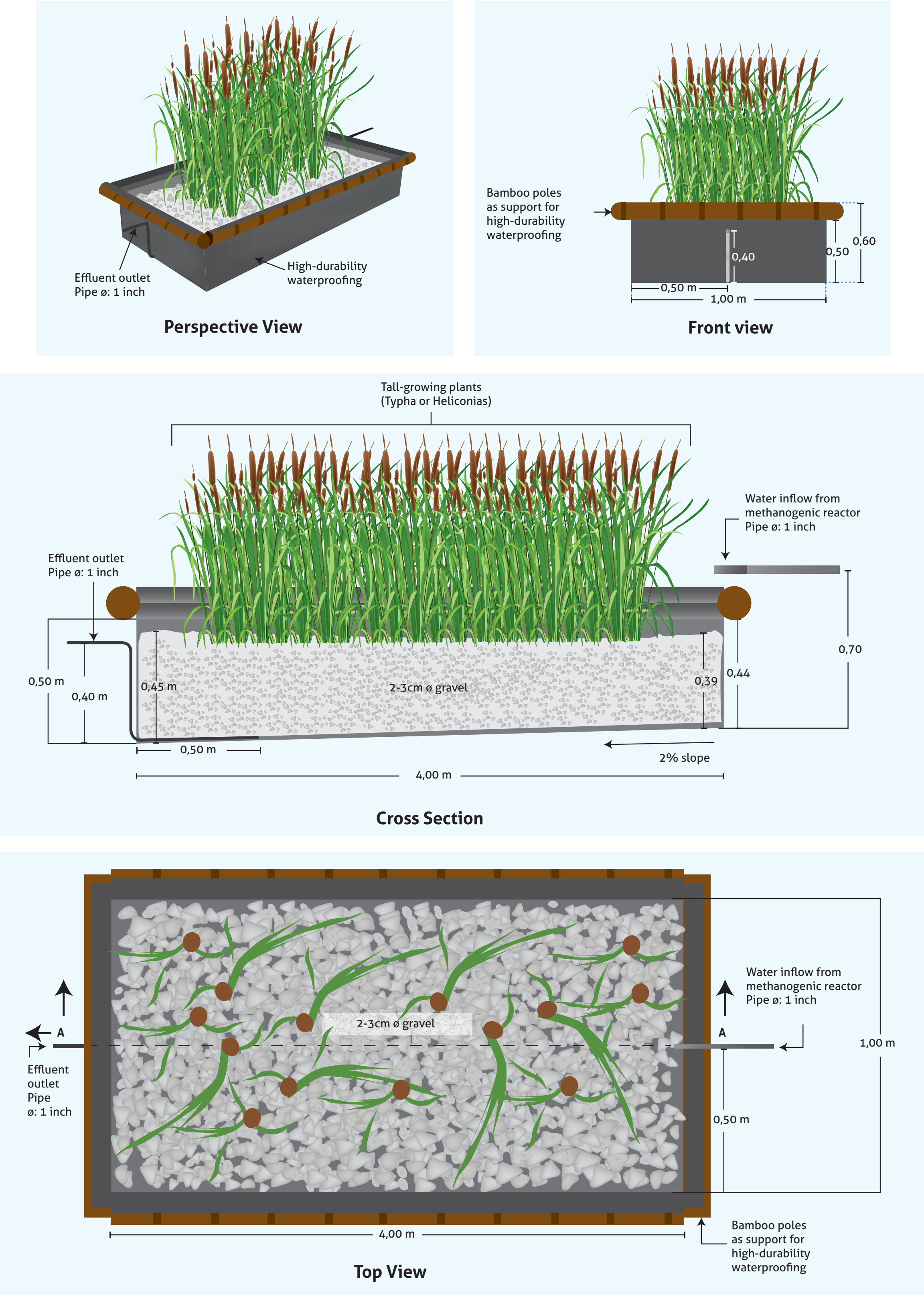


Figure 35. Diagram of wetlands built in IWM Project.

Drain fields (RAS, 2000)

A series of narrow and relatively surface trenches, filled with a porous medium (typically gravel), which are used for final disposal of effluents to soil.

Location

They should be located downstream from anaerobic filters or artificial wetlands, in soils whose characteristics allow absorption of the effluent coming from the treatment system, in order to prevent groundwater contamination. The distribution pipes must be located on a bed of clean rocks with a 10 to 60 mm diameter.

Sizing

The recommended dimensions for construction of drain fields are shown in Table 20.

Table 20. Recommended dimensions of drain fields.

Parameter	Dimension
Diameter of pipes	0,10 – 0,15 m
Slope	0,3% – 0,5%
Maximum length	30 m
Bottom width	0,45 to 0,75 m

The required absorption area is calculated based on characteristics of soil, determined in the drain tests (Figure 36) according to the following steps:

a) A 60x60cm hole is dug up to the depth of the projected drain field (about 60 cm), then, another 30x30x30cm hole is dug in the middle.

b) The hole is filled with water. Saturation is achieved by filling the hole with water as often as necessary for 1 hour.

c) Water is allowed to drain completely, then the hole is immediately filled again with clean water up to 30 cm, and the time that it takes for the water level to fall 2.5 cm is noted, using a ruler; the average time it takes for the 30 cm to drain may also be used.

For example, if in 30 minutes the water level drops 5 cm, the percolation rate will be 30 min/5 cm = 15 min/2.5 cm. This percolation rate is expressed in minutes/inch.

Figure 36. Percolation tests for design of drain fields.

After the tests, soil samples are taken from the excavation, and texture is determined (physical property relating to size, distribution, and continuity of pores).

The required absorption area is calculated based on soil characteristics, determined in the percolation tests. Typical values that may be used in design are shown in Table 21.

Table 21. Typical absorption areas according to percolation rates (RAS, 2000).

Percolation rate	Absorption area required at the bottom of the field (m^2)	
	Rooms	Schools
Minutes/inch	Per room	Per classroom
2	4,50	0,8
3	5,50	1,0
4	6,50	1,1
5	7,50	1,2
10	9,0	1,7
15	12,0	2,0
30	16,5	2,8
60*	22,0	3,5

** Above 60 minutes, this solution is not recommended.*

Table 22 shows the recommended application rates according to percolation rate and soil texture.

Table 22. Application rates depending on percolation rate and soil texture (RAS. 2000).

Percolation rate (min/inch)	Soil texture	Soil porosity	Application rate (m^3/m^2-day)
< 1	Coarse sand or gravel	Rapid absorption	Not recommended
2			
3			
4	Fine Sand Sandy loam	Medium absorption	0,05
5			0,03
10	Clay loam	Slow absorption	
15			0,02
30			
45	Compact clay	Semi-permeable soil	0,008
50			
>60		Impermeable soil	Not recommended

With the application rate and daily flow rate of water to be drained, the drain field area is determined.

Operation and maintenance

A distribution tank to receive the effluent from the anaerobic filter or artificial wetland and distribute it to the trenches, must be installed at the beginning of the drain field. Design of trenches is based on ground conditions, flow rate, and available area. Three trenches 0.6 to 1.5 m deep, whose length depends on the soil absorption capacity, are built. The object of this system is to distribute effluent into the subsoil, reducing environmental impact on groundwater by filtering the effluent through pores. This system is not suitable when land is swampy or clay, the water-table level is high, or available area is insufficient.

The upper hole of the distribution tank is the inlet and is connected to the outlet of the anaerobic filter or wetland. The three remaining lower holes are the outlets and are connected to the perforated drain pipes (Figure 37). If any of the three outlets is not used, it must be blocked up with a short plugged pipe. They must be operated in aerobic conditions. For this purpose, vent pipes protected against entry of insects must be installed.

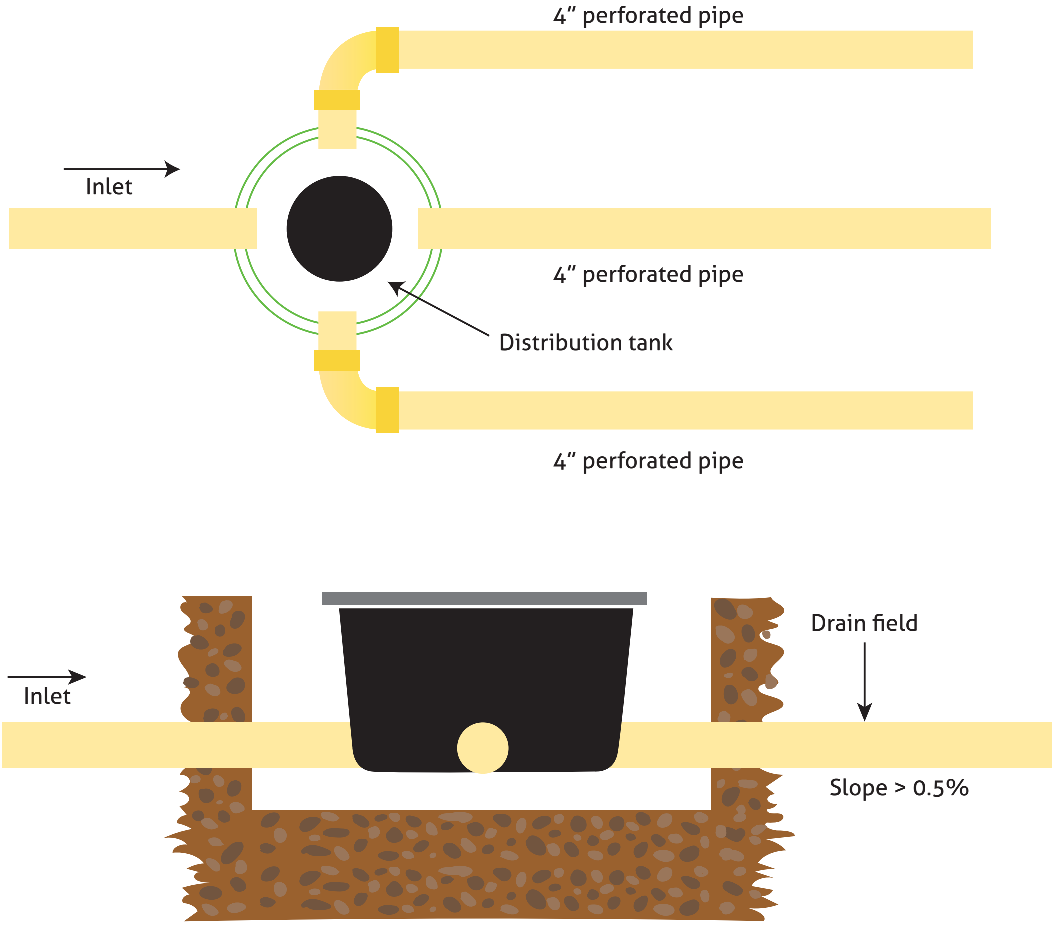


Figure 37. Distribution tank diagram.
Source: colombit, 2000

Once the distribution tank is installed, the pipes are coupled; for this purpose, a series of perforations must be made in two lines, with a 3/16" drill bit, each separated 10 cm (Figure 38).

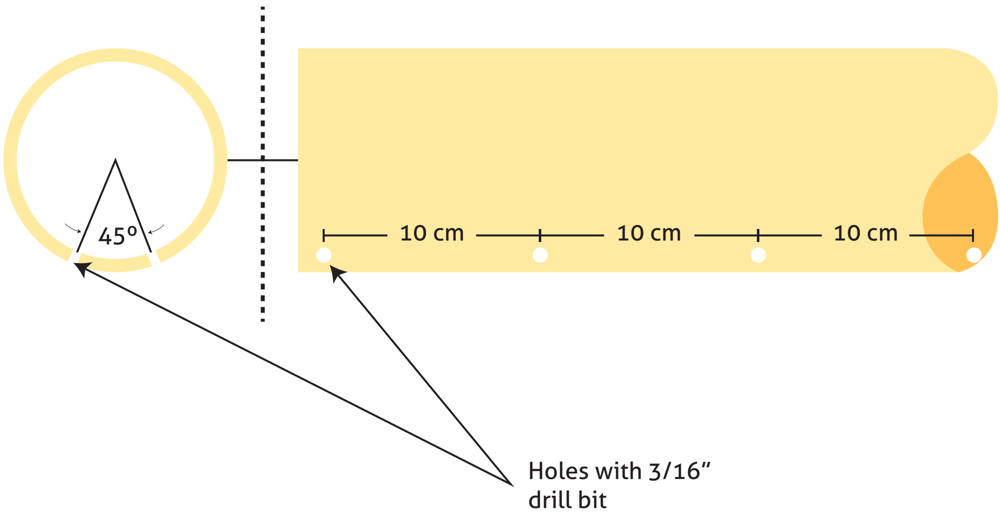


Figure 38. Diagram of holes in distribution pipes.
Source: colombit, 2000

A trench 60 cm wide and at least 60 cm deep is dug. It is filled with a 15 cm bed of 2-6cm ø gravel. The pipes are laid with the perforations pointing downward; then another 15 cm of gravel is added, to fill up the trench with the material remaining from the excavation (Figure 39).

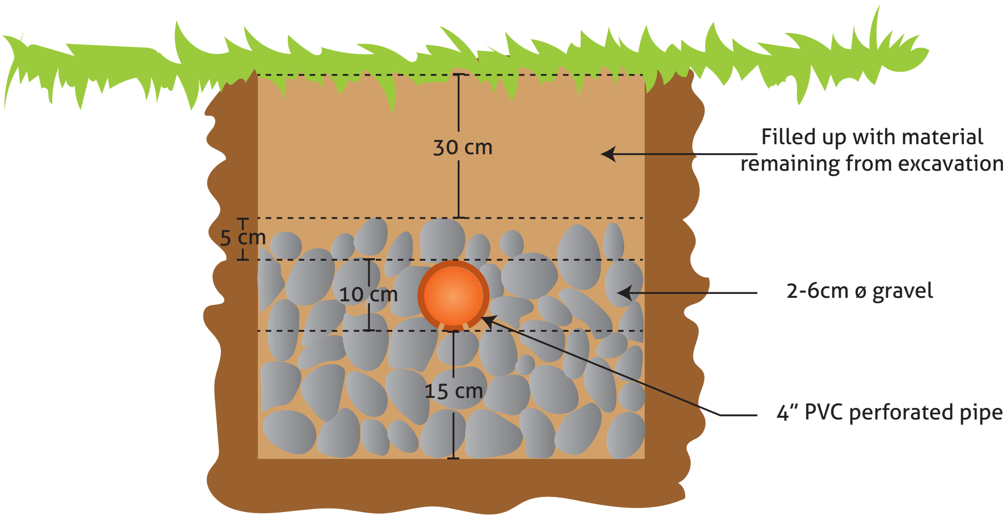


Figure 39. Diagram of one of the drain trenches.
Source: colombit, 2000

It is important to ensure that the amount of effluent to be distributed by each of the branches is the same, so there is homogeneous absorption into the subsoil.

To extend the drain system lifecycle, the following is recommended:

1. All the trenches must have the same length.
2. On flat ground, the lines must be parallel to the contour lines.
3. To allow good ventilation, the lines may end in small pits of 90 cm in diameter, preferably filled with gravel.
4. Grass is to be planted in the field to help absorb the effluent.
5. The use of dosing chambers (DCh) with siphons allows for good effluent distribution in the drain field.

Figure 40 shows the integrated domestic wastewater treatment model recommended, which complies with environmental regulations.

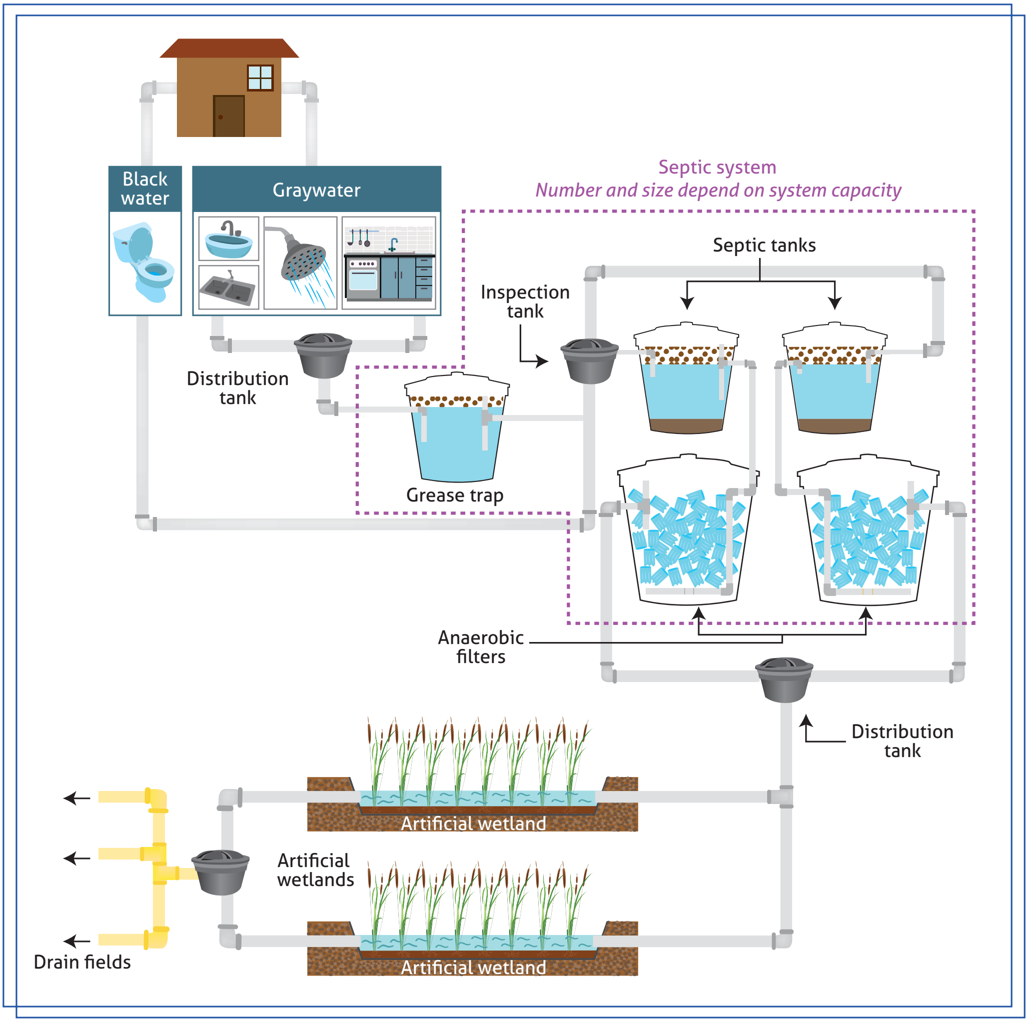


Figure 40. Integrated domestic wastewater treatment system diagram.

Table 23 shows the recommendations to be followed for good performance of domestic wastewater treatment systems.

Table 23. Recommendations for good performance of domestic wastewater treatment systems.

What must be done	What must not be done
Use water efficiently to prevent overloading of the septic system. Repair leaking faucets or toilets. Use high-performance accessories. Use bathroom cleaners and commercial laundry detergents moderately.	The septic system is not a trash can. Do not throw dental floss, sanitary napkins, condoms, diapers, cotton swabs, cigarette butts, coffee waste, paper towels, paint, or dangerous chemicals into the system.
Avoid disposing of compounds such as acetone, oils or alcohol, because they do not decompose easily.	Do not use caustic drain cleaners for a clogged drain. Use a flexible rod instead to unclog pipes.
Be aware of location of the septic system. When cleaning, do not remove all of the sludge.	Do not wash or disinfect the septic tank after sludge removal.
When any part of the system is opened, allow time for ensuring adequate ventilation, because accumulated fumes can cause explosions.	Never use matches or torches to inspect a septic tank.
Keep records of repairs, pumping, inspections, permits issued, and other system maintenance activities.	Do not drive or park cars on any part of the septic system; this may compact the soil and damage pipes, tanks, or other system components.

5

WATER TREATMENT ON COFFEE FARMS

COFFEE WASTEWATER TREATMENT

Coffee wastewater treatment

In the different countries producing washed coffee, a number of systems for treatment of wet coffee processing wastewater have been evaluated.

In Colombia, the two research branches of the FNC, the National Coffee Research Center (Cenicafé) and the Laboratory of Research on Coffee Chemistry and Natural Products (LIQC, merged into Cenicafé in the 1990s), along with universities and Regional Autonomous Corporations (environmental authorities), have conducted research in this area over the last 30 years.

The application of different coffee wastewater treatment technologies has been based on the coffee processing method and regulations in each of the producer countries as to disposal of liquid waste.

Ávila and Ruiz (1989), in Colombia, studied the physical processes of sedimentation and flotation as preliminary treatments of coffee wastewater before its being subjected to biological processes, concluding that sedimentation is a process fit for treatment systems, unlike the results obtained with flotation, which from an economic point of view is not feasible for incorporation into treatment systems.

Noyola (1989), in Mexico, concludes that the biological process of anaerobic digestion is the appropriate treatment for wet coffee processing wastewater, and second-generation anaerobic reactors (sludge blanket and filter) are the suitable ones for purification.

Buitrago and Ramírez (1991), in Colombia, evaluated coagulation with chemical salts of aluminum and iron as a primary coffee wastewater treatment and found that the most appropriate conditions for the process were pH between 6.0 and 7.5, 30 ppm of alum, and sedimentation time of 20 hours, to remove 57% of suspended solids and 40% of dissolved solids.

Waser *et al.* (1991) report on the use of anaerobic biological sludge blanket reactors in Nicaragua for treatment of coffee wastewater. For neutralized influents, they report COD removal efficiencies above 80% in anaerobic reactors with sizes of between 20 and 35 m3, temperature between 18 and 22° C, and applied pollution load of 2 kg COD/m3-day.

Ochoa and Ramírez (1993), in Costa Rica, report technical feasibility for using physical processes in primary sedimentation tanks and then biological processes in oxidation lagoons as systems for coffee wastewater treatment in that country. They report that lagooning is appropriate as secondary coffee wastewater treatment and that these treatment systems can remove between 40% and 46% of the organic load for influents with pH of 4.0 and BOD concentrations of 10,000 to 15,000 ppm.

Lardé (1996), in El Salvador, investigated chemical treatment of coagulation of coffee wastewater with a concentration of 7,100 to 18,500 ppm of total solids, using calcium hydroxide, and found as optimal coagulant doses between 0.4 % and 0.6% w/v, and estimated reductions of 39.7% in BOD5 with the optimal coagulant dose.

Vásquez (1997), in Costa Rica, reports that 15% of wet mills have biological treatments in anaerobic lagoons, with removal efficiencies greater than 50% for coffee wastewater treatment; 5% have biological treatment in aerated lagoons, which involve high energy costs.

Coffee wastewater characteristics

Colombian coffee has an intrinsic quality, associated with wet processing of the fruits (requiring water) and thus falling into the category of "washed mild coffee." In that sense, water must be used with environmental responsibility, adopting ecofriendly production technologies.

Pulp removal and its transport without water to roofed pits is the most important preventive environmental action, as this practice prevents 74% of potential pollution of coffee processing byproducts from reaching water sources through the pulp, which can be transformed and value-added (Zambrano and Isaza, 1998).

The remaining 26% of pollution is prevented by correctly disposing of the mucilage mixed with coffee pulp, which acts as a biological filter. This, coupled with composting or worm composting of the mix, produces organic fertilizer. Other applications are its use as animal feed or its treatment in biological systems (Zambrano *et al.*, 2010).

Coffee wastewater is biodegradable, but has physicochemical properties particularly aggressive to the environment: low pH, high acidity, and high organic matter concentrations, 60 to 240 times more polluting than those of domestic wastewater (Zambrano *et al.*, 2010).




Coffee wastewater treatments evaluated at Cenicafé

At Cenicafé, different technologies that reduce environmental impacts of coffee wastewater have been researched and evaluated.

Modular Anaerobic Treatment System (SMTA in Spanish)

This is a system because it consists of a set of units arranged in series, in which wastewater flows by gravity. The different units host, respectively, preliminary treatment (pulp trap), primary treatment (hydrolytic-acidogenic reactor, HAR), and secondary treatment (methanogenic reactor), the effluent now being ready to be post-treated in an artificial wetland (similar to that designed for domestic wastewater treatment) and led to a drain field (idem).

It is modular because units can be added to increase the treatment system capacity if the production area or coffee production on the farm increases, resulting in greater organic loading.

It is an anaerobic treatment because it is a biological system that operates without oxygen, adding methanogenic bacteria that transform organic pollution (dissolved in wastewater) into biogas (basically CO2 and CH4).

The units are black polyethylene tanks in order to absorb solar energy to increase temperature in the units, favoring biological activity.

The system consists of four elements: a pulp trap, a hydrolytic-acidogenic reactor, a distribution tank, and a methanogenic reactor (Figure 41).

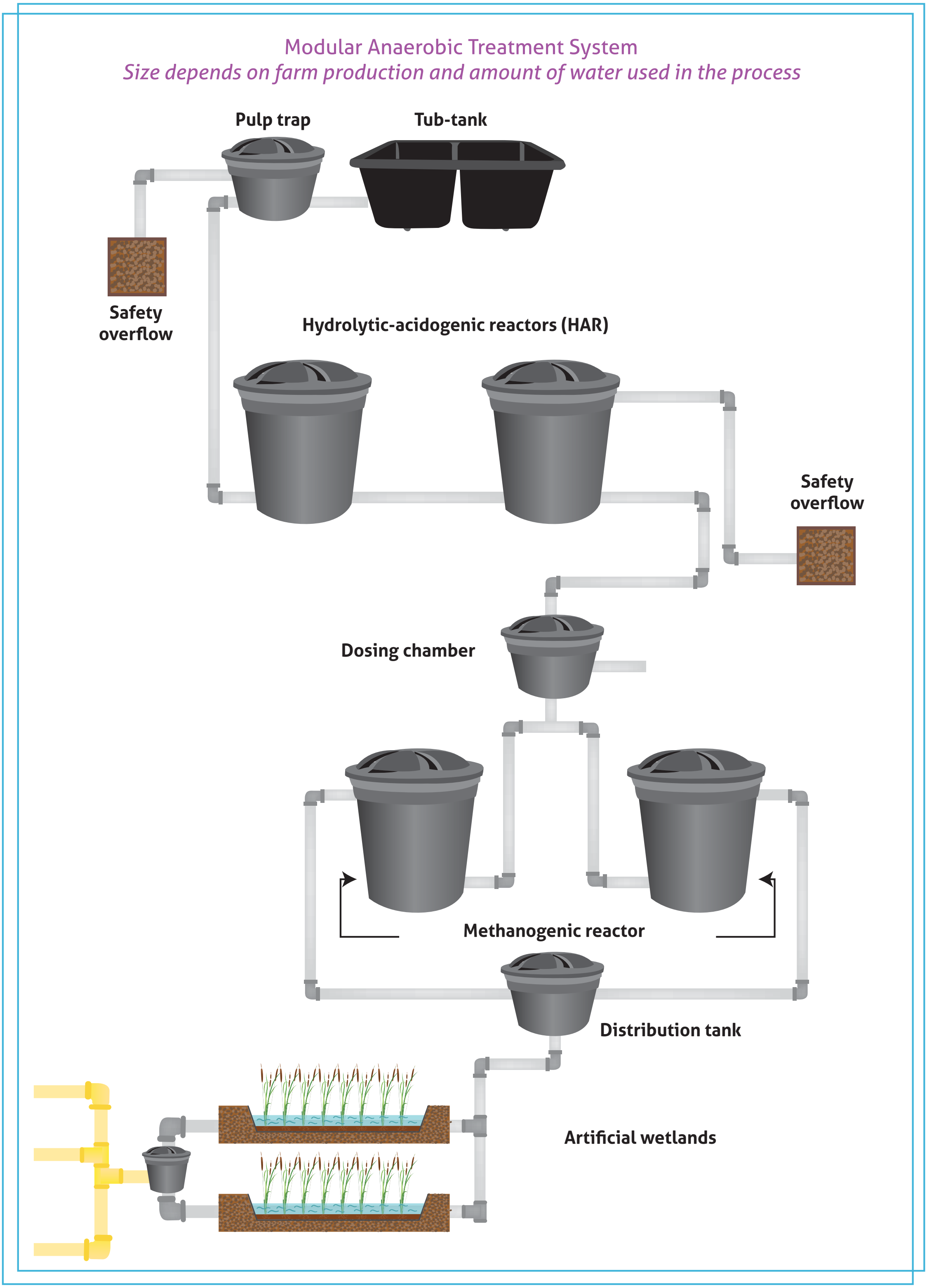


Figure 41. Modular Anaerobic Treatment System Diagram.

The previous step to installing an SMTA is having a fermentation tank with capacity for processing the coffee produced on the peak day and washing it with the four-rinse method (Zambrano, 1993), which consumes 4 to 5 L of water per kilogram of dry parchment coffee.

Pulp trap

Wastewater from the washing stage is carried to a pulp trap, shown in Figure 42.

The goal of the pulp trap is to intercept beans, peels, and pulp that may be present in the wastewater and cause pipe clogging and treatment inefficiencies, as they are very slowly degraded. It is built with a black polyethylene tank of 150 L.

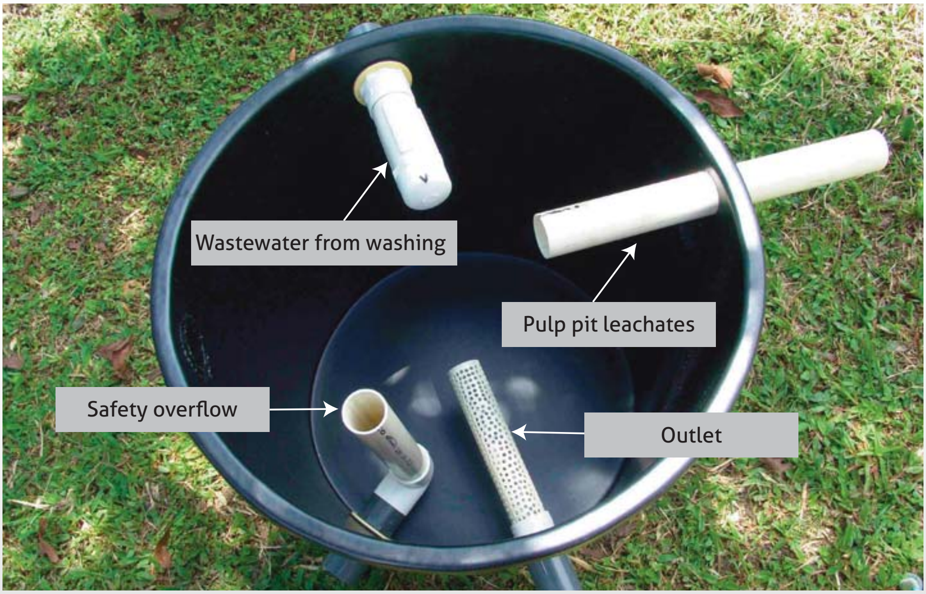


Figure 42. Pulp trap diagram.

In addition to wastewater from coffee washing, the leachates generated in the pulp pit (because of its decomposition) are led to the pulp trap, which has a safety overflow in case of hydraulic overload that leads to a hole filled with coffee stems of 1 m3 of volume.

Hydrolytic-acidogenic reactor (Rodríguez *et al.*, 2017)

This consists of a polyethylene tank that hosts hydrolysis and acidification reactions, as well as processes of flotation and sedimentation of solids. They are designed to retain wastewater for 3 days.

For calculation of volume of this unit, the following information is required:

1. *Annual production:* arrobas (unit of measurement equivalent to 12.5 kg) of dry parchment coffee per year (@/year of dpc).
2. *Peak day:* Percentage of annual production.
3. *Peak week:* Percentage of annual production.
4. *Water consumption:* L/kg of dpc.

Volume of the Hydrolytic-Acidogenic Reactor (HAR) is calculated trough Equation 10:

$$V_{HAR} = 60 \times (0{,}9/1000) \times 1{,}25 \times 3 \times (1/100) \times (1/5) \times Pw \times Pa \quad (10)$$

$$V_{HAR} = 0{,}000405 \times Pw \times Pa$$

Where:

60 = gc, conversion factor from @ of dpc to kg of coffee cherry (4.8 x 12.5)

0.9 = liters of water consumed in washing of 1 kg of coffee cherry (cc)

1,000 = gc, conversion factor of L to m^3

1.25 = safety coefficient

3 = Two volumes for biochemical reactions and a volume for storage

1/100 = To correct in %

Pw = Peak week in %

Pa = Annual production in arrobas of dpc

Hydrolytic-acidogenic reactor´s elements

To promote the liquid-solid separation in this unit, the reactor includes a circular device or conduit consisting of a 1½" polyethylene hose, with ½" cross cut holes every 6 cm. The hose is covered with non-returnable bottle pieces and is located at the bottom, where the inlet of the hydrolytic reactor is also located. This device prevents resuspension of settled material (which could reach the subsequent dosing chamber) because the pressurized water from the hose holes (coming from the pulp trap) hits against the plastic bottle pieces, losing turbulence and its ability to remix sediments (Figure 43).

It also features a gooseneck tube, 2/3 of the tank height, which takes wastewater from the middle third of the hydrolytic reactor (site of the lowest concentration of suspended solids) and carries it to the dosing chamber, reducing the risks of plugging the latter.

Finally, for maintenance of the unit, next to the tee inlet there is a pipe to drain sludge at the end of the coffee harvest.

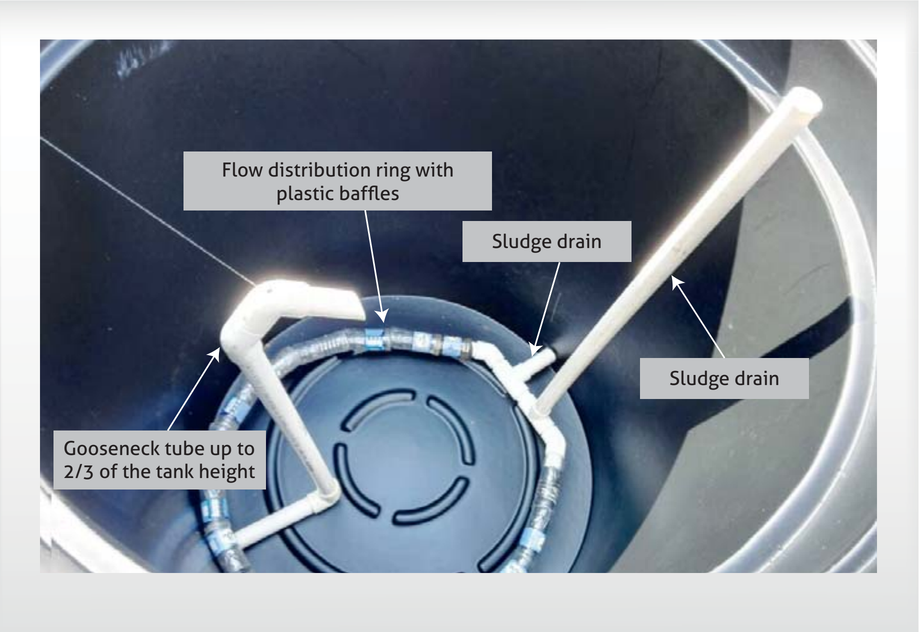


Figure 43. Hydrolytic-Acidogenic Reactor diagram.

Dosing chamber (Rodríguez *et al.*, 2017)

This unit regulates the flow entering the methanogenic reactor to ensure the hydraulic retention time necessary for biological wastewater treatment, in order to meet the standards required by regulations.

Figure 44 shows in detail the different connections and elements of the dosing chamber. The effluent from the hydrolytic-acidogenic reactor enters the unit through a 1" ball valve (A), which cuts the flow in case of an eventuality or for maintenance purposes; the valve is equipped with a float valve (B), which limits water level to maintain a constant pressure, and is installed 6 cm below the top edge of the tank.

The chamber features a sludge drain, located 7 cm from the bottom; it consists of a 1½" PVC pipe 1m long, a male adapter, and a PVC threaded plug (C). There is also an outflow regulator (D), located 10 cm from the bottom, consisting of a ½" PVC-P pipe 8 to 10 cm long and a threaded cap with a 5/64" hole. The chamber is filled with gravel (filter medium), and a mosquito net is placed over the gravel, held by a ½" low-density recycled-polyethylene hose ring to increase efficiency of the filtration system.

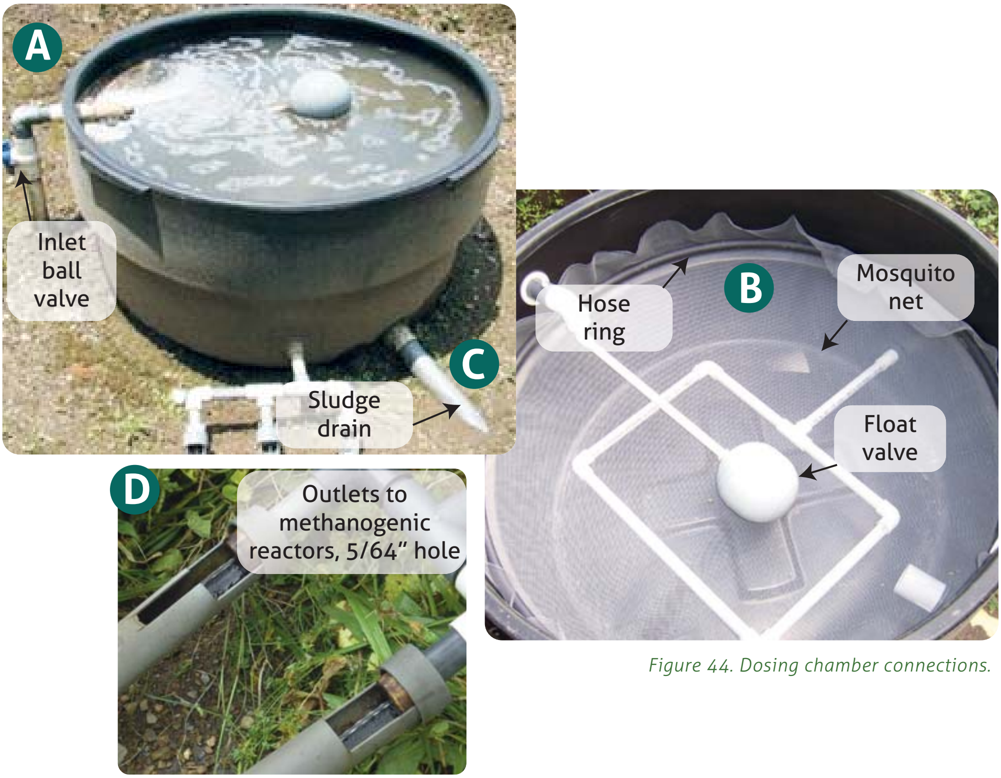


Figure 44. Dosing chamber connections.

To maintain good dosing chamber operation, installing a small solids trap next to it is recommended. This trap consists of a filter of 10 cm in diameter made of mosquito net, which retains solids that can clog the dosing chamber outlet and limit or block the flow to the methanogenic reactor (Figure 45).

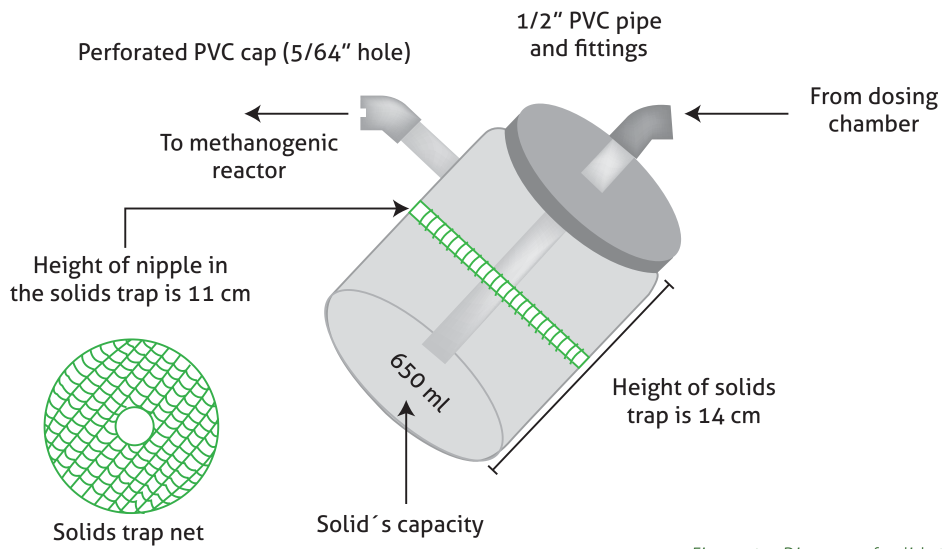


Figure 45. Diagram of solids trap.

Figure 46 shows its location in the dosing chamber.

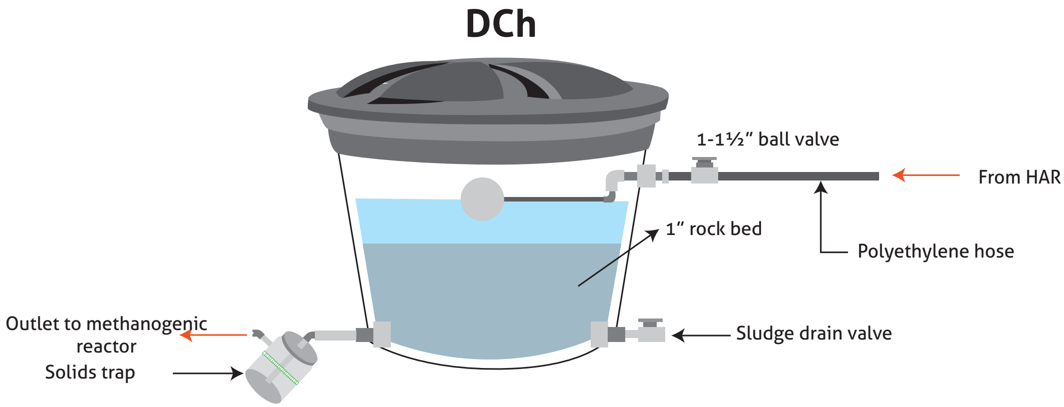


Figure 46. Location of solids trap after the dosing chamber.

Methanogenic reactor

This consists of a polyethylene tank where coffee wastewater methanogenesis reactions occur. It is designed to retain wastewater for 3 days.

For calculation of volume of this unit, the following information is required:

1. *Annual production:* arrobas of dry parchment coffee per year (@/year of dpc).
2. *Peak Day:* Percentage of annual production.
3. *Peak Week:* Percentage of annual production.
4. *Water consumption:* L/kg of dpc.

Volume of the methanogenic reactor (MR) is determined through Equation 11:

$$V_{MR} = 60 \times (0{,}9/1000) \times (1/100) \times 27{,}4 \times (1/8{,}75) \times (1/5) \times Pw \times Pa \quad (11)$$

$$V_{MR} = 0{,}000338 \times Pw \times Pa$$

Where:

60 = gc, conversion factor of @ of dpc to kg of coffee cherry (4.8 x 12.5)

0.9 = liters of water consumed in washing of 1 kg of coffee cherry

1,000 = gc, conversion factor of L to m^3

27.4 = COD concentration in wastewater, in kg/m^3

8.75 = COD applied in kg/m^3

Pw = peak week in %

Pa = Annual production in arrobas of dpc

To promote the methanogenesis reactions and microorganism activity, the reactor is inoculated with manure of cattle or pigs dissolved in water (in 1:1 ratio); this mix is subjected to strong, constant agitation to homogenize it, ensuring an inoculation rate of 1 to 2%. Also, the reactor is filled with some of the following support media: pieces of bamboo, non-returnable bottles or tires, corncobs (Figure 47).

Figure 47. Support media used in methanogenic reactors.

To favor growth of methanogenic microorganisms, the addition of the following only during installation of the Modular Anaerobic Treatment System is recommended: a carbon source to have between 4 and 5 kg of soluble COD per m3 of the reactor, a nitrogen source to balance the C/N ratio, and a neutralizer to have a pH close to 7.

Artificial wetland

This is designed in the same way as the one designed for domestic wastewater.

In this case, the precaution is taken of using as rate constant the value found for coffee wastewater.

$\mathbf{K_T} = K_{20}(1{,}06)^{(T-20)}$, T en °C (Reed *et al.*, 1995, cited by Rodríguez, 2009).

$\mathbf{K_{20}} = 0{,}149\ d^{-1}$, according to Rodríguez, 2009, for coffee wastewater.

Reuse pits

Their purpose is to use coffee wastewater, pulp and other organic materials from the farm for production of organic fertilizer, preventing discharges to the soil or surface/underground water bodies.

Reuse of coffee wastewater for production of organic fertilizer accelerates decomposition of organic matter and generates an organic fertilizer (enriched with wastewater nutrients) that can be used in agricultural production. In addition, the following types of environmental expenses for wastewater treatment would be avoided:

1. Permits for discharges (costing about COP 80,000 every 5 years).
2. Annual wastewater characterizations (costing about COP 200,000).
3. Payment for annual visit of officials of the Regional Autonomous Corporation (about COP 200,000).
4. Payment of retribution tax.

To design a greenhouse-type coffee pulp reuse pit, the following data is needed:

- Annual coffee production of the farm (in arrobas of dry parchment coffee per year).
- Percentage of wet-processed coffee in the peak harvest week.

The amount of water used in wet coffee processing must be lower than 1 L/kg of coffee cherry or than 5 L/kg of dpc.

The greenhouse-like reuse pit is a special construction made of bamboo and matting, isolated from soil, roofed and with walls covered with plastic, which stores, dehydrates-hydrates-dehydrates, and decomposes coffee pulp and other organic matter from the farm (particle size similar to that of pulp) into organic fertilizer for later use.

The pit should have concrete columns for greater durability (Figure 48). The pulp must have been removed and be transported to the pit without water and evenly distributed, using all the area available in the first compartment of the pit.

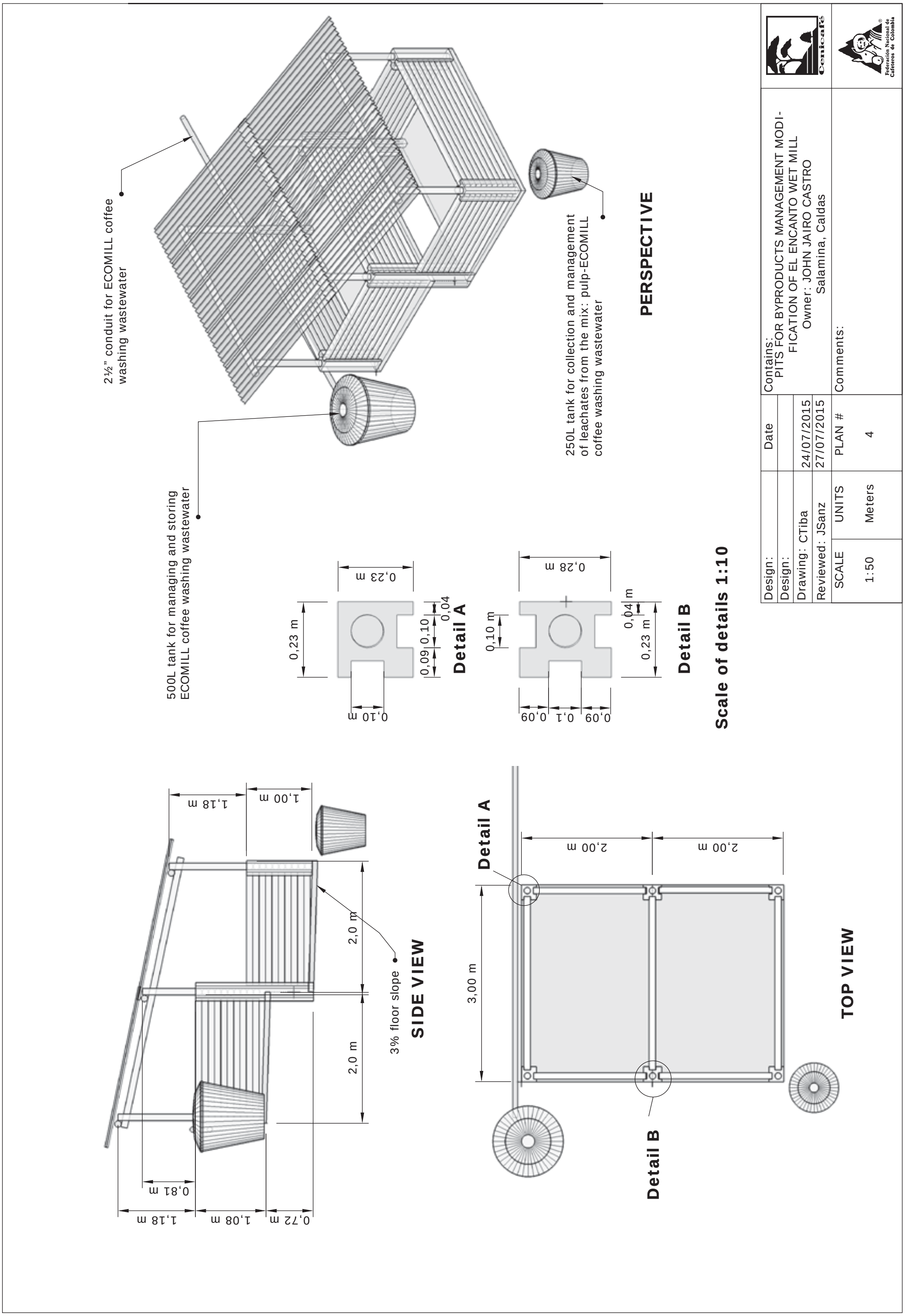


Figure 48. Aspects and dimensions of a pulp pit for a farm producing 180@/year of dpc and a 15% peak week. (Source: Tibaduiza and Ramire, 2015).

The pit must have four compartments, all the same size, to facilitate composting. Equation 12 is used for determining the area of the first pit compartment:

$$A_{Compartment1} = 0{,}0008 \times P \times \%PW \quad (12)$$

Where:

$A_{Compartment1}$ = Area of first pit compartment (m^2)

0,0008 = Constant

P = Annual coffee production (@ of dpc).

% PW = Coffee production in peak week (%).

The compartments must have 1 m of effective height (bamboo walls) for storing the pulp.

The floor may be the ground itself, once leveled, with a 2% slope to the front of the pit, and covered with gauge-6 plastic to prevent infiltrations. The floor may also be of cement, but as the pulp leachates corrode it, it is necessary to cover it with plastic or tiles.

The slope leads the leachates to a DWV PVC drain, which carries them out for their collection, while allowing access of cold, dry air, which contributes to dehydration and decomposition of the organic matter in the pit.

On the plastic, bricks are placed in rows of 25 cm, separated 10 cm each. Finally, on the bricks are placed two layers of matting, overlapped and arranged at right angles (Zambrano and Cárdenas, 2000).

The pit walls are covered with gauge-6 transparent plastic held by bamboo columns. Between the front wall and the roof, a 30cm space is left to allow exit, by natural convection, of warm air, saturated with water vapors and volatile fatty acids produced during decomposition of the organic matter. On one side, a door is built for allowing access to the pit.

The pit roof may be made of bamboo, with plastic and zinc, Eternit, or plastic tiles.

By the first pit compartment, a polyethylene tank is located to store wastewater from the washing stage, and close to the last compartment, a tank of the same material is located to collect and store leachates.

To calculate the size of the tank where wastewater from washing is stored, Equation 13 is used:

$$\text{Volume WWT} = \frac{2 \times P \times \%PW \times 60}{500} \quad (13)$$

The size of the tank where leachates are collected is calculated through Equation 14:

$$\textbf{Volume LT} = \frac{P x \%PW x 60}{500} \quad (14)$$

Where:

Volume WWT = Volume of washing wastewater tank, L

Volume $_{LT}$ = Volume of leachate tank, L

P = Annual coffee production (@ of dpc).

%PW = Coffee production in peak week (%)

Once the greenhouse-type pulp pit is built and equipped, the coffee pulp is evenly distributed in the first compartment, using a rake or shovel, in such a way that it occupies the entire area.

Wastewater from the first three coffee rinses is stored in the tank located by the first compartment (wastewater from the fourth rinse may be directly used in irrigation of seedlings, worm composting, or coffee crops). The day after being generated, the stored wastewater is fully added to the pulp, using a shower or irrigation device, taking care to evenly distribute it over the entire area occupied by the pulp. This step is repeated daily, adding fresh pulp to that contained in the first compartment, leveling it over the entire available area, and adding wastewater.

Fifteen days after the pulp is deposited in the first compartment, or sooner if this is already filled, all the pulp is moved to the second compartment, distributing it evenly over the entire area. The pulp deposited in the second compartment is irrigated with the collected leachate. As the first compartment is now free, it will continue receiving fresh pulp, which is moistened with new wastewater.

After another 15 days, or sooner if the first compartment is filled, the pulp is moved from the second to the third compartment and from the first to the second compartment, always evenly distributed and moistened.

Another 15 days later, or sooner if the first compartment is filled, the pulp is moved from the third to the fourth compartment, from the second to the third one, and from the first to the second one, evenly distributed and moistened.

After another 15 days, or sooner if the first compartment is filled, pulp is removed from the fourth compartment to a place that stores organic fertilizer, and moved from the third to the fourth compartment, and so on, repeating the above-mentioned operations.

Vegetation filters

Vegetation filters are treatment systems that aim to maximize soil potential to remove contaminants from wastewater. Its function is based on application of wastewater to a vegetation surface, of either forest or herbaceous type, to use capacity of the soil-plant-microorganisms system to degrade pollutants. Wastewater, once in contact with the ground, is subjected to multiple processes, including evapotranspiration, filtration, biodegradation, adsorption, absortion and uptake of nutrients by plants. If the system has been well designed, the treated effluent should reach the aquifer with acceptable quality, according to discharge regulations.

This technology has been used for treatment of multiple effluents, both domestic (De Miguel *et al*., 2014) and industrial (De Bustamante, 1990), or wastewater from landfill leachate (Zupanc and Justin, 2010). Though an example of its application for coffee wastewater has not been found so far, such systems have been frequently used with other relatively similar wastewaters, such as those from the olive oil industry (Azbar *et al*., 2010) and other food industries (Aryal and Reinhold, 2015), all of them characterized by high organic load and, in many cases, low pH.

In general, wet coffee processing effluents are directly discharged into a stream or water body, and it is possible to determine water quality effects. Other times, they are discharged to the ground, either by infiltration in a high-permeability area or by applying them to the ground or a forest area (for example, bamboo). It is well known that soil can act as a reactor, degrading part of the organic pollutants found in wastewater and partially attenuating their impact.

The use of vegetation filters for coffee wastewater treatment therefore has great potential, as it is a robust, low-cost technology, with low operation and maintenance requirements, and which may be easily adapted to the coffee landscape.

But for its possible adoption by Colombian coffee growers, it is essential to perform studies that certify that such technology is viable and sustainable in the long term. Therefore, the IWM Project developed a series of preliminary studies with different objectives:

1. To evaluate the capacity of vegetation filters to remove contaminants from coffee wastewater.
2. To determine the optimal hydraulic and organic loads for a suitable design.
3. To assess the effect of vegetation on capacity of removal of pollutants, as well as potential biomass production rate.

For that purpose, an experiment with six plots was designed, where three coffee wastewater volumes were applied to two types of vegetation (Table 24, Figure 49).

Table 24. Description of plots evaluated.

Plot	Hydraulic Load	COD Load*	Vegetation Type
P5 NV	5 mm/day	200 g COD/day	Natural vegetation (NV)
P5 VG	5 mm/day	200 g COD/day	Vetiver grass (VG)
P10 NV	10 mm/day	400 g COD/day	Natural vegetation (NV)
P10 VG	10 mm/day	400 g COD/day	Vetiver grass (VG)
P20 NV	20 mm/day	800 g COD/day	Natural vegetation (NV)
P20 VG	20 mm/day	800 g COD/day	Vetiver grass (VG)

* The load applied was calculated based on pre-treated wastewater concentrations.

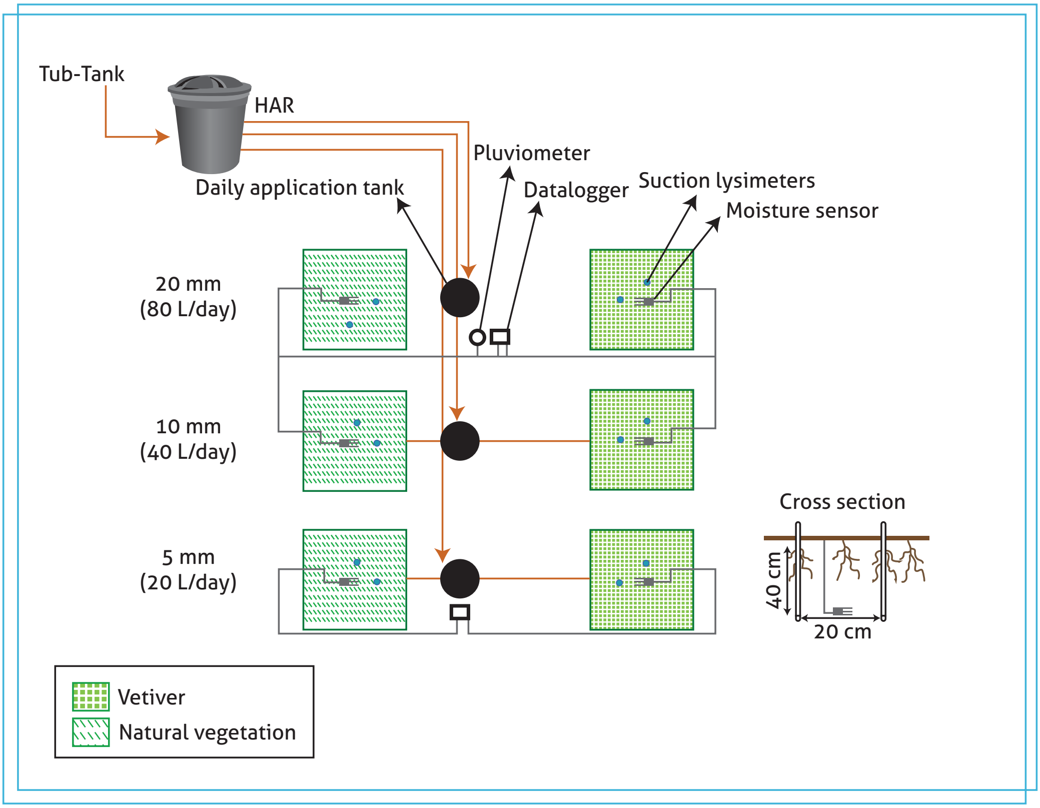


Figure 49. Diagram of experimental vegetation filter plots.

The hydraulic loads applied daily were 5, 10, and 20 mm (1 mm = 1 L/m2) to determine the maximum volume assimilated by the soil. In three of the plots, vegetation grew spontaneously, mainly hilograss (*Paspalum conjugatum)* and Guinea grass (*Panicum maximum*). In the other three plots, vetiver grass (*Chrysopogon zizanioides*) was sowed with high density (bunches every 10 cm). This species was selected for its ability to resist very wet soils, its large root development, and its capacity to absorb pollutants.

Vegetation height was controlled, with regular cuts to 35 cm, in order to maximize its growth capacity and, therefore, its ability to uptake nutrients. The experiment was conducted at the National Coffee Research Center (Cenicafé), in Manizales, Caldas, on a site of very low slope (less than 1%), a sandy-clay loam texture, and a 1.9% organic matter content.

To simulate coffee farm conditions, wastewater was applied for 10 weeks (harvest period), although the wastewater quality monitoring was extended another 10 weeks (20 weeks in total) to assess possible washing of pollutants by the rain. Each plot's area was 4 m2 (2x2m). The coffee effluent applied came from an ecological wet mill (Ecomill®), with high organic load, pretreated in a hydrolytic-acidogenic reactor (HAR), which reduced organic load nearly 50%. This pretreatment is required to remove part of the suspended solids, reduce organic load, and prevent clogging problems in the irrigation system. Wastewater was then applied to the experimental plots through a trickle irrigation pipeline, leveled to ensure homogeneous water distribution (Figure 50). Thanks to the use of a flow rate regulator designed by Cenicafé, a constant flow of 0.39 L/min (Figure 50) was supplied.

Wastewater from tub-tank
being pre-treated in the HAR.

Wastewater after primary treatment

Appearance of control plots (natural vegetation)

Overview of land application tanks. One per plot.

Appearance of plots with vetiver grass

Figure 50. Coffee wastewater is applied to the plots.

Unlike most treatment systems, a vegetation filter does not have an outlet point for treated water, so it has to be monitored through collection of drained (percolated) water at some depth. For that purpose, each experimental plot was equipped with two suction lysimeters, which extracted water percolated through soil for its later characterization in the lab. These lysimeters were placed at a depth of 40 cm. A soil moisture sensor was also placed in the soil of each plot, at a depth of 40 cm, to continuously monitor water content, as well as a rain gauge which recorded precipitation (Figure 51).

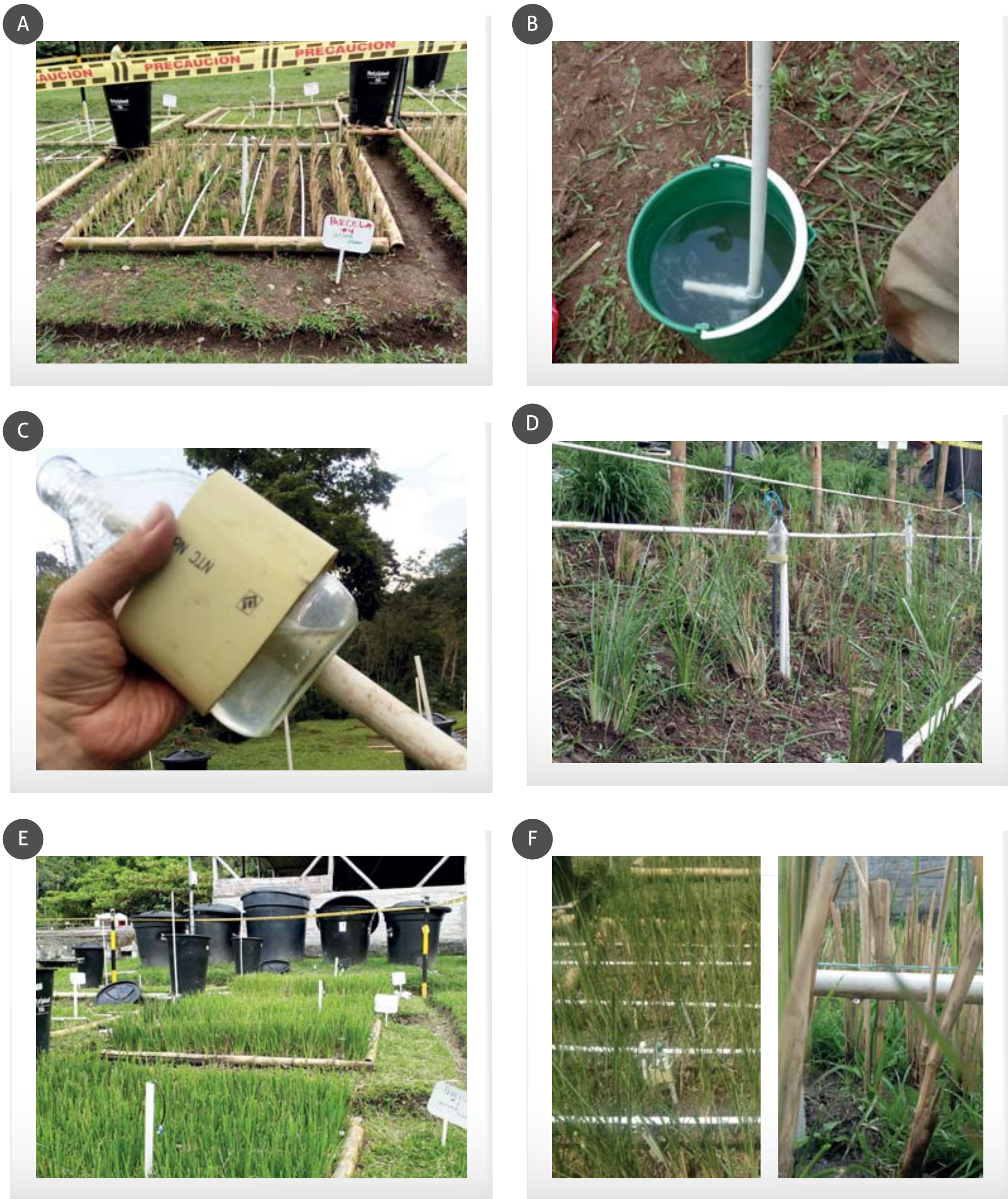


Figure 51. (a) The plots before the experiment; (b) Horizontal suction lysimeter; (c) Sampling container and irrigation system; (d) Leveling of irrigation pipes; (e) Plots at completion of the experiment; (f) Flow distribution system.

Main results

Below is a summary of the main results obtained during the 20 experimentation weeks regarding vegetation filter capacity for removal of pollutants, evolution of soil properties, and biomass production.

Removal of contaminants from water

Coffee wastewater was characterized by high organic load, with a COD over 20,000 mg/L, an acid pH (3.20), and high content of suspended solids (5,800 mg/L) (Table 25).

Table 25. Characterization of coffee wastewater applied to vegetation filters and percolates collected in the different plots.

Parameter / sample type	pH*	COD* (mg/L)	COD ** removal (%)	COD *** removal (%)	Conductivity * (µS/cm)	P-PO4* (mg/L)	P-PO4** removal (%)	TN * (mg/L)	TN ** removal (%)
Coffee wastewater	3,2	20261	-	-	2916	12,2		597,8	-
HAR Output	4,3	10163	49,8		1550	11,9	2,5	228,1	61,8
P20 NV Output	6,6	117	98,9	99,4	99	0,4	96,6	174,2	23,6
P20 VG Output	5,8	1425	85,9	92,8	1520	0,6	95,0	440,2	-
P10 NV Output	6,3	147	98,5	99,3	111	0,2	98,3	255,6	-
P10 VG Output	6,6	159	98,4	99,2	432	0,2	98,3	147,8	35,2
P5 NV Output	5,7	108	98,9	99,5	57	0,3	97,5	159,8	29,9
P5 VG Output	6,3	73	99,3	99,6	37	0,3	97,5	146,1	37,2

* Average value of wastewater and percolates collected from week 4 to week 10 of experimentation.

** % of removal calculated from coffee wastewater that entered the soil.

*** % of removal calculated from coffee wastewater that entered the HAR.

Thanks to the pretreatment system installed (HAR), the organic load was reduced by almost 50% before land application (values below 10,200 mg/L of COD) because of the flotation, sedimentation, and filtration processes therein and the device implemented to regulate the outflow, also resulting in 79% of suspended solids removed (up to 1,200 mg/L) and a slight increase in pH (4.3).

As to nitrogen compounds, coffee wastewater contains high concentrations, mostly in organic form, with a total nitrogen (TN) value of almost 600 mg/L, of which the HAR was able to remove over 60%.

During the 20 experimentation weeks, it was confirmed that soil has high capacity to remove contaminants, mainly organic load from coffee wastewater. The average COD concentration found in the percolates was low, with values below 1,500 mg/L in all the plots evaluated (Figure D).

Soil capacity to remove COD from the HAR effluent ranged from 86% (for the P20 VG plot) to over 98% for the rest of the plots (Table 52); COD removal rates are much greater if the system is evaluated as a whole: from 92% in the worst case to 99%.

Appearance of water entering the plot (bucket)

Sampling with suction lysimeter

Appearance of percolated water.
Plots with vetiver grass.

Figure 52. Sampling and appearance of water entering and exiting the soil.

The average pH values found in the drained water showed a slightly acid pH, between 5.7 and 6.6, a considerable increase from applied water. Similarly, conductivity fell substantially in most plots, except for P20 VG. As to phosphates (P-PO4), removal was very significant, above 95%, with concentrations below 0.7 mg/L.

Due to problems in characterization of nitrogen compounds, it was not possible to fully assess the system capacity to remove total nitrogen (TN). Despite this, removal rates in plots where it was assessed ranged from 24% to 37%. It is important to mention that most of the TN was found in organic form (above 90%).

Quantification of suspended solids, required according to discharge regulations, was not possible due to sampling system characteristics. Even so, it is well known that soil has a large physical filtration capacity, removing most suspended solids from the water applied. This effect has been tested in the laboratory by percolating a coffee wastewater sample through an undisturbed soil column from the experimentation area, observing rates of removal of suspended solids above 95%, with concentrations below 100 mg/L in drained water.

If results obtained from the different experimentation plots are compared to the values allowed by the Colombian regulation for discharges of coffee wastewater to surface water bodies, established by Resolution 631 of 2015, vegetation filters provide proper wastewater treatment, meeting, for all the volumes tested (5, 10, 20 mm), the discharge requirements regarding pH, COD, and suspended solids. Likewise, on average all treatments complied with the limits for discharges to soil (Decree 1594 of 1984), which sets an organic load removal rate above 80%.

Evolution of soil properties

In a vegetation filter, soil acts as a bioreactor; therefore, controlling evolution of its properties is essential for correct long-term operation. That's why soil samples were taken before and after wastewater application for its characterization in the laboratory.

The main changes observed (Table 26) were an increase in concentration of organic matter in soil, from 1.9% to values above 4.0% in most plots; an increase in pH of soil, and higher values for nitrogen and potassium in most plots. In the case of phosphorus, plots with vetiver grass (P20 VG, P10 VG, and P5 VG) always showed values higher than control plots (natural vegetation).

Table 26. Main properties of soil before and after coffee wastewater application.

Parameter	Before application (compound sample)	After application of coffee wastewater					
		P20 NV	P20 VG	P10 NV	P10 VG	P5 NV	P5 VG
pH	3,80	5,60	5,60	5,90	5,00	5,50	4,90
MO (%)	3,90	2,40	5,80	4,10	5,80	4,20	5,10
N (%)	0,18	0,12	0,26	0,19	0,26	0,20	0,23
P (mg/kg)	710	456	512	169	670	371	960
K (cmol/kg)	0,25	0,58	0,82	1,11	0,52	0,47	0,30

For the other variables analyzed (Ca, Mg, Al, Fe, Mn, Zn, Cu, B, and S, not shown in the Table), no significant changes were observed, except for values of iron and manganese, which rose from 528 mg/kg and 25 mg/kg before wastewater application to about 600 mg/kg and 70 mg/kg, respectively. In the case of Mn, a close relation between volume applied and concentration in soil was observed, with higher values in the plots with higher volumes. Boron also increased slightly in soil after wastewater application, from 0.18 mg/kg to values ranging from 0.36 to 0.54 mg/kg.

Despite changes in soil, all the variables analyzed showed acceptable values from the agricultural point of view, so application of coffee wastewater has not generated a considerable change in soil properties so far.

Biomass production

Finally, biomass production has been quantified during the 20 experimentation weeks. As shown in Figure 53, plots with vetiver grass have biomass production similar to plots with natural vegetation, the vetiver plot with the lowest wastewater application (P5 VG) being the one with the largest production, with values reaching 23,000 kg/ha of dry matter. In the case of natural vegetation plots, the one with the highest wastewater application (P20 NV) showed the largest biomass production, with values reaching 24,000 kg/ha of dry matter. During the experiment, it was not observed that coffee wastewater application had produced visual negative effects on the condition or growth of plants.

Figure 53. Biomass production in vegetation filters (kg/ha of dry matter).

6

WATER TREATMENT ON COFFEE FARMS

IMPLEMENTATION OF WATER TREATMENT SYSTEMS UNDER THE IWM PROJECT

Selection criteria

The criteria for selecting interventions were based on the objective of the Project and aligned with the work plans on ecological wet processing and sustainability of investments, with the support of the Extension Service, and considering the impact on resources in each of the 25 river basins. Proximity of discharges to water bodies was considered, giving priority to those located less than 200 m away. Similarly, farms with the greatest impact on water resources were chosen to achieve the greatest possible impact of implementations on recovery of surface water quality.

Farms were examined before installing water treatment solutions to determine the most relevant needs of the selected coffee farms regarding installation of treatment systems and water consumption, in order to install appropriate water-saving devices.

Reduction of pollution in IWM river basins through implementation of wastewater treatment systems

Reduction of pollution in the IWM river basins was determined based on the 3,346 wastewater treatment systems installed in the 25 IWM river basins, for both coffee wastewater (CW) and domestic wastewater (DW). Table 27 summarizes pollution reductions, expressed in tons of COD/year.

Table 27. Reduction of pollution load according to IWM interventions.

Department	Pollution of river basin by CW (t of COD/ year)	Pollution of river basin by DW (t of COD/ year)	Reduction of pollution with CW systems (t of COD/year)	No. of interventions with CW treatment systems	Reduction of pollution with DW systems (t of COD/year)	No. of interventions with DW treatment systems
Antioquia	1.868	41	784	373	23	376
Caldas	2.175	69	377	316	26	436
Cauca	828	84	147	443	17	276
Valle del Cauca	2.201	41	806	275	27	420
Nariño	825	51	222	231	13	200
Total	7.896	287	2.336	1.638	107	1.708

Table 27 summarizes an overall reduction of 2,336,257 kg of COD/year for coffee wastewater, with a reduction of 467,230 kg of COD/year on average per department, and an overall pollution reduction of 106,598 kg of COD/year for domestic wastewater, on average 21,320 kg of COD/year per department.

Figure 54 shows results of pollution prevented per department with the domestic wastewater treatment systems implemented by the IWM Project.

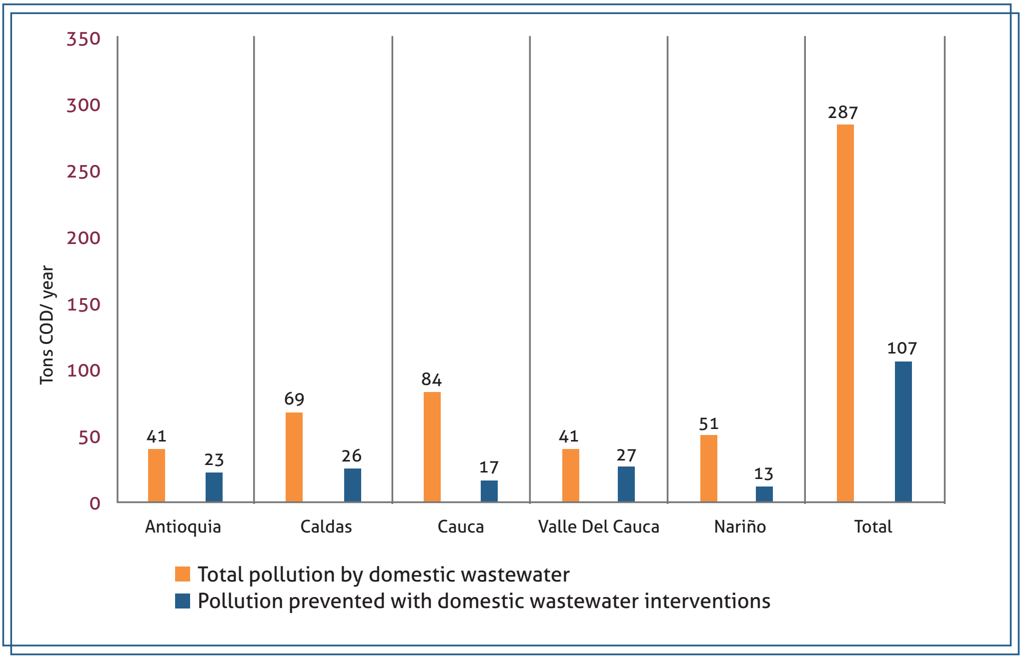


Figure 54. Organic pollution prevented at household level with wastewater treatment systems implemented by IWM.

In the Antioquia department river basins, pollution prevented was 56.1% of total pollution; in the river basins of Caldas, it was 37.68%; in the river basins of Cauca, 20.24%; in the Nariño river basins, 25.49%, and in the Valle del Cauca department, 65.85%.

The domestic wastewater treatment systems prevented over 37% of this type of pollution generated by 50% of the farms located less than 200 meters from the bodies of water.

Figure 55 shows results of pollution prevented per department with the coffee wastewater treatment systems implemented by the IWM Project.

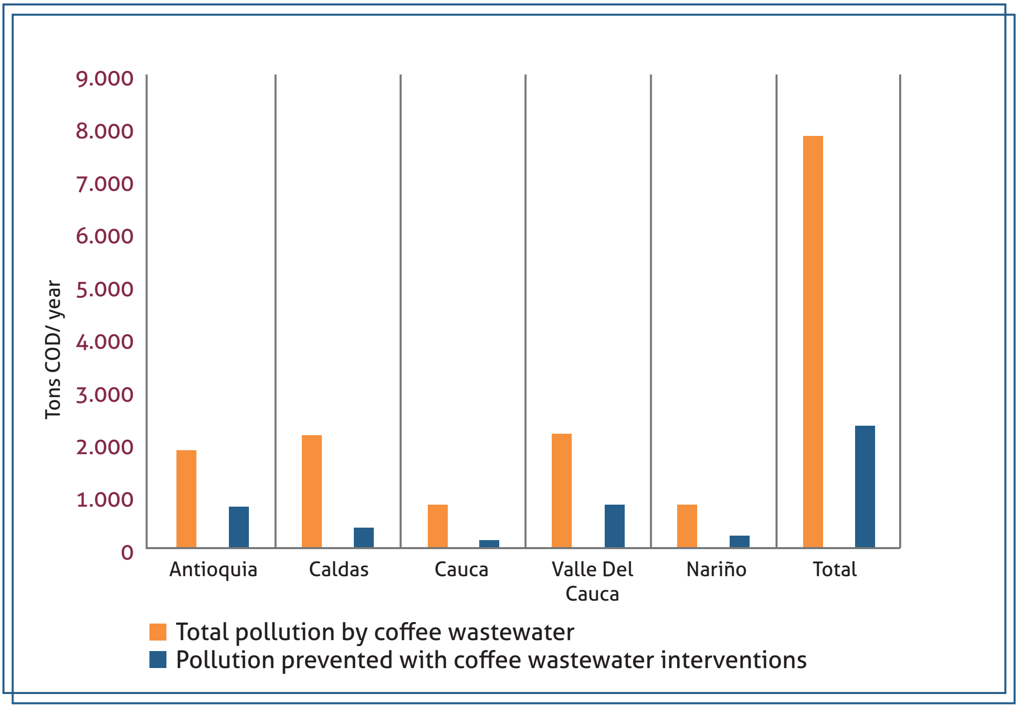


Figure 55. Organic pollution prevented with coffee wastewater treatment systems implemented by IWM.

In the Antioquia department river basins, pollution prevented was 41.90% of total pollution; in the river basins of Caldas, 17.30%; in the river basins of Cauca, 17.75%; in the Nariño river basins, 26.90%; and in the Valle del Cauca river basins, 36.61%.

Coffee wastewater treatment systems prevented 29.5% of pollution generated by 50% of the coffee farms located less than 200 m from water bodies.

Figure 56 shows the overall polluting potential of both domestic and coffee wastewater discharged by 50% of coffee growers located less than 200 m from water bodies, and the respective pollution prevented by the IWM Project implementations.

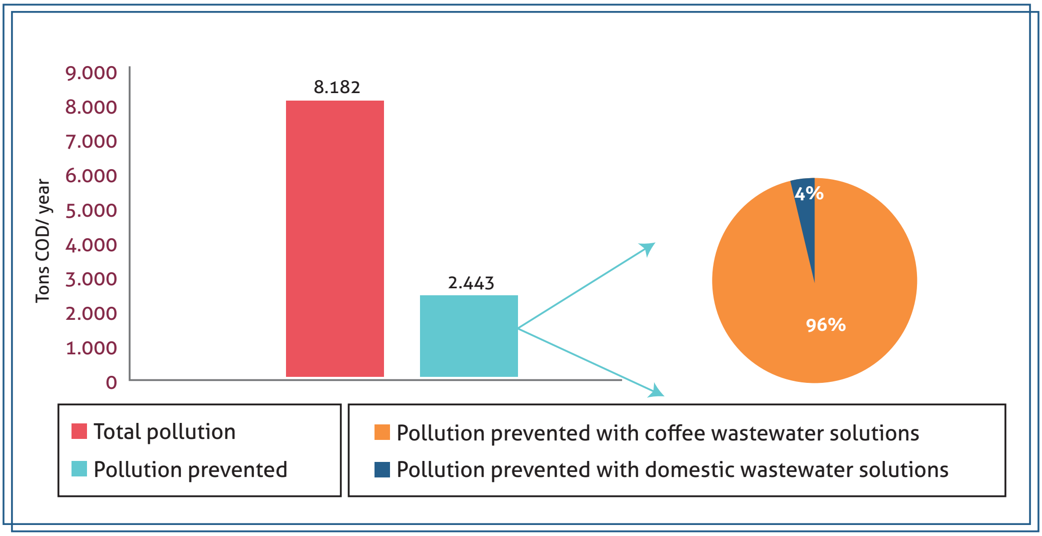


Figure 56. Total estimated and prevented pollution in wastewater generated by 50% of farms located less than 200 m from water bodies.

Of total pollution prevented, 96% was through coffee wastewater treatment solutions and 4% through domestic wastewater solutions.

Types of domestic wastewater treatments implemented and their contribution to pollution prevention in the river basins

In the 25 river basins, the IWM Project installed 686 grease traps and 1,022 septic systems on coffee farms located less than 200 m from water bodies.

Figure 57 shows total pollution (as COD) from 50% of the coffee farms located less than 200 meters from water bodies (the target population for domestic wastewater treatment systems) and pollution prevented by solution type.

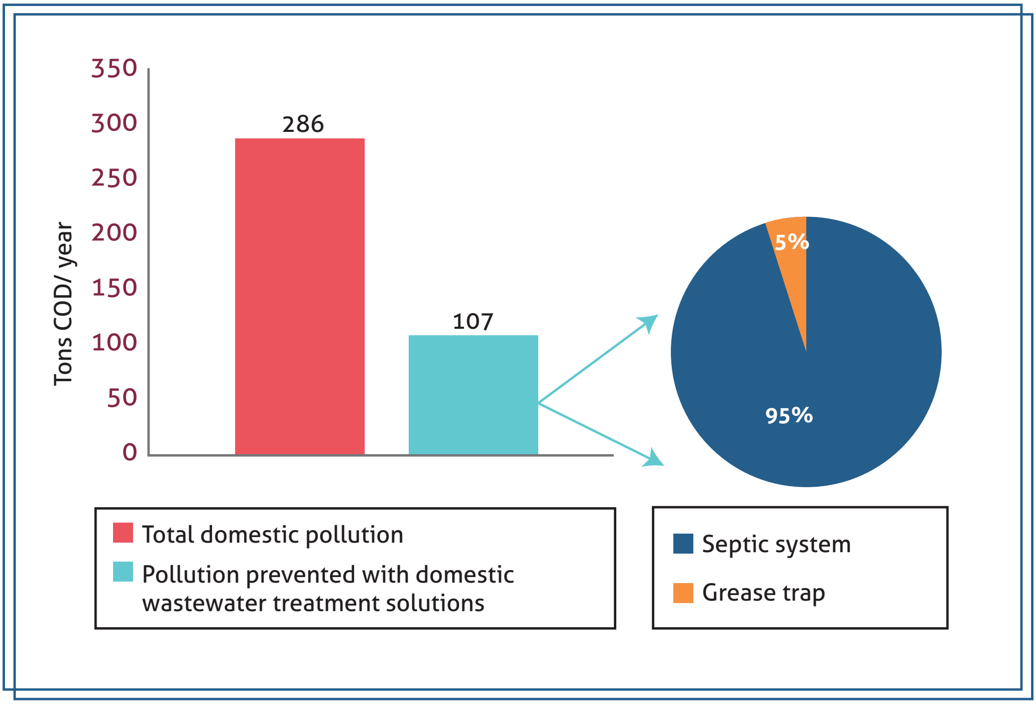


Figure 57. Total estimated and prevented pollution in domestic wastewater from 50% of farms located less than 200 m from water bodies.

Out of the domestic wastewater treatment solutions implemented, grease traps have helped control 5% of pollution and septic systems the remaining 95%.

Types of coffee wastewater treatments implemented and their contribution to pollution prevention in the river basins

In the 25 river basins, the IWM Project installed 575 full Modular Anaerobic Treatment Systems (SMTA), 585 pulp pits, 165 partial SMTA, and 313 artificial wetlands.

Figure 58 shows total pollution by coffee wastewater, expressed as COD, from 50% of the farms located less than 200 m from water bodies (the target population for treatment systems) and pollution prevented by solution type.

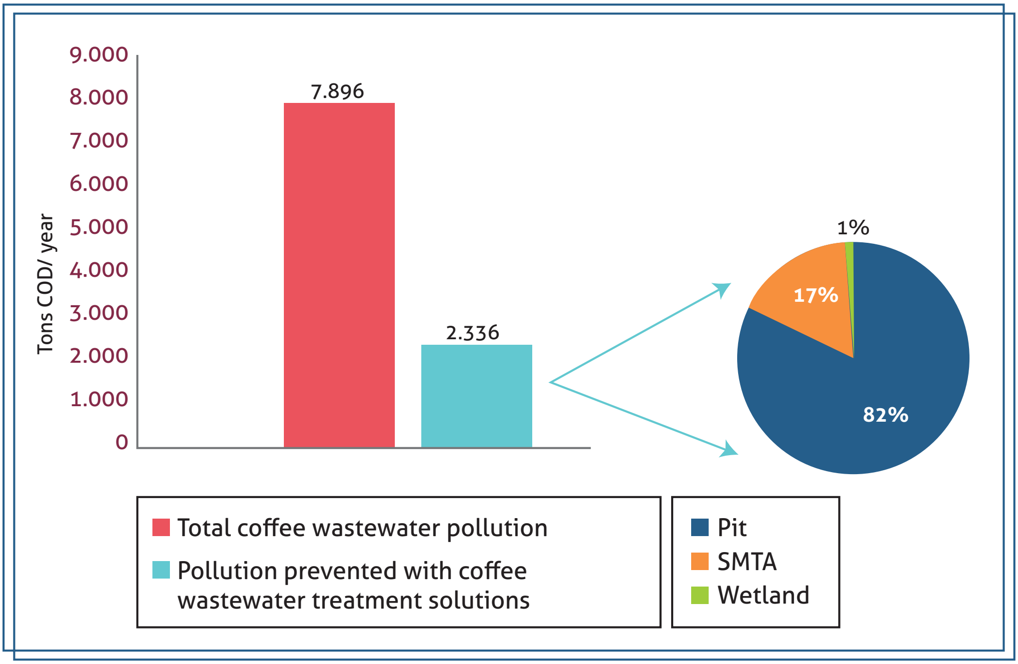


Figure 58. Total estimated and prevented pollution in coffee wastewater from 50% of farms located less than 200 m from water bodies.

Out of the solutions implemented for coffee wastewater treatment, the pulp pits have helped control 82% of pollution, the SMTA, 17%, and wetlands, 1%.

Ratios of pollution prevented in the river basins (through wastewater treatments) to improved surface water quality

Figure 59 shows the relation between pollution reduction through wastewater treatment solutions in 11 IWM river basins, assessed in seven surface water quality monitoring campaigns (M), and improvement of the overall surface water quality indicator in the river basins, comparing initial conditions and those at the end of the IWM Project.

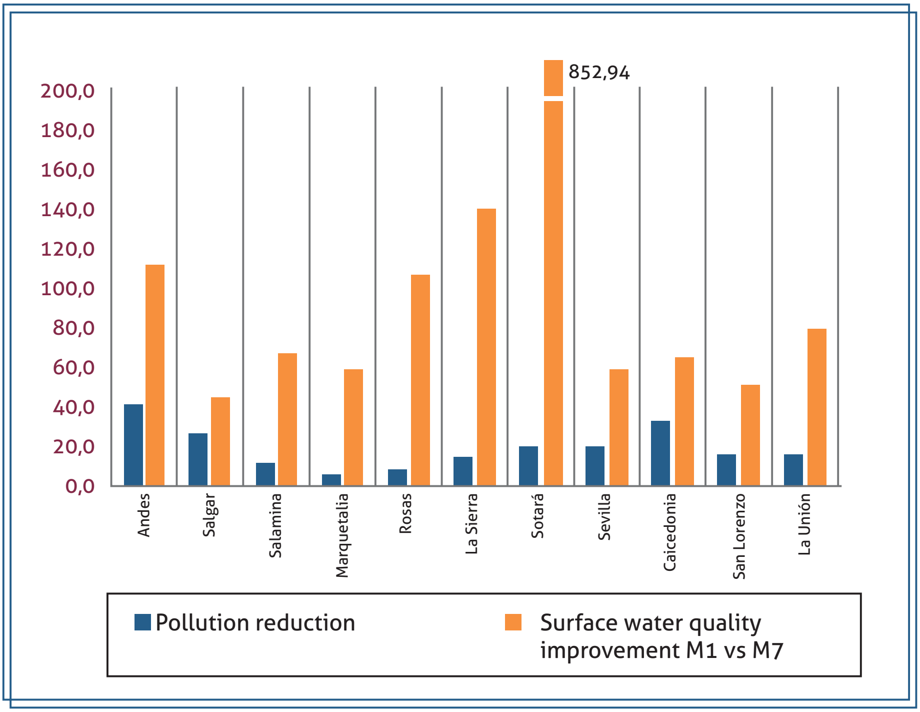


Figure 59. Relation between pollution reduction (through implementation of treatment systems) and overall indicator of water quality in the IWM river basins by comparing initial and final conditions.

For all the river basins, results of Figure 59 show that lower water pollution through implementations substantially improved surface water quality.

Although all river basins showed this multiplying effect, it was not of the same magnitude, as in some river basins the wastewater sources were closer to the water body or the discharges were greater.

The river basin that showed the greatest impact of wastewater treatments on surface water quality was that of the Quilcacé river, in Sotará, Cauca: with a 20.1% pollution reduction, surface water quality improved almost 853%, a multiplying factor of 42.4 (Table 28).

The river basin with the lowest impact of wastewater treatments on surface water quality was La Gulunga, in Salgar, Antioquia: with a 27% pollution reduction, surface water quality improved almost 45%, a multiplying factor of 1.66.

On average, pollution prevented in the 11 river basins assessed up to the seventh water quality monitoring campaign was 19.36% (as a result of wastewater treatment solutions). The average improvement in surface water quality was 149.12%, a ratio or multiplying factor of 9.

Table 28. Ratios of surface water quality improvement to pollution prevented in the river basins.

River basin	Municipality	Department	Pollution reduction (%)	Water quality improvement (%)	Improvement to Reduction
La Chaparrala	Andes	Antioquia	41,77%	112,23%	2,69
La Gulunga	Salgar		27,00%	44,87%	1,66
La Frisolera	Salamina	Caldas	11,86%	67,39%	5,68
Los Saínos	Marquetalia		5,59%	59,68%	10,67
San Marcos	Sevilla	Valle del Cauca	19,54%	58,65%	3,00
Barragán	Caicedonia		32,97%	65,24%	1,98
El Marquez	Rosas	Cauca	8,37%	107,40%	12,84
Esmita	La Sierra		15,08%	140,95%	9,35
Quilcacé	Sotará		20,11%	852,94%	42,41
El Molino	San Lorenzo	Nariño	15,79%	51,64%	3,27
La Fragua	La Unión		14,92%	79,38%	5,32
Average			19,36%	149,12%	8,99

7

WATER TREATMENT ON COFFEE FARMS

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

Water purification systems

- According to the IWM Project baseline, only 31% of coffee growers have access to drinking water. The Project evaluated different technologies for purification of water in households (including microfilters, nanofilters, and distillation systems), and it was demonstrated that nanofilters are the best option from the cost-effective point of view.
- Durability and effectiveness of purifiers depend on both quality of water to be treated and proper maintenance.
- The IWM Project installed water purifiers for 900 families (about 2,800 people), as well as 64 community purifiers (for 3,300 students). All the purifiers installed produced water that complies with the Colombian drinking water regulations.
- Purification systems installed in households are more cost-effective than centralized ones, especially in the rural coffee producing regions, where most of the water used does not need to meet drinking water quality standards.
- Installation of community purifiers raised greater awareness in local communities, leading also to lower truancy, and encouraged local actions to ensure sustainability of the Project's investments, such as collection of money by parents to purchase new filters that continue supplying drinking water to schools.

Domestic wastewater treatment

- The Project baseline found that very few coffee farmers had domestic wastewater treatment systems, resulting in negative environmental impacts on soil and water. The dynamic monitoring of water bodies in the Project river basins showed that domestic wastewater has a polluting impact on water higher than expected, so it is important to treat it.
- The IWM Project provided 1,708 domestic wastewater treatment solutions, reducing pollution by 37% in terms of organic load.
- For good operation of domestic wastewater treatment systems, design, operation and maintenance are equally important. For a treatment system to be complete, it must include the following components: grease trap, septic tank, anaerobic filter, and final disposal (drain fields or artificial wetlands, among others).
- Removal of sludge from the septic tank, an essential step in operation and maintenance of the system, has become an obstacle for adoption of this technology. This problem was solved by using the inverted-siphon device developed by Cenicafé.

Coffee wastewater treatment

- The baseline showed that very few farms have coffee wastewater treatments. The IWM Project made a significant contribution to improving this type of treatment with several solutions: reuse pits, anaerobic systems, and vegetation filters.
- The IWM Project provided 1,638 coffee wastewater treatment solutions, including primary, secondary treatments, and artificial wetlands, reducing pollution by 29.5%.
- The Project generated knowledge and capacity to select the adequate combination of solutions for a specific farm, depending on its size (small, medium-sized or large), weather conditions, and soil and landscape characteristics.
- Adoption of available technologies has greatly improved thanks to the Project training sessions for the Extension Service and coffee farmers, reducing the gap between available technologies and implementation in the field.

Vegetation filters

- Pollution removal results lead to the conclusion that this technology is suitable for post-treating ecological wet coffee processing wastewater, showing high organic load removal rates.
- The three volumes applied (5, 10 and 20 mm) produced percolates that were below the discharge limits established by Resolution 631 of 2015 regarding parameters of COD, pH, and suspended solids.
- A direct relation between the type of vegetation used and purification rates has not been observed.
- A deterioration of soil properties that may put the long-term viability of vegetation filters into question has not been observed either.

RECOMMENDATIONS

- The inclusion of household treatment systems (drinking water and wastewater) in the River Basin Management Plans is recommended, given their significant impact on pollution of water resources and human health.
- Coffee pulp management in roofed pulp pits, through composting or vermicomposting, has considerable impact on conservation of natural resources (water, air and soil) and prevents 74% of pollution from wet coffee processing byproducts.
- Reducing the amount of water to be treated is important to prevent hydraulic overloads in water treatment systems. Therefore, water must be saved in wet coffee processing as much as possible.
- Use of Hydrolytic-Acidogenic Reactors (HAR) as coffee wastewater pretreatment systems significantly reduces the organic load to be applied to soil, as well as suspended solids, minimizing clogging problems in effluent irrigation systems.
- For cost-effectiveness of interventions, the following recommendations should be taken into account: 1. Design of long-lifecycle treatment systems (in terms of materials), 2. Most polluting byproducts must be prioritized (pulp, mucilage, first rinses of coffee), 3. Select the sites most critical to water bodies (located less than 200 m from the main water body).
- The process started with the IWM Project should continue, preferably with the possibility of reusing coffee wastewater, ultimately aiming at zero discharges.
- In the IWM Project, almost all coffee farmers co-financed (in different ways) the technology they received. For future implementations, the same approach is recommended to reduce risks of losing the investments and thus ensure operation and maintenance of the treatment systems installed.
- In this experience, the results of using vegetation filters for treatment of coffee wastewater are very promising. Despite this, scaling up the experiment to coffee farm level and for a longer time is recommended, so as to ensure proper functioning in the long term. These experiences should serve to improve implementation of this technology on coffee farms, evaluating other types of soils and vegetation, and adapting the system to the coffee landscape (slope, land availability, etc.).

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Carlos Guerrero

Valle Extension Service

Beatriz Rodríguez

Wilson Osorio

Luis Isaza

Nariño Extension Service

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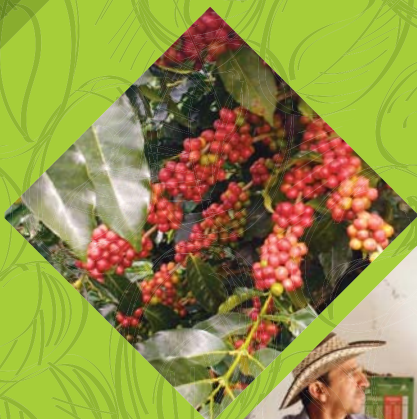

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