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RESEARCH ARTICLE

Construction of a Solar Still Prototype to Reduce Extreme Water Hardness in the Mayan Community Ejido 20 de Noviembre

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ABSTRACT

Available water in natural sources at the Mayan community Ejido 20 de Noviembre presents extreme hardness; it exceeds the maximum limit established by Mexican regulations. Consequentially, the water found in these sources is not suitable for human consumption, a critical use for the villagers in drought seasons when water scarcity is more severe. Therefore, affordable alternatives are required to treat water resources that can be used locally. In this sense, the objective of the research was to develop a solar still prototype in order to test the technology's performance in water treatment available in the community. The prototype development consisted of 6 stages: still model selection, dimension definition, 3D modeling, material selection, assembly, and prototype testing. The device testing at the community was carried out over a period of 3 days, during which well water with an initial hardness of 3500 mg/l $CaCO_3$ was used. A significant hardness reduction was recorded after the solar distillation process, obtaining values of 119.3 mg/l $CaCO_3$, which indicates that the solar distillation technology serves to reduce the water hardness of the community.

Keywords: Mayan community, Solar still, Water hardness, Water treatment.

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1. Introduction

Ejido 20 de Noviembre is a small Mayan community called "El 20" by its inhabitants, located in the municipality of Calakmul, Campeche, Mexico, at coordinates 89°18′24.907″ W, 18°27′07.164″ N. It has just over 500 inhabitants, according to the latest INEGI 2020 population census. It is composed of Mayan families (all members are considered Mayans) and non-Mayan families (families where one or more members are not considered Mayans). Agriculture, forestry, and beekeeping are the main sources of livelihood. They have a long tradition of making handicrafts, which they sell to earn additional income from the infrequent tourists who visit the area. It currently consists of a preschool, a primary school, grocery shops, four churches (Presbyterian, Baptist, Jehovah's Witness, and Catholic), and a library. There is no sewerage or piped water, but there is mains electricity, and some families also have satellite internet connectivity. The community is governed by customs and traditions, where the highest authority is the Junta Ejidal [Ejidal Council]. However, a Citizen Governance Committee was recently formed, a decision-making body made up of neighbors of "El 20", including nonejidatarios, in such a way that it seeks the progress and wellbeing of the community in general [1].

The area has a warm subhumid climate, according to the "Unified Technical Document on Timber Forest Harvesting, Advanced Level, in Ejido 20 de Noviembre, Municipality of Calakmul, Campeche [2]", published in 2014. A typical year has 1,100–1,200 mm of precipitation, with March being the driest month and September the wettest. The coldest month is January, and the hottest month is May. The average annual temperature is 26 °C. According to information on the Weather Spark website, the average daily incident shortwave solar energy is 6.5 kWh during the period of maximum brightness and 5.1 kWh during the period of maximum darkness [3]. The altitude ranges from 200 to 280 meters above sea level. The soils of the Yucatan Peninsula are generally deposited on sedimentary limestone rocks. The substratum, which is also called saskab or sahkba regionally, is distinguished by a high calcium carbonate content and a high permeability degree.

When the water comes into direct contact with the soil, the calcareous substrate causes an increase in suspended solids and makes the water unfit for human consumption. Also, in "El 20", extreme water hardness is a major problem. The Official Mexican Standard NOM-127-SSA1-1994 establishes that water fit for human consumption in Mexico must have a calcium carbonate level of less than 500 mg/l [4]. According to the tests carried out by the Action Lab Mexico team in its 2021 version, 100 German degrees of hardness (dH), or 1785 mg/l $CaCO_3$, were recorded, proving that the water from the wells and the river is above the limits established by the Mexican standard. In addition to its natural characteristics, the municipality of Calakmul has a drinking water and sewerage problem in urban areas [5]. This problem is exacerbated in less urbanized areas [6], such as "El 20", which lacks the aforementioned services.

The community faces a lack of drinking water as a result of its natural characteristics and the infrastructure in place. Water scarcity is defined by the United Nations Educational, Scientific, and Cultural Organization (UNESCO) as a situation in which the demand for water in all sectors, including the environment, cannot be met due to the impact of water use on the supply or on the quality of the resource. Water scarcity is both a natural and a human-induced phenomenon (2015) [7]. In this sense, the water scarcity of "El 20" is caused by the effects on supply. The lack of piped water services makes it difficult for villagers to access drinking water; in this respect, the community desires a piped water system that is free of charge and that they can manage autonomously under the considerations and needs of its inhabitants. Regarding the impact on quality, the characteristics of the soil cause an increase in the concentration of dissolved solids above what is required by national standards in the available water sources (wells and a river that crosses the community). In the above circumstances, the inhabitants of "El 20" face a significant health risk, as access to poor-quality water may encourage its consumption, especially during the dry season when rainwater reserves are depleted. Some studies [8], [9] warn of the consequences of prolonged consumption of hard water, which can lead to kidney-related diseases. According to testimonies and surveys conducted by ALM between 2018 and 2020, kidney stone disease in the community is prevalent. Thus, there is a connection between community economics, public health, and the water problem. It is anticipated that by addressing the poor water quality problem and providing additional drinking water sources to those already available, conditions associated with kidney dysfunction will decrease, keeping the economy of households in "El 20" stable.

2. Drinking Water Sources in the Community

To meet drinking water demand, the community has alternative sources. One is purchasing bottled water at a cost of around 35 pesos per 20-liter jug; this source is exclusively for drinking. The main source of water comes from rainwater harvesting; most of the houses have incorporated a rainwater harvesting system in which the rain that falls on the roof is directed through pipes to one or more cisterns. There is also a communal rainwater harvesting system located on the local sports field, which is the largest in terms of both square meters of catchment area (roof) and cubic meter capacity of the cistern. Rainwater is used for numerous purposes, mainly for cleaning (personal hygiene, washing dishes, washing clothes). The inhabitants of the community "El 20" have developed their own techniques, mainly decantation, for the treatment of well water in order to reduce its hardness and use it for domestic purposes. In some cases, the well water is placed in containers and left for approximately 3 days, during which the particles settle out. An ancestral technique that is almost forgotten today is to place well water in containers to which ash is added and then left to settle. The technique has an empirical indicator of hardness through the addition of soap; if the treated water generates foam after adding soap and shaking it, it is ready for use; otherwise, the decanting period is extended or a greater quantity of ash is added until the foam indicator is exceeded. Since this is an empirical indicator specific to the community, it is up to individual judgment to decide at what point the water is considered ready for use. This is how the inhabitants of El 20 deal with the problem of water scarcity, in addition to an awareness of water rationing and water use.

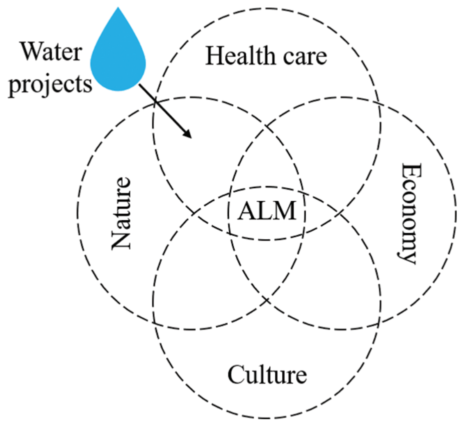

Fig. 1. Focus areas in action lab Mexico.

3. Community Approach

The strategy and community engagement were carried out as part of the Action Lab Mexico (ALM) project, which commemorated 10 years of working with the villagers of Ejido 20 de Noviembre in its 2022 version. The aim of the project is to work closely and cooperatively with the Mayan community of "El 20" to help bring about lasting and useful changes within the community that will improve the lives of its citizens. The project creates connections between the local population, academia, civil society, and the public and private sectors in Finland and Mexico [1]. The initiatives developed by ALM enable the people of "El 20" to maintain their environment and culture whereas achieving financial and health security. The work described here was developed at the intersection of the fields of health and environment (see Fig. 1), where

TABLE I: Volume (Liters/Day) of Water Required for Hydration [10]

	Normal conditions	Manual work at high temperatures	Total needs in pregnancy/ lactation
Adult woman	2.2	4.5	4.8 (pregnancy) 3.3 (breastfeeding)
Adult male	2.9	4.5	
Children	1.0	4.5	

TABLE II: Evaluation of Different Solar Stills [11]

Distiller type	Reference No.	Unit cost in $US	Daily production l/m^2/day
Single slope	40	79.95	4.1
	48	100	1.7
Double slope	19	200	3.07
Hybrid	21	879.56	7.54
	50	550	12.48
Hemispheric	25	233	4.2
	26	958	5.7
Pyramid	51	582.3	4.1
Various domestic designs	52	35	1.6
	53	290	1.2

water management initiatives are carried out that include the collection, storage, treatment, and distribution of water for various uses. In this case, priority has been given to water treatment to reduce the extreme hardness of one of the natural water sources available in the community to below the maximum level allowed by Mexican regulations for water suitable for human consumption.

4. Solar Water Distiller

Poor water quality is one of the contributing causes of water scarcity in the community, and prolonged use of hard water poses a potential health risk. Therefore, the aim of this research is to develop a prototype solar still in order to test the performance of the technology in treating the water available in the community.

There are numerous methods for making water potable [12]. Drinking water is produced using sophisticated purification techniques such as reverse osmosis, ozone, UV, electrolysis, activated carbon filtration, and vapor compression. However, residents in remote locations are unable to purchase and use these expensive technologies [13]. Yadav and Sudhakar argue that alternative solar energy technologies are still considered the best option for renewable energy water supply in remote locations at an affordable cost [11].

Small-scale solar still fabrication is simple and requires very little maintenance [14]. By using solar energy collected in a covered tray to evaporate and condense water, a passive solar distillation system creates clean water while removing all organic and inorganic contaminants [15]. For the purpose of producing pure water, many different designs of solar stills have been created. However, due to their low yield (around 2–3 l/m^2/day) and low thermal efficiency (max. around 30%), solar stills are not commonly used [16], [17]. Although their performance is below expectations, some simple solar still designs are capable of purifying 4.1 liters per square meter of water during the day [18]. When exercising outdoors in hot weather, the World Health Organization (WHO) recommends drinking 4.5 liters of water per day (see Table I). In other words, a solar still with a 1 m^2 solar collector can help to almost completely meet a person's daily water requirement.

Given the available information, solar distillation technology could serve as a complementary drinking water source for "El 20" people, as it is possible to treat hard water found in wells and rivers to produce drinking water, which is especially useful during the dry season when rainwater reserves are depleted.

The formalization and development of a product or service involve considerable costs, which is why before reaching the formal stages, some products or services have been tested and evaluated using prototypes.

Due to the fact that solar distillation technology has not been tested in the community, this work focuses on the development of a solar water distiller prototype to evaluate the viability of the technology in the Mayan community of Ejido 20 de Noviembre and determine whether there is a reduction in the hardness of the well water after the solar distillation process. To do this, the dissolved solids' concentration in the water produced must be measured to determine if it is within the range allowed by Mexican regulations (NOM-127-SSA1-1994).

TABLE III: Decision Matrix for Distiller Model Selection

Type of distiller	Reference no.	M. O.	S.G.	R.A.M.	L.M.R.	A.E.S.	O.S.	Total
Single slope	40	1	1	1	1	1	1	6
	48	0	1	1	1	1	1	5
Double slope	19	1	1	1	1	1	1	6
Hybrid	21	1	1	0	0	0	1	3
	50	1	1	0	0	0	1	3
Hemispheric	25	1	0	0	1	1	1	4
	26	1	0	0	1	1	1	4
Pyramid	51	1	0	0	1	1	1	4
Various domestic designs	52	0	1	1	1	0	1	4
	53	0	1	0	0	0	1	2

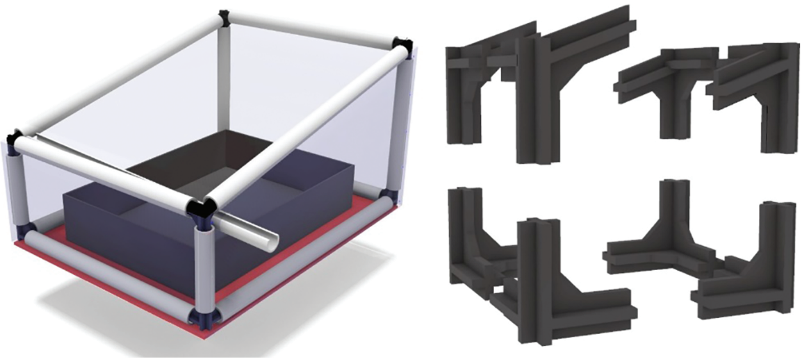

Fig. 2. CAD modelling of solar still and cross joints.

Fig. 3. Tray assembly.

5. Prototype Development Process

The solar distiller development that was tested on site is described below. The development process consists of six stages: (1) distiller model selection, (2) dimensions definition, (3) 3D modeling, (4) material selection, (5) assembly, and (6) prototype testing.

5.1. Distiller Model Selection

In order to choose the still model that best fits the project criteria, Table II [11], which evaluates several models of solar stills, was used as a starting point.

To aid the decision-making process, a choice matrix (see Table III) was constructed by placing the following desirable distiller characteristics: Minimum output of 2.5 m^2/day (M. O.), simple geometry (S.G.), readily available material (R.A.M.), low maintenance requirements (L.M.R.), absence of electronic systems (A.E.S.), and open source system (O.S.). The single response type is used to calculate the values of each attribute, with a positive response having a value of 1 and a negative response having a value of 0.

Based on the obtained results, two types of distillers stand out: the first one with a single slope, reference number 40, and the second one with a double slope, reference number 19, obtained the best scores (see Table III). The economic factor ultimately determines which distiller is chosen; as shown in Table II, distiller number 40 costs US$ 79.95 and produces 4.1 l/m^2/day, whereas distiller number 19 costs US$ 200 and produces 3.07 l/m^2/day. Due to the fact that the distiller reference number 40 is less expensive and more efficient than the distiller reference number 19, the design for the distiller construction was based on their specifications. The solar still identified with reference number 40 corresponds to the model created by [18].

TABLE IV: Laboratory Test Results of the Solar Still

Dissolution	Initial hardness (mg/l $CaCO_3$)	Final hardness (mg/l $CaCO_3$)
Calcium oxide (CaO)	7093	39.95
Table salt (NaCl)	6928	22.73

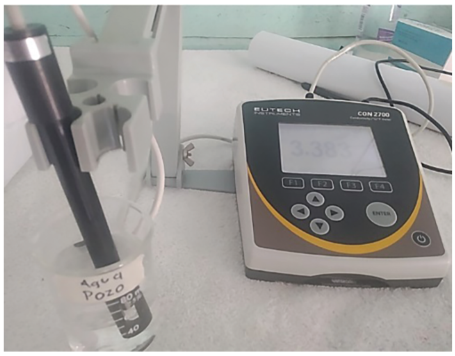

Fig. 4. Sample measurement with conductivity meter.

TABLE V: Hardness Values of Three Water Sources at the Community, Ejido 20 de Noviembre

Water source	Initial hardness (mg/l $CaCO_3$)	Conductivity (μs)
Bottled	70	71.49
River	3300	3230
Well	3500	3383

5.2. Dimensions Definition

The maximum luggage dimensions of 550 mm × 400 mm × 250 mm were taken into account because the prototype would be transported by air. Subsequently, the

Fig. 5. Testing of the solar still prototype in the community.

measurements were adjusted based on the selected materials, resulting in the final dimensions of the tray of 450 mm × 350 mm × 250 mm.

5.3. 3D Modelling

The modeling process was carried out simultaneously with the material selection. The model had to be compact and easy to assemble and disassemble to be transported. The joints (crosspieces) of the structure were designed to facilitate the assembly of the tray and to maintain the necessary angle in the slope of the prototype, which had to coincide approximately with the latitude of the place where the device would be installed, in this case, 20° (see Fig. 2).

5.4. Material Selection

Two considerations were made in the choice of materials: portability and accessibility to hardware stores and supermarkets. The cross joints were manufactured using additive manufacturing (3D printing), given their required function and their non-commercial characteristic angle of 20°. This led to the creation of the following bill of materials:

- PVC tube structure, outer diameter 22 mm, inner diameter 17 mm
- Solar collector, baking tray 350 mm × 250 mm × 250 mm × 70 mm
- Wooden base 4 mm 450 mm × 350 mm
- Condensation cover, clear glass 3 mm 450 mm × 350 mm
- 4 flat head wood screw 1/8″
- Tray walls, PET acetate plastic 0.75 mm
- Plastic zip ties
- Insulating tape
- PLA 3D printed cross joint
- Adhesive tape
- Liquid or stick silicone.

5.5. Assembly

The first step is to assemble the PVC pipes and the PLA cross joints that make up the structure. Next, the wooden base is attached to the structure with the 1/8″ flat-head wood screw. The next step is to place the water-distilled collecting tube, and finally, the PET walls are secured to the structure with the plastic straps. The result is shown in Fig. 3.

5.6. Solar Still Test

Two solutions were used for the test: the first one containing 500 ml of water and 1 g of calcium oxide (CaO), commonly known as quicklime; the second one containing 500 ml of water and 1 g of salt (NaCl). The distillation results are shown in Table IV. Each solution was processed on a different day to allow cooling of the tray and to have similar conditions. The approximate distillation time was for a period of 6 hours between 13:00 and 19:00 hours.

To determine the solutions' total hardness before and after the distillation process, a conductivity meter was used to measure the dissolved solids in water. In this case, the measurement unit used was part per million (ppm), which is equivalent to milligrams per liter of calcium carbonate (mg/l $CaCO_3$). Table IV confirms that the prototype works to reduce the total hardness of the treated water.

TABLE VI: Results of the Solar Water Distiller Prototype

Well water distillation values				
Day	Well water load (ml)	Production/day (ml)	Hardness (mg/l $CaCO_3$)	Conductivity (μs)
1	250	45	119.3	127.5
2	500	120	42.63	45.99
3	500	110	26.10	28.25

Note: The initial hardness of the well water is 3500 mg/l $CaCO_3$ see Table V.

6. Solar Distiller Prototype Testing at the Community "El 20"

The solar distiller test was carried out from April 2 to 4, 2022, at the "Ejido 20 de Noviembre", previously measuring the hardness and conductivity of three water sources (see Fig. 4), the local branded bottled water, river water, and well water, obtaining the values shown in Table V.

Well water is the closest and most widely used source for most of the residences in the community, which is why it was chosen to test the prototype (see Fig. 5). Table VI shows the daily production of distilled water as well as its conductivity and hardness levels.

7. Conclusion

According to Table VI, the well water hardness was significantly reduced after going through the solar distillation process. The well water that had an initial concentration of 3500 mg/l $CaCO_3$ was then reduced to a range between 119.3 mg/l and 26.1 mg/l $CaCO_3$, still remaining within the specified limits of the Mexican standard NOM-127. This demonstrates how solar distillation technology could decrease the hardness of the water available in the Ejido 20 de Noviembre community.

Given the conditions of sunlight, the energy that drives the operation of the distiller, and the community's water resources that derive their hardness from natural soil characteristics and not from industrial waste, solar distillation technology is feasible in the Ejido 20 de Noviembre area.

The concentration of dissolved solids in the water was significantly reduced as a result of the distillation process; however, to confirm whether the community's water treated by solar distillation satisfies the remaining criteria set by Mexican standards like NOM-127 to be designated as potable water, an exhaustive study is necessary.

The distiller model selection criteria are relevant to replicate the construction and testing of the distiller in sites with potential to use this technology, as well as for the adoption of the technology by the villagers of "El 20". This could be observed when the results were presented to the inhabitants of the community; some members of the citizen committee showed interest in the solar still.

It is recommended to continue working on the project in the coming years to develop a larger pilot program. The formalization of a larger capacity solar still should address the problem of low water production through new designs, the incorporation of alternative technologies such as solar concentrators, heat energy storage by means of phase change materials such as salts, waxes, or sand, as well as testing the scale to verify the convenience of increasing or reducing the size of the devices. All of the above with the aim of providing the community with an alternative source of drinking water to complement the current ones and allow them to take advantage of their water resources, mainly during the dry seasons when the main source of water, rainwater harvesting, is not available.

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