EVALUATION OF THE WATER QUALITY PRODUCED BY SOLAR DISTILLERS: SYSTEMATIC REVIEW AND POTENTIAL APPLICATION IN SOUTHERN MADAGASCAR

ANDRIAMANAMPISOA Tsiry Angelos [1], RASOLONDRAIBE Hyacinthe Wenceslas [2], RATSIMBA Marie Hanitriniaina[3], ANDRIANAIVORAVELONA Jaconnet Oliva [4], ANDRIANARISON Edouard [5]

[1, 2, 3, 4, 5]*École Supérieure Polytechnique d'Antananarivo, Université d'Antananarivo, Madagascar*

ABSTRACT

This article presents a systematic review of existing literature on the evaluation of water quality produced by solar distillers, with a particular focus on their potential application in southern Madagascar. The aim is to improve access to safe drinking water for local populations. The adopted methodology strictly follows the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. To this end, 142 recent scientific articles published in English and French between 2014 and 2024 were reviewed to identify relevant knowledge and extract useful data. A total of 29 studies were selected, including 24 international scientific articles focusing on the evaluation of water quality before and after solar distillation, as well as 5 studies specific to the Malagasy context. The combined analysis of these studies revealed that various types of non-potable water, including those heavily contaminated, can be effectively purified through solar distillation. High concentrations of physical, chemical, and microbiological contaminants are significantly reduced, making the water compliant with drinking water standards. Finally, a comparison of the results obtained with the water characteristics of southern Madagascar allowed for an assessment of the feasibility and efficiency of solar distillers in this specific context.

Keywords: *Solar distillation, Literature review, PRISMA, Access to safe drinking water.*

1. INTRODUCTION

The southern regions of Madagascar, characterized by an arid to semi-arid climate, face a chronic water shortage. Local populations endure worsening water scarcity each year due to limited rainfall, estimated at 380 mm per year [1]. Simultaneously, population growth, particularly in urban areas, is exacerbated by rural-urban migration [2], which further increases the demand for drinking water. To meet their water needs, local communities primarily rely on untreated sources, such as wells and rivers, often using water whose quality and potability are not assured. Ensuring the safety and quality of the water used is critical to their well-being.

In this context, a systematic literature review was conducted to evaluate whether the use of solar distillers could provide a sustainable approach to improve access to safe drinking water in southern Madagascar. The primary objective was to identify solutions that enhance the availability of potable water while addressing local challenges. Among the technologies examined, double-slope solar distillers are a promising option to meet the growing demand for water [3].

This research focuses specifically on the effectiveness of solar distillers in improving the quality of nonpotable water. Solar distillation is a sustainable and cost-effective method for water purification that harnesses solar energy to produce potable water. The process involves heating impure water in a solar still, where sunlight evaporates the water, leaving contaminants behind, followed by condensation of the vapor on cooler surfaces to yield clean water. At the international level, it is recognized as a sustainable and accessible alternative for producing drinking water. Considering these contextual factors, this systematic review focuses on two main areas.

- Evaluation of the effectiveness of solar distillers in removing organoleptic, physical, chemical, and microbiological contaminants from water

- Analysing the potential socio-economic impacts of this technology on local communities.

This review analyzes relevant studies on the evaluation of the quality of distilled water to identify the key parameters influencing the quality of the water produced. The findings of this analysis are also intended to provide valuable insights to local decision makers and development stakeholders, aiming to promote the most suitable solutions to address the specific challenges of accessing safe drinking water in southern Madagascar.

2. METHODOLOGY

This literature review was conducted in strict adherence to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, a recognized methodological framework for structuring and reporting systematic reviews and meta-analyses. The following steps were performed methodically.

Step 1: Defining the Research Question

The PICOT (Population, Intervention, Comparison, Outcome, Time) method was employed to structure the research problem of this systematic review.

- **Population**: The target population included open-access (open-source) scientific articles.
- **Intervention**: Conducting a systematic review of the literature.
- **Comparison**: A meta-analysis of the available data.
- **Outcomes**: Identifying the relevance and reliability of solutions to improve the quality of distilled water.
- **Time**: Only recent studies published within the last ten years (2014–2024) were included.

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Step 2: Specifying Eligibility Criteria

The inclusion criteria for this systematic review were as follows:

- Scientific studies evaluating water quality before and after the solar distillation process.
- Research addressing the need for drinking water in the specific context of southern Madagascar.
- Articles or literature reviews published in English or French between 2014 and 2024.

Exclusion criteria included:

- Articles published before 2014.
- Studies focusing solely on the quantity of water produced after solar distillation have not yet evaluated its quality.

Table 1 summarizes the inclusion and exclusion criteria used in this study.

Table -1: Inclusion Criteria for Studies

Publication Date	**Peer Review**	**Languages of Literature**	**Geographic Location**
2014 to 2024	Article/Thesis reviewed by an evaluation committee	English, French	Southern Madagascar, Other Countries

Step 3: Defining the Search Strategy

The following key terms were defined based on the study topic to guide the documentary research strategy: solar distillation, distilled water, physicochemical water quality, chemical water quality, and microbiological water quality. These terms were used to search scientific databases, such as Google Scholar (open access), ScienceDirect, and other accessible online sources. The objective was to identify the relevant academic articles related to the topic under study. For inclusion, a study had to feature at least one of the key terms in the list of keywords or within the content of the articles reviewed.

Step 4: Evaluation of Selected Studies
This step involved reviewing the selected studies by analyzing their titles, abstracts, and results. The main objective was to evaluate the methodological quality of the studies in order to ensure that they established a clear and relevant connection to the research topic. The evaluation criteria were as follows:

- Presence of comparative analyses of water quality before and after the solar distillation process.
- Comprehensive consideration of the parameters defining water potability (physicochemical, chemical, and microbiological).
- Existence of solid and rigorously documented methodological evidence.

Step 5: Data Extraction
Data necessary to clarify the understanding of the topic and answer the research question were extracted using a pre-established form in Microsoft Excel. This data included:

- Study characteristics: author, year of publication, country of origin;
- Types of water to be purified: identification of the water sources studied;
- Parameters defining the quality of distilled water:
    - Organoleptic parameters (taste, smell, colour);
    - Physico-chemical parameters (pH, conductivity, turbidity);
    - Chemical parameters (presence of heavy metals, nitrates, etc.);
    - Indicators of chemical pollution;
    - Microbiological quality before and after solar distillation;
    - Potability standards according to WHO recommendations and Malagasy national standards.
- Evaluation of results: analysis of the findings in relation to the study's objectives.

Step 6: Evaluation of Study Quality
The methodological quality of the included studies was evaluated using a set of specific questions to ensure reliability and relevance of the results. The questions posed were as follows.

- Is the methodology clearly described and detailed?
- Are the water samples analyzed varied, representative, or limited to a single type?
- Were the parameters defining water potability systematically tested before and after the solar distillation process?
- Are the theoretical results clearly presented and supported by solid, verifiable evidence?
- Are there any elements that may introduce bias in the results or their interpretation?
- Are the studies directly relevant to the research question posed?

Step 7: Meta-analysis of Results
Quantitative data extracted from various studies on the evaluation of the water quality produced by solar distillers were combined. The goal was to generate a robust and reliable synthesis method for distilled water. For this analysis, a fixed-effects model was adopted, allowing for the evaluation of the combined effects of different studies while assuming homogeneity of effects across them.

3. RESULTS

The objective of this systematic literature review is to identify the key parameters that influence the quality of water produced through solar distillation by analyzing studies on the quality of distilled water. This section describes the included studies and a meta-analysis of the extracted data.

3.1 Description of Studies Included in This Systematic Literature Review

In accordance with the defined inclusion and exclusion criteria, 29 studies were included in this systematic review based on the inclusion and exclusion criteria. These comprised 25 academic scientific articles, two scientific reports, and two doctoral theses. The studies were conducted in various countries, primarily Asia and Africa, and were published between 2014 and 2024.

Table 2 presents the distribution of literature according to the themes addressed.

Table -2 : Distribution of Literature by Theme

Themes Addressed	Quality of Water Distilled Using Solar Energy	Water and Climate Context of Southern Madagascar
Distribution of Literature	23 scientific articles and one doctoral thesis.	One doctoral thesis, 2 scientific articles, and 2 scientific reports.

- ***Analysis of Excluded Studies***

Initially, 40 studies, published before 2014, were identified. These studies primarily focused on improving the performance of distilled water production without considering the quality of the water produced. Additionally, 31 studies, published before 2014, analyzed only a limited number of physicochemical parameters such as pH, electrical conductivity (EC), and total dissolved solids (TDS). Some of these studies highlighted the desalination of brackish water in remote areas with arid climates, but did not provide comprehensive data on the parameters defining water quality before solar energy utilization.

Subsequently, 22 other studies published after 2014 focused on experiments aimed at increasing the quantity of water produced through solar distillation. However, these studies did not evaluate or demonstrate the quality of water obtained after distillation.

Finally, certain studies were excluded after a full-text review because they lacked sufficient data on water quality or were limited to theoretical results without experimental validation. These exclusions were made in accordance with the eligibility criteria to ensure the scientific rigor of this review.

Figure 1 clearly illustrates the primary reasons for excluding a significant number of publications in this review.

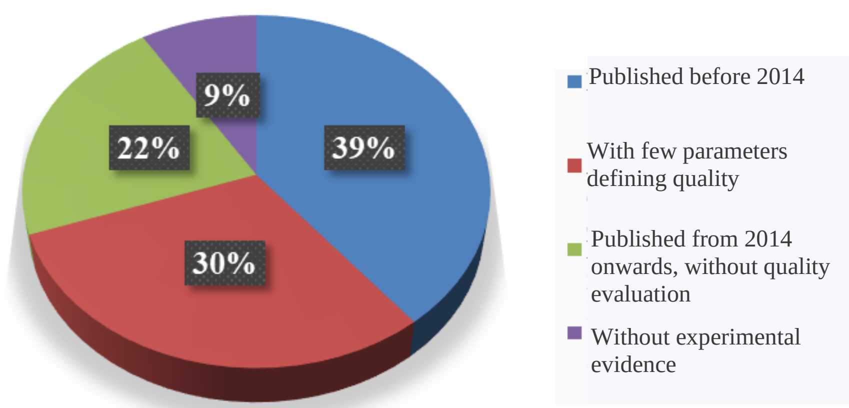

Fig -1 : Pie Chart of Excluded Studies

Figure 2 provides a summary of the results from the inclusion and exclusion processes of the collected studies, in accordance with the established criteria and following the PRISMA guidelines.

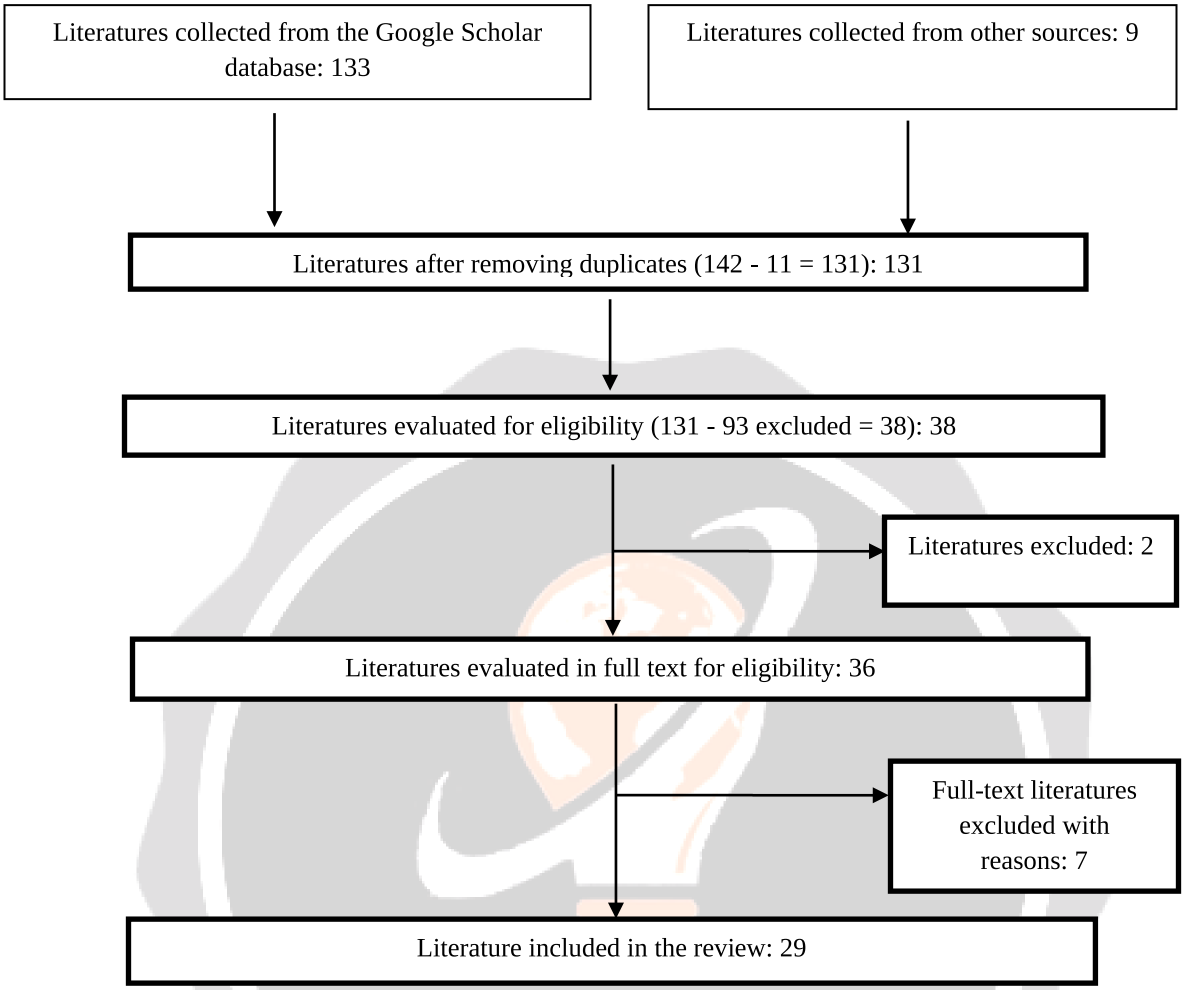

Fig -2 : Results of the application of the PRISMA flow diagram

- ***Summary of Included Studies***

Table 3 presents a synthesis of the results from the included studies, providing an overview of the main characteristics of these studies and the water quality parameters analyzed. A total of 23 scientific articles were reviewed to extract essential knowledge for this review. These articles, published between 2014 and 2024, focus on experimental studies and the evaluation of solar distillers' performance in potable water production.

The included research was conducted in various countries and distributed as follows: 14 studies by researchers from Asia, 6 by researchers from Africa, and 3 by researchers from the Americas. These studies were examined thoroughly to ensure an in-depth and relevant analysis.

Table 3 also provides a synthesis of the selected articles' characteristics, including the following information: authors, title, year of publication, country of origin, and presence or absence of key terms. Regarding data specifics, it details elements related to the evaluation of distilled water quality, such as laboratory analysis methods, number of distilled water samples, and diversity of parameters considered. Finally, the main results of each study examined are presented in this table, offering an overview of the knowledge extracted and the conclusions obtained.

According to the characteristics coded in Table 3 using Microsoft Excel, all the analyzed studies included at least one of the predefined key terms. Regarding the water quality analysis, 12 studies did not provide details or list the parameters evaluated. In contrast, 12 other studies mentioned the use of in-situ measuring devices and laboratory analysis methods. A notable study by Bilal *et al.* (2016) [4] conducted comparative analyses of water before and after distillation in three different laboratories, providing strong evidence for the effectiveness of the solar distillation process in purifying brackish water. Number of samples studied

- Two samples were analysed in the works of M. Edwin *et al.* (2015) [5], El Agouz (2014) [6], Chala Diriba *et al.* (2016) [7], S. V. Kumbhar (2019) [8], S. B. Danjuma *et al.* (2018) [9], and F. T. do Nascimento *et al.* (2018) [10].
- Kumar *et al.* (2014) [11] tested three samples.
- Four samples were studied by Kalbande *et al.* (2017) [12].
- Finally, five samples were analyzed by Sivakumar *et al.* (2016) [13] and Basharat *et al.* (2017) [14], with a detailed presentation of the water quality before and after distillation.

Table -3 : Synthesis of the literature review on distilled water quality

Authors, "*Title*" [References]	**Year**	**Country**	**Nb. of key-words**	**Analysed parameters**	**Parameter analysis method**	**An. Lab.**	**Nb. of samples**	**General results**
A. Ahsan *et al.* « *Assessment of Distillate Water Quality Parameters Produced by Solar Still for Potable Usage* » [15]	2014	Malaysia	3	pH, Salinity, TDS, EC, Escherichia. Coli, arsenic	P.C. M.B.	1	1	100% elimination of bacterial contaminants.
M. Edwin *et al.* « *Performance and Chemical Analysis of Distilled Saline Water Production Using Solar Distillation System.* » [5]	2015	India	3	pH, EC, TDS, Na^+, K^+, Ca^{2+}, Mg^{2+}, CO_3^{2-}, HCO_3^-		1	2	Reduced parameter levels, in line with WHO standards.
S.A. El-Agouz *et al.* « *Experimental investigation of stepped solar still with continuous water circulation.* » [6]	2014	Egypt	1	pH, EC, TDS, T.H., Ca^{2+}, K^+, Mg^{2+}, Cl^-, A.T.		1	2	Reduction of salts after distillation.
Chala Diriba Gurmu *et al.* « *Experimental Evaluation of Basin Type Solar Still for Saline and Fluoride Water Purification (A Case on Giby-Deep Well Water, Dupti,*	2016	Ethiopia	1	pH, T.H., TDS, Salinity, T.A., Coliformes .T.	P.C.	1	2	100% elimination of salinity with a significant reduction in fluoride content.

Authors, "*Title*" [References]	Year	Country	Nb. of key-words	Analysed parameters	Parameter analysis method	An. Lab.	Nb. of samples	General results
Afar-Ethiopia. » [7]								
Hamza Bilal *et al.* *« Desalination of brackish water using dual acting solar still. »* [4]	2016	Pakistan	2	pH, TDS, EC, Na^+, Ca^{2+}, Mg^{2+}.	P.C. **C** M.B.	3	1	Significant reduction in TDS after distillation.
S. R. Kalbande *et al.* *« Evaluation study of solar water desalination system for saline track area of vidarbha region. »* [12]	2017	India	1	pH, EC, TDS, T.H., Na^+, HCO_3^-, Cl^-	P.C. **C** M.B.	1	4	Efficient desalination of samples after distillation.
Ashish Kumar *et al.* *« Distillate water quality analysis and economics study of a passive solar still. »* [11]	2014	India	2	Colour, odour, appearance, pH, T.H., T.A., Cl^-		1	3	Synthetic water quality becomes human drinking water quality.
K. Palpandi & R. Prem Raj *« Performance Test on Solar Still for Various TDS Water and Phase Change Materials. »* [16]	2015	India	1	NTU, pH, EC, TDS, T.A., T.H., Ca^{2+}, Mg^{2+}, Na^+, K^+, Fe, Mn^{2+}, NH^{3+}, NO_{2-}, NO_3^-, Cl-F, PO_4^{2-}, SO_4^{2-}	P.C.	1	1	Reduction in TDS content.
Ali Riahi, *et al.* *« Sustainable potable water production using a solar still with photovoltaic modules-AC heate. »* [17]	2015	Malaysia	1	Colour, pH, NTU, Nitrate, iron, TDS.		1	1	The physico-chemical quality of the lake water complies with the WHO drinking water standard.

Authors, "*Title*" [References]	**Year**	**Country**	**Nb. of key-words**	**Analysed parameters**	**Parameter analysis method**	**An. Lab.**	**Nb. of samples**	**General results**
R. S. Hansena, *et al*. *« Enhancement of integrated solar still using different new absorber configurations: An experimental approach. »* [18]	2015	Malaysia	1	pH, EC, TDS, Cl^-, Na^+, SO_4^{2-}, Mg^{2+}, Ca^{2+}, K^+		1	1	The physico-chemical and chemical quality of the salt water complies with drinking water standards after distillation.
Dr. K. Shanmugasundaram, *« Experimental Study on Different Designs of Solar Still and its Uses. »* [19]	2017	India	1	Odour, taste, pH, TDS, EC		1	1	Brackish well water of good organoleptic and physico-chemical quality after solar distillation.
V. Sivakumar et E. Ganapathy Sundaram *« Experimental studies on quality of desalinated water derived from single slope passive solar still. »* [13]	2016	India	1	Colour, odour, appearance, pH, CE, TDS, T.H., NTU, Na, K, Ca^{2+}, Mg^{2+}, Cl^-, F^-, SO_4^{2-}, PO_4^{2-}, NO_2^-, NO_3^-, NH^+_4, Fe, T.A..	P.C. **C**	1	5	Improved quality of distilled water after solar distillation.
B. Nasri *et al.* *« Improvement of Glass Solar Still Performance Using Locally Available Materials in the Southern Region of Algeria. »* [20]	2019	Algeria	1	pH, EC, TDS, T.H., Cl^-, SO_4^{2-}, NO_3^-	P.C. **C**	1	1	The dissolved substance content is considerably reduced.
J. J. Feria-Diaz *et al.* *« Mild hybrid energy dual-slope solar stills: Design and performance. »* [21]	2023	Mexico	2	pH, EC, TDS, NTU, T.H., Cl^-, T.A., salinity, total coliforms, Escherichia coli	P.C. **C** M.B.	1	1	The salinity of the seawater has been reduced by solar distillation.

Authors, "*Title*" [References]	**Year**	**Country**	**Nb. of key-words**	**Analysed parameters**	**Parameter analysis method**	**An. Lab.**	**Nb. of samples**	**General results**
S. V. Kumbhar *« Double slope solar still distillate output data set for conventional still and still with or without reflectors and PCM using high TDS water samples. »* [8]	2019	India	1	pH, T.A., T.H., Cl^-, NTU, TDS	**C**	1	2	Waste water of good quality after distillation.
K. Shanmugasundaram *et al.* *« Transforming Brackish Water into Ingestion Liquid Using Solar Still, Physico-Chemical Analysis. »* [22]	2021	India	1	Odour, taste; pH, EC, NTU, TDS, T.A., T.H., Mg^{2+}, Ca^{2+}, Fe, SO_4^{2-}, PO_4^{2-}, Cl^-, Nitrate, SiO_2.	**C**	1	1	Effectively purified brackish water.
H. H. Maambo & I. Simate *« Performance Improvement of Solar Water Stills by Using Reflectors. »* [23]	2016	Zambia	1	pH, TDS, NTU, T.A., T.H., faecal coliforms, total coliforms.		1	1	Lake water quality accepted by the WHO drinking water standard.
W. M. J. Karen *et al.* *« Desalination of seawater using carbon-coated solar absorber in solar still. »* [24]	2022	Malaysia	None	Salinity, pH	P.C.	1	1	Seawater becomes drinking water after distillation.
M. Benghanem *et al.* *« IoT-based performance analysis of hybrid solar heater-double slope solar still. »* [25]	2021	Algeria	2	pH, EC, TDS, Salinité		1	1	Eau distillée of acceptable physico-chemical quality according to WHO standards.
B. Jamil & N. Akhta *« Effect of specific height on the performance of a single slope solar still: An experimental study. »* [14]	2017	India	1	pH, EC, NTU, T.A., TDS, Cl^-	P.C. **C**	1	5	Brackish well water of good organoleptic and physico-chemical quality after solar distillation.

Authors, "*Title*" [References]	Year	Country	Nb. of key-words	Analysed parameters	Parameter analysis method	An. Lab.	Nb. of samples	General results
L. Mu *et al*. *« Enhancing the performance of a single-basin single-slope solar still by using Fresnel lens: Experimental study. »* [26]	2019	Mexico	1	pH, EC, Cl^-, Na^+, SO_4^{2-}, Mg^{2+}, Ca^{2+}, K^+, TDS.	P.C. **C**	1	1	Distilled water of good physico-chemical and chemical quality.
S. B. Danjuma *et al*. *« Design Construction and Performance Evaluation of Solar Still for Rural Dwellers. »* [9]	2018	Nigeria	1	pH, NTU, EC, TDS, T.H., T.A., Cl^- Total coliforms, E. coli	**C**	1	2	Bacteriologica l and physical contamination eliminated by solar distillation.
F. T. do Nascimento *et al*. *« Efficacy of a solar still in destroying virus and indicator bacteria in water for human consumption. »* [10]	2018	Brazil	1	Total coliforms, Escherichia coli, viruses	M.B.	1	2	100% elimination of pathogens in heavily contaminated water.

Note :

- **An. Lab.**: Analysis Laboratory;
- **C**.: Chemical;
- **EC**: Electrical Conductivity
- **M.B.**: Microbiological,
- **Nb. of keywords**: Number of keywords;
- **Nb**. **of samples**: Number of samples;
- **NTU**: Nephelometric Turbidity Unit
- **P.C**.: Physico-chemical;
- **T.A**.: Total alkalinity
- **T.H.**: Total Hardness;
- **TDS**: Total Dissolved Solid

Regarding drinking water quality parameters, only the study by F. T. do Nascimento *et al.* (2018) [10] highlighted the bacteriological parameters of distilled water. The other 22 articles analyzed all physico-chemical parameters (pH, EC, TDS, NTU, Total Hardness). Table 4 lists the various parameters analyzed in more detail.

Table -4: Parameters defining water quality in the studies included

Authors, Year, [Reference]	**Physico-chemical parameters**	**Chemical parameters**	**Organoleptic parameters**	**Bacteriological parameters**	**Other chemical contaminants**
A. Ahsan *et al*. , 2014 [15]	Yes	No	No	Yes	Yes
M.Edwin *et al*., 2015 [5]	Yes	Yes	No	No	No
S.A. El-Agouz, 2014 [6]	Yes	Yes	No	No	No
C. D. Gurmu *et al*., 2016 [7]	Yes	No	No	Yes	No
H. Bilal *et al*., 2016 [4]	Yes	Yes	No	No	No
S.R. Kalbande *et al*., 2017 [12]	Yes	Yes	No	No	No
A. Kumar *et al*., 2014 [11]	Yes	Yes	Yes	No	Yes
K. Palpandi *et al*., 2015 [16]	Yes	Yes	No	No	No
A. Riahi *et al*., 2015 [17]	Yes	No	Yes	No	No
R.S.Hansen *et al*., 2015 [18]	Yes	Yes	No	No	No
Dr K. Shanmugasundaram, 2017 [19]	Yes	No	Yes	No	No
V.Sivakumar *et al*., 2016 [13]	Yes	Yes	Yes	No	Yes
B.Nasri *et al*., 2019 [20]	Yes	No	No	No	Yes
J. J. Feria *et al*., 2023 [21]	Yes	No	No	Yes	No
S.V. Kumbhar, 2019 [8]	Yes	No	No	No	No
K. Shanmugasundaram *et al*., 2021 [19]	Yes	Yes	Yes	No	Yes
H. H. Maambo *et al*., 2016 [23]	Yes	No	No	Yes	No
W. M. J. Karen *et al*., 2022 [24]	Yes	No	No	No	No
M. Benghanem *et al*., 2021 [25]	Yes	No	No	No	No
B. Jamil, 2017 [14]	Yes	No	No	No	No
L. Mu a *et al*., 2019 [26]	Yes	Yes	No	No	No
S. B. Danjuma *et al*., 2018 [9]	Yes	No	No	Yes	No
F. T. do Nascimento *et al*., 2018 [10]	No	No	No	Yes	No

- ***Relevant studies on the context of southern Madagascar***

Table 5 shows the characteristics of research studies on the climatic context and groundwater quality in southern Madagascar as well as those on the proposed solutions to water scarcity in the region.

Table -5: Characteristics of studies on the context of southern Madagascar

Authors [Reference]	Year	Type of documents	Language of literature	Title	Extracted knowledge
J. R. Rasoloariniaina [27]	2016	PhD Thesis	French	Quantitative and ichthyological aspects of groundwater in the south-western region of Madagascar.	Typical climate of the southern part, characteristic of the water of the coastal plain, causes of water shortage.
J. B. Randriatsitohaina *et al*. [2]	2022	Scientific article	French	Vulnerability of Toliara to water shortage, South-West region of Madagascar	The climate of southern Madagascar and the problem of insufficient drinking water.
C. Gondard-Delcroix *et al*. [1]	2023	Report	French	Development in Madagascar's deep south: some lessons from development projects	The state of the drinking water supply
L. H. Rasolofomana [28]	2015	Report	French	Vitality and vulnerability of water resources in Madagascar.	Water quality.
T. A. Andriamanampisoa *et al*. [3]	2024	Scientific article	French	Identification of the Greenhouse Effect Solar Distiller Model adapted to southern Madagascar: Pugh Matrix approach.	In the context of southern Madagascar, the right solution to the water shortage.

3.2. Narrative summary and meta-analysis of results on distilled water quality

The work analyzed in this systematic review highlights the performance of solar distillers in terms of drinking water production, both quantitatively and qualitatively. With regard to the quality of the water produced, the included studies have shown that solar distillation, regardless of the type of device used, significantly improves the quality of the water by eliminating physical, chemical, and microbiological impurities.

Studies by Shanmugasundaram et al. (2021) [22], Riahi *et al.* (2015) [17], and Kumar *et al.* (2014) [11] have also highlighted a significant improvement in organoleptic parameters, such as the visual appearance of water, owing to the action of solar radiation. In addition, several studies have highlighted that solar distillation eliminates 100% of the salinity in brackish water [7], as well as pathogenic bacteria [9] [10] [21] [23]. A study by F. T. do Nascimento et al. (2017) [10] also confirmed the effectiveness of the process in destroying viruses present in heavily contaminated water.

However, the type of solar distiller used affects the rate of reduction of various contaminants. The parametric results on water quality before and after distillation were processed using Microsoft Excel and are summarized in a statistical table.

- **Results of physico-chemical analyses**

Table 6 presents the physicochemical results from the 15 studies that analyzed the physical variables.

Table -6: Summary of physico-chemical results for water before and after solar distillation

[Reference]	Type of water to purify	Type of solar distillation	pH		EC (mS/cm)		TDS (mg/L)		Turbidity (NTU)	
			Before T	After T	Before T	After T	Before T	After T	Before T	After T
[15]	Water contaminated with arsenic	Passive single slope solar still	8	5.7	286.1	138	185.4	89.6		
[5]	Tap water	Passive single slope solar still	7.7	7.1	4.6	0.5	660	81		
	Salt water		9.8	7.1	34.1	0.5	38790	81		
[6]	Salt water	Staged solar still	8.2	5.9	2370	41	1681	27		
	Sea water		8.3	6.6	57100	62	40772	41		
[21]	Sea water	Double slope active mode solar still	8.2	7.2	44100	23	24696	12.9	2.4	1.0
[24]	Sea water	Solar still with absorber active mode	7.8	6.6						
			7.8	6.7						
			7.8	6.5						
			7.8	6.6						
[7]	Brackish water	Single slope solarium still, passive mode	8.6	7.1			1390	8.9	0.1	0.1
[4]	Brackish water	Passive and active solar stills	6.9	6.1	3.8	0.15	1250	105		
[9]	Brackish water	Single slope solar still, active mode	8.2	7.6	190	20	100	10	22	1
			8.2	7.6	210	22	120	10	25	1
[12]	Salt water	Simple solar still basin, active mode	7.0	7.0	1.49	0.03	953.6	19.2		
			7.0	7.0	1.5	0.04	960	25.6		
			7.3	7.0	2.4	0.04	1536	25.6		

[Reference]	Type of water to purify	Type of solar distillation	pH		EC (mS/cm)		TDS (mg/L)		Turbidity (NTU)	
			Before T	After T	Before T	After T	Before T	After T	Before T	After T
			7.2	6.9	3.04	0.06	1945.6	38.4		
[16]	Well water	Simple active solar still	7.3	6.5	577	54	398	40	0.1	0.1
[13]	Salty well water	Single slope solar still, passive mode	7.1	6.9	3300	165	2310	116	1.4	0.5
			7.4	8.0	13560	252	9492	176	3.5	0.3
			7.6	6.9	38400	187	26880	131	1.2	0.5
			7.8	6.6	44300	332	31010	232	4.6	0.1
			7.3	7.2	6650	126	4655	88	2.5	0.5
[17]	Lake water	Double slope solar still, active mode	7.2	6.9			650	22.5	38.5	1.0
[14]	Saline feed water	Single slope solar still, passive mode	7.6	7.4	901	20.1	466	9.5	1.7	0.7
			7.3	7.4	910	24.4	470	11.5	2.0	1.2
			8.2	7.5	896	25.8	460	2.7	1.0	3.7
			7.3	7.5	897	25.1	464	11.9	0.5	1.3
			7.3	7.6	902	29.3	465	13.9	5.2	1.8
[25]	Groundwater	Hybrid double-slope solar still	7.7	7.2	7550	384	3770	210		
[26]	Groundwater	Active single slope solar still	7.9	6.5	891	78.4	492	28.2		
		WHO standard	6.5 – 8.5		Max 250		Max 600		5	
		Malagasy drinking water standard	6.5 - 9		Max 3000		Not mentioned		5	

Table 6 shows the four water characteristics that were mainly analyzed in the 15 studies to assess the effectiveness of water purification by solar distillation.

- **pH:** Before distillation, the pH values varied between 9.8 and 6.8. After distillation, they ranged from 8.03 to 5.72, thus complying with the international and national drinking water standards.
- **Electrical conductivity (EC):** Before purification, the values ranged from 57,100 µS/cm (seawater) to 1.49 µS/cm (brackish water). After solar distillation, the values ranged from 384 µS/cm to 0.03 µS/cm. The maximum value complies with national standards, whereas the minimum value complies with both national and World Health Organization (WHO) standards.
- **Total dissolved solids (TDS):** The concentrations before purification ranged from 40,772 mg/L (seawater) to 100 mg/L (brackish water). After distillation, the values complied with national and WHO standards, with concentrations ranging from 232 mg/L (distilled water) to 10 mg/L (distilled brackish water).

- **Turbidity** Before treatment, only the lake water exceeded acceptable standards, with a turbidity value of 38.45 NTU. After solar distillation, all the purified water was clear, with values between 0 NTU and 3.73 NTU, in compliance with the international (WHO) and Madagascan national standards.

These results confirm the effectiveness of solutions based on solar distillation for desalinating salt and brackish water and making them drinkable.

➢ **Results of chemical analyses**

Table 7 presents the results related to the chemical quality of the water analyzed in six studies that evaluated the majority of the chemical elements influencing this quality.

Table -7: Comparison of chemical parameters of water before and after solar distillation

[Reference]	Type of water to be purified	Na^+ (mg/L)		K^+ (mg/L)		Ca^{2+} (mg/L)		Mg^{2+} (mg/L)		Cl^- (mg/L)		F^- (mg/L)		T.A.- (mg/L)	
		Before T	After T	Before T	After T	Before T	After T	Before T	After T	Before T	After T	Before T	After T	Before T	After T
[6]	Sea water	13.8	1.8	420	1.4	1920	0.8	1536	3.4	21.3	10.8			183	0.5
	Salt water	505	1.2	15	0.8	52	0.6	80	1.8	369	2.4			162	0
[5]	Salt water	10752	91	392	1.6	409	0.6	1278	1.1	18971	18				
	Tap water	421	91	2.1	1.6	1.08	0.6	2.6	1.1	110	18				
[16]	Well water	48	4	12	1	44	2	16	1	87	7			142	14
	Sea water	3480	7	660	1	880	6	293	1	8050	10	0.8	0.2	112	16
[18]	Feed water	1856	41.2	95	1.6	119	12.5	143	2.1	3010	52.4				
[13]	Well water	226	14	16	1	408	14	43	3	810	28	0.8	0.1	284	34
	Salt water	5440	34	130	4	2800	22	336	6	13800	63	0.4	0.1	220	54
		770	7	40	0	432	13	86	3	2050	12	0.8	0.1	240	38
		1620	26	60	2	840	19	144	3	4380	50	0.9	0.2	272	42
		4840	16	110	2	2640	15	288	4	12200	28	0.4	0.1	220	44
[26]	Groundwater	62.6	4.4	1.2	0.3	108.4	4.2	12.1	1.2	92.4	10.8				
	WHO standard	Max 150		< 100		100–300		Max 50		Max 250		Max 1.5		250	
	Malagasy standard	Not mentioned		Not mentioned		Max 200		50		250		1.5		Not mentioned	

Table 7 shows that, prior to the solar distillation process, concentrations of normal chemical elements generally did not comply with the drinking water standards established by the WHO and Malagasy national standards. This includes high levels of sodium and chloride in salt water [5] [13]. On the other hand, fluoride concentrations before (0.92 to 0.38 mg/L) and after solar distillation (0.16 to 0.2 mg/L) complied with international and national drinking water standards. As for total alkalinity, initial values ranged from 284 to 112 mg/L, but were reduced after distillation to levels of between 54 and 0 mg/L, the latter being in line with WHO standards.

In summary, the distilled water obtained from the six studies that analyzed the chemical elements contributing to the chemical quality of the water were distinguished by their purity and excellent chemical quality owing to the solar distillation process.

- **Results of analyses of man-made chemical elements**

Six studies analyzed the concentrations of man-made chemical elements present in distilled water samples. Table 8 presents the results of the analysis.

Table -8: Results for other chemical elements in distilled water

[Reference]	Type of water to be purified	SO_4^{2-} (mg/L)		PO_4^{2-} (mg/L)		NO_2^- (mg/L)		NO_3^- (mg/L)		NH_4^+ (mg/L)		Fe (mg/L)		Arsenic (mg/L)	
		Before T	**After T**	**Before T**	**After T**	**Before T**	**After T**	**Before T**	**After T**	**Before T**	**After T**	**Before T**	**After T**	**Before T**	**After T**
[16]	Well water	32	2	0.06	0.01	0.06	0.21	1	1						
	Sea water	353	5	0.08	0.01	0.03	0.26	6	1			0	0		
[15]	Arsenic-contaminated water													0.30	0.001
[17]	Lake water							7.26	0.43			18.20	0.06		
[13]	Well water	74	3	0.04	0.04	0.77	0.11	10	4	0.50	0.92	0.30	0.09		
	Salt water	462	4	130	4	0.10	0.45	6	9	1.08	0.15	0.66	0.10		
		98	2	0.02	0.03	0.60	0.12	7	4	0.49	1.14	0.30	0.11		
		87	4	0.04	0.03	0.84	0.07	7	4	0.92	1.60	0.33	0.12		
		416	3	0.05	0.03	0.35	0	9	5	0.87	0.35	0.31	0.07		
[20]	Salt water	904	6.40					27.65	0.91						
[26]	Groundwater	191	1.6												
	WHO standard	Max 250 (mg/L)				Max 50 (mg/L)		Max 50 (mg/L)		Max 0.5 (mg/L)		Max 0.3 (mg/L)		10 (µg/L)	
	Malagasy standard	Max 250 (mg/L)		Max 5 (mg/L)		Max 0.1 (mg/L)		Max 50 (mg/L)		Max 0.5 (mg/L)		0.5 (mg/L)		0.05 (mg/L)	

Table 8 shows that some samples contained concentrations of sulphates, phosphates, ammonium, nitrites, nitrates and iron that did not comply with potability standards before distillation, while others met these standards. After the solar distillation process, the concentrations of the chemical elements mentioned were significantly reduced, becoming compliant with international (WHO) and Madagascan national standards, with the exception of ammonium. The variations in concentrations before and after distillation are detailed as follows:

- Sulphates: from 1.6 to 6.407 mg/L before distillation.
- Phosphates: from 0.04 to 4 mg/L before distillation.
- Nitrites: from 0 to 0.45 mg/L before distillation.
- Nitrates: from 0.43 to 9 mg/L before distillation.
- Ammonium: present in five samples with concentrations ranging from 0.15 to 1.6 mg/L before treatment.
- Iron: In the six samples analyzed, the concentrations ranged from 0 to 0.12 mg/L before distillation.

One particular case was observed for a sample containing 0.3 mg/L arsenic before treatment; this concentration was reduced to 0.001 mg/L after solar distillation. These results confirm the effectiveness of the solar distillation process in eliminating the majority of man-made chemical contaminants and improving the chemical quality of treated water.

- **Results of analyses of microbiological parameters**

Drinking water does not contain pathogenic micro-organisms [2]. Therefore, microbiological parameters must also be analyzed. The results of the bacteriological analyses of a number of selected studies are presented in table 9.

Table -9: Microbiological parameters of distilled water

[Reference]	Types of solar distillers	Type of water	Total Coliforms		Escherichia Coli	
			Before T	After T	Before T	After T
[21]	Double slope solar still, active mode	Sea water	65	0	12	0
[15]	Single slope solar still, passive mode	Brackish water	0	0	0	0
[23]	Solar still with reflector	Lake water	129	0	33	0
[9]	Single slope solar distiller, active mode	Brackish water	150	0	120	0
			143	0	124	0
[10]	Double symmetrical solar still slope, active (pilot scale)	Raw water	>2419,6	<1	365,4	<1
		WHO standard	0 /100 ml of water		0/100 ml of water	
		Malagasy standard	0 /100 ml of water		0 /100 ml of water	

As shown in Table 9, the water used for purification initially contained high concentrations of coliform bacteria, ranging from 65 to 2419.6 units (CFU/100 ml). After the solar distillation process, these concentrations were reduced to undetectable levels (0 CFU/100 ml) in line with international and national drinking water standards. Similarly, the concentrations of Escherichia coli observed before treatment varied between 12 and 365.4 CFU/100 ml. After exposure to the sun's rays, these values were also reduced to zero (0 CFU/100 ml), thus meeting the potability standards.

In summary, the results confirmed the effectiveness of different types of solar distillers in eliminating microbiological contaminants. Overall, solar distillation proved to be an effective method for eliminating physical contaminants, significantly reducing the concentrations of chemical contaminants, and improving the microbiological quality of water by eliminating 100% pathogenic bacteria.

4. DISCUSSIONS

With the aim of providing a sustainable solution for drinking water production in the arid regions of southern Madagascar, this study focused on assessing the quality of water produced by different types of solar distillers. The data extracted from the included studies showed a certain heterogeneity linked to variations in the types of solar distillers used, the methods used to analyze the parameters defining water quality, and the specific climatic conditions. Despite these disparities, the results demonstrate the effectiveness of solar distillers in purifying water using solar energy while meeting drinking water standards.

4.1. Calculation of the combined effects of the fixed-effect model

Tables 6, 7, 8, and 9 highlight three heterogeneity criteria. For example, the variations observed in certain parametric variables, such as pH, nitrite, and nitrate [13], as well as pH and turbidity [14], which increase after solar distillation, could be attributed to sampling errors in certain studies. It is important to note that these errors were not explicitly mentioned or discussed in the interpretation of the results of the studies, which could influence the reliability of the conclusions.

4.2. Variation in distilled water quality

- **Depending on the type of solar distiller**

Single-slope and double-slope solar distillers operate similarly and have been shown to produce drinking water by effectively reducing high concentrations of physical, chemical, and bacteriological contaminants. Owing to these devices, brackish water, seawater, and heavily contaminated water can be purified to a quality that meets drinking water standards.

The stepped solar distiller demonstrated superior performance, particularly by significantly reducing electrical conductivity (EC), total dissolved solids (TDS), and total hardness. Conversely, the non-inclined solar still basin showed relatively limited effectiveness in improving water quality (Table 6). Furthermore, considering the type of action (active or passive), the active solar stills showed a greater reduction in contaminants than the passive devices, which achieved only a moderate reduction in impurities.

In conclusion, regardless of their configuration or mode of operation, solar distillers produce water that complies with the international and national drinking water standards.

- **Depending on the type of climate**

The performance of solar distillers varies according to the climatic conditions. In arid climates, these devices significantly reduce the physical, chemical, and microbiological impurities present in the water. In contrast, in tropical or subtropical climates, the distilled water obtained is generally pure, but the rate of reduction in contaminants remains slightly low. These observations highlight the major influence of climatic conditions on the efficiency of solar distillation.

- **Comparison of southern Madagascar with other arid regions**

According to the results of this literature review, the southern region of Madagascar is characterized by an arid to sub-arid climate [1], and access to drinking water remains a major challenge [2]. To address this problem, the use of a double-slope solar distiller was identified as an appropriate solution [3]. Taking these observations into account and comparing the performance of double-slope solar distillers reported in various studies (Table 6), it appears that the quality of local brackish or seawater after distillation could comply with the standards set by the WHO and Malagasy regulations.

4.3. Gaps in some of the included studies

The results of the literature review highlight a lack of in-depth studies on the long-term impact of the use of solar distillers on local natural resources and cultural practices. In addition, some of the studies had inadequate sample sizes, limiting the reliability of the conclusions. More representative quantitative samples are required to guarantee robust results. In southern Madagascar, studies on the water context have not yet assessed the quality of locally distilled water, although the recent application of double-slope solar distillation has been recommended [3].

5. RECOMMANDATIONS

In the course of this systematic literature review, the gaps identified could guide new lines of research aimed at providing sustainable solutions to the water shortage in southern Madagascar. In addition, it is essential to develop strategies to prevent health risks associated with the consumption of non-potable water, particularly among vulnerable populations such as children and pregnant women, by providing a method of instantaneous analysis of water quality adapted to the local context.

6. CONCLUSION

This systematic review assessed the quality of water produced by solar distillers, which is a potentially applicable solution in southern Madagascar. Following the PRISMA guidelines, 29 relevant studies were selected. An in-depth synthesis was conducted, along with a critical analysis and comparison of the available results. Based on theoretical and experimental evidence, this study identified the effectiveness of solar distillers in purifying water by reducing or eliminating various dissolved contaminants in nondrinking water. The water quality obtained, based on the combined results of the selected studies, complied with the potability standards set by the WHO and Malagasy regulations. Finally, recommendations were formulated to guide future research in this field.

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