

Characterization and Sustainability Assessment of Water-based Metal Oxide Nanofluids

Hamed Nazerian, Tommaso Angiolini, Maurizio Ferretti, Andrea P. Reverberi, Marco Vocciante*

Dipartimento di Chimica e Chimica Industriale, Università degli Studi di Genova, Genova, Italy
marco.vocciante@unige.it

The development of nanofluids (NFs) as advanced thermal carriers has attracted considerable attention due to their potential to improve the heat transfer efficiency in a variety of industrial applications. This study focuses on the properties of water-based nanofluids containing CuO and Al₂O₃ nanoparticles and evaluates the environmental sustainability of the produced prototypes through life cycle analysis (LCA). The synthesis process involved the preparation of nanofluids by dispersing nanoparticles in base fluids, followed by a characterization of their thermophysical properties. Key parameters, such as nanoparticle concentration, morphology, and stability to achieve superior thermal conductivity and minimal flocculation were considered. The environmental impact of the produced nanofluids was evaluated using an LCA procedure (CO₂ footprint analysis), encompassing the entire lifecycle from raw material extraction to disposal. While nanofluids offer substantial improvements in thermal performance, the analysis revealed that their environmental footprint is influenced by factors such as energy consumption during synthesis, nanoparticles potential toxicity, and waste management practices. The study underscores the importance of adopting green synthesis methods and sustainable practices to mitigate the ecological impact of nanofluids. These findings provide valuable insights into the trade-offs between enhanced thermal efficiency and environmental sustainability, paving the way for the development of eco-friendly nanofluids for industrial applications.

1. Introduction

The growth in the welfare level, increasing energy demand, and reduction in fossil fuels have forced researchers to seek new energy sources. New research is being conducted to improve existing technologies and develop new ones. Heat exchangers (HEXs) have many different applications, including in heating, cooling, and energy conversion systems, as well as in microelectronic fields. However, the low thermal conductivity of conventional working fluids, such as ethylene glycol and water, results in low thermal efficiency of HEXs.

To enhance heat transfer performance in thermal systems, researchers have increasingly turned to the development of advanced working fluids. Among these, nanofluids (NFs) – which are colloidal suspensions of nanoparticles (NPs) within conventional base fluids – have shown considerable promise. Since their introduction (Choi and Eastman, 1995), NFs have been recognized for their ability to significantly boost thermal conductivity, improve heat transfer rates, and enhance overall energy efficiency (Sajid and Ali, 2019). These benefits are particularly pronounced when nanofluids are used in conjunction with high-performance thermal devices, leading to further energy savings (Vocciante and Kenig, 2021).

The incorporation of nanoparticles – such as metal oxides, pure metals, or carbon-based nanomaterials – into base fluids results in a marked increase in effective thermal conductivity. This improvement is attributed to several mechanisms, including Brownian motion of the particles, thermophoretic effects, interfacial layering between particles and fluid, and the formation of enhanced conductive pathways. Experimental studies have consistently shown that even small additions of nanoparticles can lead to substantial gains in convective heat transfer coefficients and overall thermal performance.

For instance, Prasad and Gupta (2016) investigated the impact of using Al₂O₃ water nanofluid at different concentrations on the thermal efficiency of a tubular HEX modified with a twisted tape insert. Their findings indicated that the nanofluid increased the Nusselt number by a maximum of 31.28 %.

Since it is sometimes impossible for a single nanoparticle precursor to cover all the desired properties, an alternative approach is to improve the thermal properties by using nanoparticles from two or more sources, which generates a hybrid nanofluid. Hybrid NFs are convenient to be used as they can provide improved thermal behavior due to the synergistic effect (Sajid and Ali, 2018). Some researchers have indicated that hybrid NFs demonstrate superior thermal behavior compared to NFs containing single nanoparticles (Bahiraei et al., 2018). Despite their promising performance, NFs present some practical difficulties, including particle sedimentation and agglomeration, as well as stability issues (Reverberi et al., 2022). Furthermore, the benefits in terms of energy efficiency must be considered in relation to the use of various resources and chemicals for their preparation in order to assess the actual advantage in terms of overall environmental sustainability.

The Life Cycle Assessment (LCA) is an analysis that estimates the environmental impact of a certain process, product, or system (ISO 14040). This allows the environmental friendliness of different processes, products, or systems to be compared and evaluated (Cirincione et al., 2024). One of the strengths of life cycle assessment (LCA) is its ability to consider and evaluate the environmental impacts of all stages of a process, product, or system's life cycle. This evaluation begins with raw material sourcing (Llorach-Massana et al., 2023), continues through usage phases (Cirincione, 2025), and extends to the end of life (Rizzo et al., 2023) and disposal of generated waste materials (Peri et al., 2022).

The aim of this work is to examine different nanofluids, in particular copper oxide (CuO) and aluminum dioxide (Al₂O₃) at concentrations of 1 % and 5 % wt, due to their common use in heat transfer applications (Sajid and Ali, 2019). The properties of these NFs will be characterized and tested, highlighting the most environmentally impactful steps of the production process in terms of Global Warming Potential. Conducting an LCA analysis will make it possible to compare the environmental impact of these nanofluid compositions with others, also granting the possibility of finding ways to improve them and the heat exchange system.

2. Materials and Methods

2.1 Nanofluid preparation

Nanofluids were synthesized using deionized (DI) water (pH ≈ 6) as the base fluid, with CuO and Al₂O₃ nanoparticles as dispersed phases. Two concentrations were prepared for each nanoparticle type: 1 % and 5 % wt, using 200 mL of DI water per solution. The preparation followed a standardized multi-step protocol:

1. Surfactant Addition

- Sodium Dodecyl Sulfate (SDS) was used as a dispersing agent to enhance colloidal stability, using a quantity three times the mass of the nanoparticles.
- The surfactant was introduced into the DI water under magnetic stirring at 500 rpm for 15 minutes.

2. Nanoparticle Dispersion

- Commercial CuO (~30 nm) and Al₂O₃ (~50 nm) nanoparticles were weighed using a precision balance.
- The required mass for each concentration was calculated using the mass and volume fraction formulas (1), which refer to the nanofluid without the dispersing agent:

$$w = \frac{m_{np}}{m_{np} + \rho_f \cdot V_f}, \quad \phi = \frac{\frac{m_{np}}{\rho_{np}}}{V_f + \frac{m_{np}}{\rho_{np}}} \quad (1)$$

where m_{np} and ρ_{np} refer to nanoparticle mass and density, and ρ_f and V_f refer to the solvent density and volume, respectively.

- Nanoparticles were gradually added to the surfactant solution under continuous magnetic stirring.

3. Dispersion Protocol

- Mechanical stirring at 700 rpm for 30–45 minutes ensured initial dispersion.
- Ultrasonication was performed in a bath sonicator at 35 kHz for 120 minutes to break agglomerates and promote uniform suspension.

4. Stability and Characterization

- Stability was monitored over 48 hours through visual inspection, zeta potential measurements, and UV–vis spectroscopy, following best practices (Hong et al., 2020).

2.2 LCA analysis

As previously stated, an LCA analysis of these nanofluid compositions will be useful for determining their environmental impact and improving the synthesis process.

The Life Cycle Assessment (LCA) methodology is structured around four main phases as outlined in ISO 14040 and ISO 14044 (2006). These phases include:

1. Goal and Scope Definition – establishing the purpose of the study, system boundaries, functional unit, and data requirements;
2. Life Cycle Inventory (LCI) – gathering and analyzing data related to material and energy flows in accordance with the defined scope;
3. Life Cycle Impact Assessment (LCIA) – translating inventory data into potential environmental impacts, such as resource depletion and human health effects;
4. Interpretation – evaluating the results to identify opportunities for reducing environmental burdens and improving sustainability.

Although LCA was initially designed for evaluating products, it is increasingly applied to processes (Vocciante et al., 2021), including chemical synthesis (Pratolongo et al., 2025), to compare environmental performance and identify the most sustainable options. In this study, the Ecoinvent 3.11 database was used for data sourcing, and results were expressed in terms of Global Warming Potential over a 100-year horizon (GWP-100), following the CML2001 - January 2016 methodology (Guinée, 2002). GWP was selected as the primary indicator due to its relevance to climate change, although other impact categories could also be considered (Favara and Skance, 2017).

To ensure clarity and comparability, a functional unit of 1 liter of final product (nanofluid) was used for each production route, adjusting reagent quantities accordingly. When specific environmental data were unavailable for certain compounds, estimates were derived from precursor data and associated production methods. The assessment encompassed the full life cycle of each process, from raw material extraction to end-of-life disposal ("cradle to grave"). In this case, the creation of the nano powders, water usage, and energy consumption of the ultrasonic bath were all considered for a comprehensive analysis of the impact.

Figure 1 shows a schematic representation of the various stages of the synthesis process under consideration, highlighting the inputs and outputs. This step of the LCA analysis is useful to schematize all the processes involved and how they influence each other. It also makes it easier to change when something in the synthesis is changed as well.

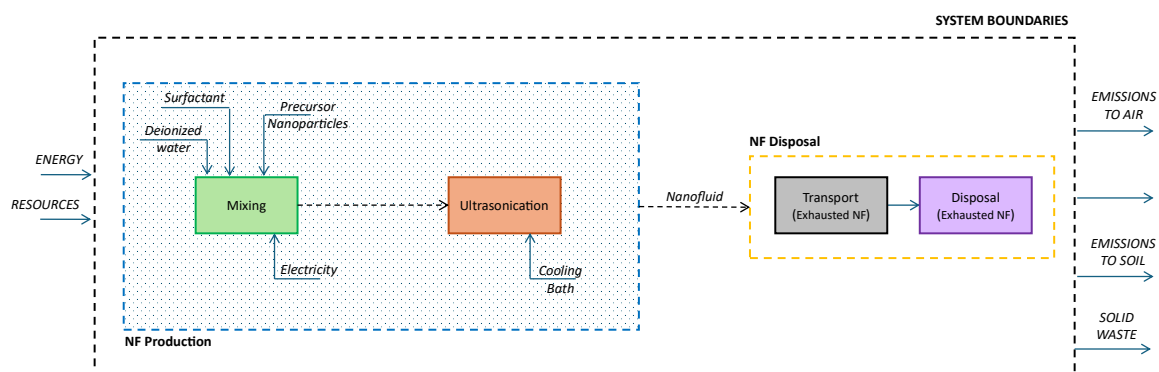


Figure 1: Block diagram of process of nanofluid production and disposal

As highlighted above, before assessing environmental impacts, all inputs and outputs to the system under consideration must be sorted and categorized, creating what is known as a Life Cycle Inventory (LCI). In Table 1 a balance sheet of the production path is reported, where the data are normalized against the production of 1 L of the synthetic product (nanofluid), thus including also the dispersing agent added to stabilize the nanofluid in the final volume. The data are reported in SI units consistent with the functional unit usually used for the relevant entry, such as 1 kg of substance or tons transported per km traveled in the case of transportation. In this regard, for disposal purposes a distance of 100 km from the treatment plant is assumed, which is already reflected in the values shown in Table 1.

Table 1: Balance sheet of the considered process; the normalized data refer to the production of 1 L of synthetic product (nanofluid) – F.U. stands for functional unit

	F.U.	CuO–water		Al ₂ O ₃ –water	
		1 % wt	5 % wt	1 % wt	5 % wt
CuO	[kg]	0.0098	0.0456	---	---
Al ₂ O ₃	[kg]	---	---	0.0098	0.0454
SDS	[kg]	0.0294	0.1369	0.0294	0.1363
Deionized water	[kg]	0.9699	0.8668	0.9691	0.8631
Mixing	[kWh]	0.025	0.025	0.025	0.025
Ultrasonic bath	[kWh]	0.480	0.480	0.480	0.480
Cooling bath	[kg]	2	2	2	2
Transportation	[t km]	0.101	0.105	0.101	0.104
Water treatment	[m ³]	0.001	0.001	0.001	0.001

For the impact assessment (LCIA), the schematic division shown in Figure 1 was maintained in preparation and disposal, where the necessary chemicals were evaluated as an additional step to obtain more information on the overall process. In this regard, the impacts for the SDS were derived from the data of the precursor reagents, specifically dodecanol (C₁₂H₂₆O), sulfur trioxide (SO₃) and sodium hydroxide (NaOH) based on the production process, which typically consist in sulfation of dodecanol with sulfur trioxide and neutralization with sodium hydroxide:



3. Results and Discussion

3.1 Nanofluids properties

The thermophysical characterization of the nanofluids produced was found to be consistent with the literature. Table 2 shows the data for some temperatures of interest in comparison with water.

Table 2: Traditional fluid (water) and selected nanofluids (CuO and Al₂O₃ at different concentration) characterization data in the temperature range of interest

Fluid	Temperature (°C)	Density (kg/m ³)	Viscosity (mPa·s)	Specific Heat (kJ/kg·K)	Thermal Conductivity (W/m·K)	Reference literature
Water	20	998	1.00	4.18	0.60	(EP, 2025)
	40	992	0.65	4.18	0.63	
	60	983	0.47	4.19	0.65	
CuO 1 % wt	20	1003	1.00	4.05	0.59	(Sohel Murshed and Estellé, 2017). (Okonkwo et al., 2021).
	40	1001	0.95	3.95	0.63	
	60	999	0.90	3.85	0.67	
CuO 5 % wt	20	1025	1.15	3.75	0.64	(Al Shdaifat et al., 2020)
	40	1019	1.05	3.65	0.68	
	60	1013	0.95	3.55	0.72	
Al ₂ O ₃ 1 % wt	20	1000	1.05	4.10	0.62	(Sohel Murshed and Estellé, 2017). (Okonkwo et al., 2021).
	40	998	1.00	4.00	0.66	
	60	996	0.95	3.90	0.70	
Al ₂ O ₃ 5 % wt	20	1030	1.20	3.80	0.69	(Sivakumar et al., 2024)
	40	1024	1.10	3.70	0.73	
	60	1018	1.00	3.60	0.77	

As expected, the selected nanofluids have a higher thermal conductivity than water, confirming the potential improvements in heat exchange processes. However, having a lower specific heat, they result in lower thermal energy transport at the same flow rate. In view of this, application performance depends heavily on how their properties vary with temperature. In particular, a general increase in thermal conductivity is expected when higher percentages of nanoparticles (NPs) dispersed in the fluid are used, which therefore favors heat transport. However, the addition of NPs leads to an increase in the complexity of rheological behavior, with viscosity that varies less predictably with temperature and flow conditions (compared to a traditional Newtonian fluid such as water) and a reduction in the thermal capacity/specific heat of the fluid.

Even without considering the increased rheological complexity, it can be observed that the reduction in specific heat is more pronounced at high temperatures. This results in a reduction in heat transport with the fluid that is not compensated for by the increase in thermal conductivity when the fluid is used for heating. Conversely, for lower temperature ranges, this loss of heat capacity is smaller, and therefore the advantage in terms of thermal conductivity leads to an overall benefit compared to the use of these NFs for cooling. This suggests optimal use as cooling fluids to replace traditional fluid (water).

3.2 Impact values

The results of the LCA analysis were obtained by calculating the impact values of each process, as shown in the schematic representations in Section 2.2, considering the quantities used during the preparation of 1 L of the relevant nanofluid reported in Table 1. In accordance with the GWP category, the impacts for each contribution to the synthesis process are expressed in terms of kg of CO₂ equivalent providing direct information on their effect on global warming.

Table 3: Impact values results, expressed in kg of CO₂ equivalent

		CuO–water		Al ₂ O ₃ –water	
		1 % wt	5 % wt	1 % wt	5 % wt
Chemicals		0.1440	0.6679	0.1039	0.4805
CuO	market for copper oxide	0.0585	0.2718	---	---
Al ₂ O ₃	market for alumina saggar	---	---	0.0186	0.0861
SDS	derived from market for dodecanol, sulfur trioxide and sodium hydroxide as per production process Eq(2)	0.0851	0.3957	0.0849	0.3940
Deionized water	market for water, deionised	0.0004	0.0004	0.0004	0.0004
Preparation		0.1667	0.1667	0.1667	0.1667
Mixing	market for electricity, low voltage	0.0082	0.0082	0.0082	0.0082
Ultrasonic bath	market for electricity, low voltage	0.1579	0.1579	0.1579	0.1579
Cooling bath	market for tap water	0.0006	0.0006	0.0006	0.0006
Disposal		0.2027	0.2107	0.2025	0.2098
Transportation	market for transport, freight, light commercial vehicle	0.2023	0.2104	0.2022	0.2095
Water treatment	treatment of wastewater, average	0.0003	0.0003	0.0003	0.0003
Total		0.5134	1.0454	0.4731	0.8571

As shown in Table 3, the results are comparable between the phases considered for 1 % wt preparations, in which disposal is the most significant entry, accounting for approximately 40 % of the total. As expected, this changes when the quantity of loaded NPs increases, raising the contribution of chemicals from 25 % to 60 % for 5 % wt fluids. Overall, the CuO NF formulation has a higher impact value, especially for 5 % wt. However, among the chemicals, the greatest impact is made by SDS. It contributes between 20 % and 45 % to the overall impact of the materials and surpasses the contribution of the NPs precursors.

4. Conclusions

The LCA analysis confirms that, apart from the sourced NPs, the main factors affecting the sustainability of NF synthesis are the use of a surfactant in the solution and the need for ultrasonication. As expected, the greatest contribution to the sustainability of the process lies in the ability to stabilize the produced nanofluid without adding surfactants or further processes. However, it seems difficult to significantly change these two aspects, as fundamental to the stability of the nanofluids in a two-step preparation, highlighting the limitations of this approach in achieving high environmental sustainability. Once innovative solutions for industrial-scale production are consolidated, one-step methods will more easily ensure the sustainable production of NFs.

Acknowledgments

This study was developed in the framework of the research activities carried out within the Project "Network 4 Energy Sustainable Transition — NEST", Spoke 8: Final use optimization, sustainability & resilience in energy supply chain, Project code PE00000021, Concession Decree No. 1561 of 11.10.2022 adopted by Ministero dell'Università e della Ricerca (MUR), CUP UNIPA B73C22001280006, Project funded under the National

Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 1.3 - Call for tender No. 341 of 15.03.2022 of Ministero dell'Università e della Ricerca (MUR); funded by the European Union – NextGenerationEU.

References

- Al Shdaifat M.Y., Zulkifli R., Sopian K., Salih A.A., 2020, Thermal and Hydraulic Performance of CuO/Water Nanofluids: A Review, *Micromachines*, 11(4):416.
- Bahiraei M., Rahmani R., Yaghoobi A., Khodabandeh E., Mashayekhi R., Amani M., 2018, Recent research contributions concerning use of nanofluids in heat exchangers: a critical review, *Applied Thermal Engineering*, 133, 137–159.
- Choi S.U., Eastman, J.A., 1995, Enhancing thermal conductivity of fluids with nanoparticles, Argonne National Lab. (ANL), Argonne, IL, United States.
- Cirrincione L., Longo S., Montana F., Peri G., Sanseverino E.R., Scaccianoce G., 2024, Life Cycle Assessment Impact Indicators for Simulation-Based Optimization of Buildings, *Proceedings in 24 IEEE International Conference on Environment and Electrical Engineering*.
- Cirrincione L., 2025, LCA of wall infill made with agriculture waste, *Advances in Bio-Based Materials for Construction and Energy Efficiency*, 337–364.
- EnergyPlus, available at: <https://energyplus.net> (accessed on 15 April 2025).
- Favara P., and Skance O., 2017, Overview of LCAs as applied to remediation projects, In: Abraham M.A. (Ed.), *Encyclopedia of Sustainable Technologies (Second Edition)*, Elsevier, US, 338–346.
- Guinée J.B., 2002, *Handbook on life cycle assessment: operational guide to the ISO standards (Vol. 7)*. Springer Science & Business Media.
- Hong W.X., Che Sidik N.A., Saidur R., 2020, Impact of different surfactants and ultrasonication time on the stability and thermophysical properties of hybrid nanofluids, *International Communications in Heat and Mass Transfer*, 110, 104389.
- ISO 14040:2006, ISO 1044:2006, International Standard
- Llorach-Massana P., Cirrincione L., Sierra-Perez J., Scaccianoce G., La Gennusa M., Peña J., Rieradevall J., 2023, Environmental assessment of a new building envelope material derived from urban agriculture wastes: the case of the tomato plants stems, *International Journal of Life Cycle Assessment*, 28 (7), 813–827.
- Okonkwo E.C., Wole-Osho I., Almanassra I.W., Abdullatif Y.M., Al-Ansari T., 2021, An updated review of nanofluids in various heat transfer devices, *Journal of Thermal Analysis and Calorimetry*, 145, 2817–2872.
- Peri G., Licciardi G.R., Matera N., Mazzeo D., Cirrincione L., Scaccianoce G., 2022, Disposal of green roofs: A contribution to identifying an “Allowed by legislation” end-of-life scenario and facilitating their environmental analysis, *Building and Environment*, 226, 109739.
- Prasad, Gupta, 2016, Experimental investigation on enhancement of heat transfer using Al₂O₃/water nanofluid in a u-tube with twisted tape inserts, *International Communications in Heat and Mass Transfer*, 75, 154–161.
- Pratolongo D., Campolucci M., Vocciante M., Pugliesi L., Di Giorgio E., Lambruschini C., Manna L., Locardi F., 2025, Lead Halide Perovskites Nanocrystals Synthesized in a Green, Reusable Solvent, *Small*, 2500535.
- Rizzo G., Cirrincione L., La Gennusa M., Peri G., Scaccianoce G., 2023, Green Roofs' End of Life: A Literature Review, *Energies*, 16 (2), art. no. 596.
- Reverberi A.P., Vocciante M., Salerno M., Soda O., Fabiano B., 2022, A sustainable, top-down mechanosynthesis of carbohydrate-functionalized silver nanoparticles, *Reaction Chemistry & Engineering*, 7(4), 888–897.
- Sajid M.U., Ali H.M., 2018, Thermal conductivity of hybrid nanofluids: a critical review, *International Journal of Heat and Mass Transfer*, 126, 211–234.
- Sajid M.U., Ali, H.M., 2019, Recent advances in application of nanofluids in heat transfer devices: a critical review, *Renewable and Sustainable Energy Reviews*, 103, 556–592.
- Sivakumar V., Visagavel K., Kumaraswamy J., Balaji E., Khalkar V., Gnanavel C., Kalyana Chakravarthy P.R., Baskar S., Vijayan V., 2024, Performance study and analysis of Al₂O₃ Nanofluid under different flow conditions. *Interactions* 245, 213.
- Sohel Murshed S.M., Estellé P., 2017, A state of the art review on viscosity of nanofluids, *Renewable and Sustainable Energy Reviews*, 76, 1134–1152.
- Vocciante M., de Folly D'Auris A., Franchi E., Petruzzelli G., Ferro, S., 2021, CO₂ footprint analysis of consolidated and innovative technologies in remediation activities, *Journal of Cleaner Production*, 297, 126723.
- Vocciante M., Kenig E.Y., 2021, Pillow-plate heat exchangers: an overview on advances, limitations and prospects, *Chemical Engineering Transactions*, 88, 865–870.