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Eco-Friendly Sustainable Drying Techniques for Sludge from Drinking Water Treatment Plants

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Abstract

The management of sludge generated from Drinking Water Treatment Plants (DWTPs) represents a growing environmental and operational challenge due to its high moisture content and disposal constraints. Conventional thermal drying techniques, although effective, are energy-intensive and contribute significantly to greenhouse gas emissions. This study presents a comparative review of eco-friendly and sustainable drying technologies applicable to DWTP sludge. A systematic analysis of published literature was conducted to evaluate solar drying, greenhouse-assisted drying, low-temperature thermal drying, waste heat-assisted drying, and bio-drying processes. The comparison was based on drying efficiency, energy consumption, carbon emission impact, economic feasibility, and scalability potential. The findings indicate that solar and greenhouse drying systems offer minimal direct energy consumption but are climate-dependent. Waste heat-assisted drying provides a balanced compromise between efficiency and sustainability by reducing primary energy demand by up to 60%. Conventional thermal drying ensures rapid moisture removal but remains the most energy-intensive option. The review highlights the need for DWTP-specific optimization strategies and supports the development of hybrid systems integrating renewable or recovered energy sources to enhance sustainability and align with circular economy principles.

I. Introduction

Drinking Water Treatment Plants (DWTPs) produce considerable quantities of sludge as a by-product of coagulation, flocculation, and sedimentation processes. The disposal and management of this sludge pose environmental and economic challenges due to its high moisture content and increasing regulatory constraints [A]. Efficient sludge drying is essential to reduce volume, transportation costs, and environmental impact. Conventional thermal drying techniques are widely implemented because of their rapid moisture removal capacity. However, these systems require high energy inputs and contribute significantly to greenhouse gas emissions [B]. As sustainability becomes a central objective in environmental engineering, eco-friendly drying alternatives have gained increasing attention. Solar drying systems have been reported as low-energy solutions capable of significantly reducing operational costs [3]. Waste heat recovery from industrial processes has also been identified as a promising strategy to improve energy efficiency in sludge treatment systems [4]. Furthermore, sustainable sludge management aligns with circular economy principles, enabling valorization in construction materials and other beneficial reuse pathways [5]. Most available research focuses on municipal wastewater sludge, while Drinking Water Treatment Plant sludge exhibits different physicochemical characteristics, including lower organic matter and higher mineral content [6]. These differences may influence drying behavior and efficiency.

The objective of this study is to conduct a comparative review of eco-friendly sustainable drying techniques applicable to DWTP sludge and to identify the most promising strategies for environmentally responsible management.

II. Methods

This study was conducted as a comparative literature review to evaluate sustainable drying techniques for sludge generated from DWTPs. The methodology consisted of systematic analysis, comparison, and critical synthesis of previously published scientific studies.

Selection Criteria

Relevant articles were identified using academic databases such as Google Scholar, ScienceDirect, and SpringerLink. Keywords included:

- DWTP sludge drying
- solar sludge drying
- waste heat sludge drying
- bio-drying sludge
- sustainable sludge management

Priority was given to peer-reviewed studies published between 2000 and 2024.

Selection Criteria

studies.Studies were selected based on:

- ✓ Quantitative reporting of moisture reduction
- ✓ Energy consumption data
- ✓ Environmental performance indicators
- ✓ Applicability to sludge drying systems

Both wastewater and drinking water sludge studies were considered, with critical differentiation between sludge types.

Comparative Framework

Extracted data were analyzed according to:

- Moisture reduction efficiency (%)
- Energy consumption (kWh/kg water removed)
- Carbon emission impact
- Economic feasibility
- Scalability potential

A qualitative and quantitative synthesis approach was applied to identify strengths, weaknesses, and research gaps.

III. Results and discussion

Comparative Performance of Drying Techniques

Solar drying systems typically achieve moisture reductions between 60% and 75%, depending on climatic conditions, with drying durations ranging from 7 to 20 days [1,3]. These systems exhibit minimal external energy consumption but remain climate-dependent. Greenhouse-assisted drying enhances temperature through the greenhouse effect, reducing drying time by approximately 25–35% compared to open-air solar drying [7]. However, land requirements may limit large-scale implementation. Conventional thermal drying achieves more than 90% moisture reduction within 24–48 hours but requires significant energy input, ranging from 800 to 1200 kWh per ton of evaporated water [2,8].

This results in high operational costs and increased carbon emissions. Waste heat-assisted drying reduces primary energy demand by 40–60% by utilizing residual industrial heat streams [4]. This method offers a balanced compromise between efficiency and sustainability, particularly in industrialized areas. Bio-drying processes achieve moderate moisture reduction (50–65%) through microbial heat generation with limited external energy input [9]. However, process control remains critical for performance stability.

Energy and Environmental Considerations

Thermal drying presents the highest carbon footprint due to fossil fuel dependency [2]. Solar and greenhouse systems demonstrate near-zero direct emissions but depend on climate conditions.

Waste heat integration significantly reduces CO_2 emissions and promotes industrial symbiosis [4,5]. Hybrid systems combining renewable and recovered energy appear to provide the most sustainable long-term solution.

Critical Analysis and Research Gap

The comparative performance of the investigated drying technologies is presented in Table 1. Solar and greenhouse drying systems demonstrate low energy consumption but remain climate-dependent. In contrast, thermal drying achieves the highest moisture reduction efficiency but at the expense of substantial energy demand and carbon emissions.

Table 1. Comparative assessment of sustainable drying techniques for DWTP sludge

Technique	Moisture Reduction	Energy Demand	CO_2 Impact	Main Limitation
Solar Drying	60–75%	Very Low	Very Low	Climate dependent
Greenhouse	70–80%	Low	Low	Land required
Thermal	>90%	Very High	High	Costly
Waste Heat	80–90%	Moderate	Low	Heat source needed
Bio-drying	50–65%	Low	Low	Process control

A major limitation identified in the literature is the predominance of studies focused on wastewater sludge. DWTP sludge differs in composition and drying behavior [6], and direct extrapolation may not be fully accurate. Further DWTP-specific investigations are required to optimize sustainable drying performance.

IV. Conclusion

This comparative review demonstrates that eco-friendly drying technologies provide promising alternatives to conventional thermal drying for Drinking Water Treatment Plant sludge. Solar and greenhouse systems offer low-energy solutions, while waste heat-assisted drying represents an efficient and sustainable compromise. However, most existing studies focus on wastewater sludge, highlighting a research gap for DWTP-specific validation. Future research should prioritize hybrid drying systems and life-cycle-based assessments to optimize environmental and economic performance.

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