Hydrothermal Carbonization of Sewage Sludge: A Sustainable Approach for Phosphorus Recovery and Greenhouse Gas Mitigation in Wastewater Treatment Plants

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Introduction

The global population is projected to reach 8–10 billion by 2050, increasing pressure on food production and resource availability. Rising food demand, coupled with rapid urbanization and economic growth, has also led to increased waste generation, particularly wastewater. Currently, 380 billion m³ of wastewater is produced annually worldwide, expected to increase by 51% by 2050. This wastewater contains valuable nutrients, including nitrogen (N), phosphorus (P), and potassium (K), which could be recovered and recirculated into agricultural production. Municipal wastewater treatment plants (WWTPs) process household wastewater, resulting in treated water and sewage sludge, a byproduct containing organic matter, pathogens, heavy metals, and nutrients. Sludge production is significant, with approximately 8.9 million metric tons reported annually in the EU. Although sludge treatment constitutes 50–60% of WWTP operational costs, it holds potential value as a fertilizer and energy source. Anaerobic digestion is a widely used technology that stabilizes sludge while producing biogas for energy recovery, offsetting up to 27% of WWTP energy consumption.

Phosphorus (P) is a critical nutrient for plant growth and global food security, primarily sourced from phosphate rock. However, P is a non-renewable resource, with global reserves potentially depleting within the next 50–100 years. The demand for P fertilizers is expected to rise, with 90% of P use dedicated to agriculture. Despite this, P use is highly inefficient—only 16% of applied P reaches final food products, while 70% of P fertilizers remain unused in soils, contributing to environmental losses and water pollution. P scarcity could lead to rising phosphate rock and fertilizer prices, disproportionately affecting farmers in developing countries and disrupting the global agri-food system. Moreover, inefficient P use contributes to “legacy P” accumulation in soils and nutrient loss to water bodies. Global P reserves are expected to decline in quality, further increasing extraction costs. Since 2000, P prices have risen by 273% and are projected to continue increasing due to supply constraints and growing demand.

A shift from the current linear phosphorus economy to a circular model is essential to sustain global P availability. The circular economy focuses on closing resource loops through recovery and reuse strategies. Nearly 98% of ingested P is found in wastewater and sewage sludge, making these sources viable for P recovery. Raw SS has limited agricultural applications due to sanitary concerns, but thermal treatments such as hydrothermal carbonization (HTC) offer a promising alternative. HTC is an advanced treatment that stabilizes sludge, removes pathogens, and concentrates nutrients into a solid hydrochar (HC) product suitable for agricultural use. By recovering P through HTC, valuable nutrients can be reintegrated into the food system, reducing dependence on mined phosphate rock. Conducting a techno-economic analysis (TEA) of HTC implementation will help evaluate its feasibility, cost-effectiveness, and environmental benefits. This approach supports the circular economy, mitigates resource depletion, and ensures sustainable agricultural production.

Methodology

Secondary sewage sludge was collected from a local WWTP (Israel) and stored at -20°C before HTC experiments. The WWTP treats 32,600 m³/day of wastewater, serving 250,000 people, producing 57,000 kg/day of wet sludge and 1,880 Nm³/day of biogas. For HTC, A 600-mL stainless steel pressurized reactor (BüchiGlasUster, Switzerland) was used. HTC was performed at 200°C for 30 min. Mass yield was 72.9 ± 3.2%. Compared to sludge, HC had higher ash content (41.8% vs. 29.8%), similar pH (6.6 vs. 6.3), lower electrical conductivity (1.3 dS/m vs. 3.1 dS/m) and increased phosphorus content (27.6 g/kg vs. 22.0 g/kg). Total carbon and nitrogen were measured using a FLASH smart 1112 CHNS–O Analyzer. Phosphorus was determined via wet digestion and ascorbic acid methods. Other elements (Na, K, Mg, Ca, Fe, Zn, Mn, Cu) were analyzed using atomic absorption spectrometry. A techno-economic analysis (TEA) was conducted to assess the feasibility of HTC integration into WWTP operations. The HTC unit was modeled to treat 21,000 tons of sludge per year over a 30-year lifespan. The reactor volume was 3.4 m³, processing 2,400 kg of wet sludge per run at 70% filling capacity.

Results and Discussion Summary

Mass Flow Analysis

Mass flow evaluation is crucial for assessing the environmental and economic benefits of HTC-treated sludge. The study focused on phosphorus (P) recovery, transforming an environmental burden into a valuable agricultural input. The HTC process was applied to sludge (100% mass basis), where initial solids contained 40.3% carbon and 2.1% P. The HTC process retained approximately 73% of the initial solids, with the majority of mass being retained in the process water, due to dehydration and organic matter breakdown. The solid product, hydrochar, contained 38.4% carbon and 2.8% P, with a P recovery rate of approximately 97%. The high recovery was attributed to rapid mineralization and precipitation during HTC. The gas phase, primarily composed of CO_2 (>90%), resulted from the thermal decomposition and decarboxylation of organic matter.

Nutrient Recovery and Fertilizer Implications

HTC enriches soil with essential macro elements (N, P, K), reducing reliance on chemical fertilizers. This has economic and environmental advantages, lowering costs for acquisition, transportation, and production of synthetic fertilizers. The prices of triple super phosphate (TSP) are 545±125€/ton, while the N and K fertilizers prices are around 418€/ton(REF) and 361€/ton(REF), respectively. The fertilizers production impacts also the GHG emissions, where, for producing 1 kg of P by TSP production 3.7 kg of CO_2 is emitted, for N 6.2 kg CO_2, and for 1 kg of K 0.25 kg of CO_2 is released. By reducing chemical fertilizer usage, HTC lowers production demand, mitigating GHG emissions and decreasing fertilizer-related expenses. This contributes to a more circular and sustainable agricultural system, reinforcing the economic and ecological benefits of HTC technology.

Environmental Contributions

In 2020, global CO_2 emissions were approximately 25,000 tons, increasing annually by 1.8%. Fossil fuel-based carbon materials are a major contributor, whereas biomass-based processes like HTC offer a carbon-negative alternative. HTC converts wet biomass into stable carbon materials that can be returned to agricultural soils, reducing overall emissions. Treating sewage sludge with HTC instead of conventional methods significantly reduces greenhouse gas (GHG) emissions (Fig. 1). Under the business-as-usual approach in Israel, sludge is transported to four major treatment plants to be converted into agricultural-grade sludge. This transport alone accounts for approximately +1208 kg CO_2-eq emissions per 123 km distance. Conversely, HTC treatment eliminates the need for sludge transportation, with only the final hydrochar product requiring transport, reducing emissions to 162 kg CO_2-eq. Additionally, the HTC process itself contributes -1250 kg CO_2-eq, making it a net negative emissions process compared to triple superphosphate (TSP) production, which emits +915 kg CO_2-eq. Most carbon in the sludge remains stored and can be returned to the soil, enhancing soil organic matter. Approximately 39% of carbon is retained, while a minor portion is released as CO_2. This carbon sequestration potential makes HTC a viable strategy for sustainable agriculture and climate change mitigation.

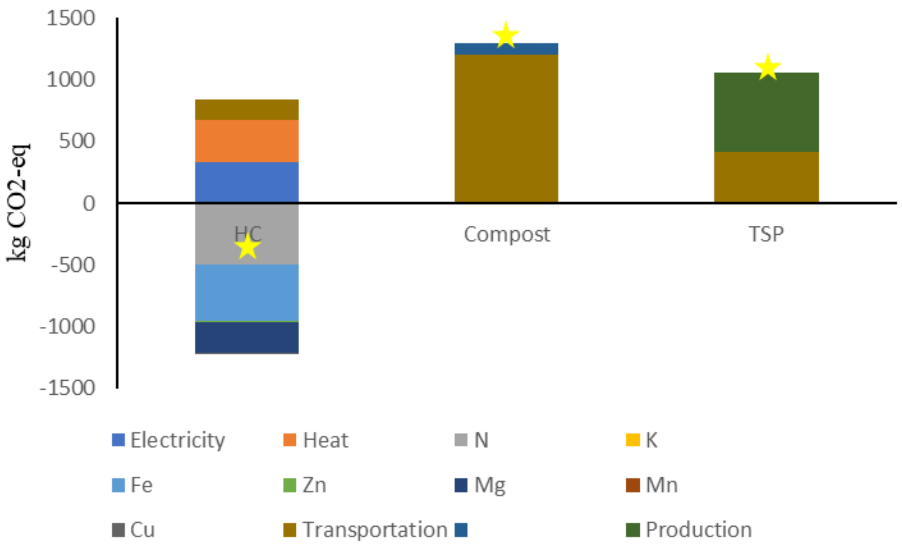

Figure 1. Greenhouse gas (GHG) emissions (kg CO_2-eq) associated with hydrochar (HC), compost, and triple superphosphate (TSP) production. Negative emissions for HC indicate its potential as a carbon-negative process, while compost and TSP production contribute positively to GHG emissions. Yellow stars highlight the total net emissions for each treatment option.

Economic Analysis

The total capital investment required to scale up an HTC unit integrated into the WWTP is estimated at €2.7 million (2024). This investment primarily covers equipment costs and other fixed expenses. The facility processes 21,000 tons of wet sludge per year, generating hydrochar as a solid product. In the base case, without considering carbon and fertilizer credits from hydrochar use as a soil amendment, the break-even point for the annual dry hydrochar production is 2,500 tons per year. At this break-even point, factoring in both fixed and variable costs, the selling price per ton of hydrochar is projected to be €260, excluding additional revenue from phosphorus (P) and carbon (C) recovery. Based on this minimum selling price and the associated costs, the estimated payback period for the project is approximately 11years.