Economic resilience evaluation of wastewater resource recovery in Qatar’s fertilizer market

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Abstract

Commercial fertilizers production represents a substantial contributor to greenhouse gas emissions when it comes to irrigated agriculture, and can, in some instances, hold the biggest share of emissions associated with the practice. With the intensification of climate change, energy intensive Haber-Bosh process, and declining phosphorus reserves, there is a need to adopt alternative and sustainable methods to meet farming nutrient requirements while reducing the burden on the environment, and while maintaining reduced economic costs. Using wastewater treatment plants byproducts, treated sewage effluent and sludge, can represent an effective mitigation strategy to reduce these emissions. In addition to that, sludge can be converted into soil amendment which can also substitute for conventional fertilizers. This study aims to evaluate the economic resilience of substituting commercial fertilizers with treated wastewater and sludge produced from wastewater treatment plants. The economic resilience of directing treated wastewater to the agricultural sector in the State of Qatar for fertigation purposes and converting sludge into biochar using pyrolysis modeled in Aspen Plus is compared with that of urea production. The economic resilience is assessed using the redundancy ratio as well as a price comparison under carbon taxation, thus internalizing the environmental cost of carbon emissions. Results indicate that treated sewage effluent and sludge biochar maintain stable redundancy ratios from 2017 to 2021, suggesting a dependable supply that could reduce reliance on traditional fertilizers. The introduction of a carbon tax, ranging from $0.03 to $0.1 per kg of CO2, markedly shifts cost competitiveness in favor of sludge biochar, highlighting its potential as an economically and environmentally superior alternative. the substitution of conventional fertilizers with treated sewage effluent and sludge biochar in Qatar presents a viable pathway to enhance agricultural sustainability. The study emphasizes the need for policy frameworks that support the integration of these practices, ensuring that Qatar's agricultural sector remains resilient in the face of environmental and economic challenges.

**Keywords**: Wastewater, sludge, resilience, resource recovery, greenhouse gas emissions.

* 1. Introduction

As the global population continues to rise, the demand for food production intensifies, leading to a parallel increase in the need for commercial fertilizers. These fertilizers, essential for boosting crop yields and ensuring food security, have become a cornerstone of modern agriculture. However, the production of commercial fertilizers is an energy-intensive process, predominantly through the Haber-Bosch method for synthesizing ammonia, contributing significantly to the carbon footprint (CF) of the food sector (Gellings and Parmenter, 2004). With agriculture accounting for a substantial share of global greenhouse gas emissions, there is a pressing need to explore alternative resources that can sustain agricultural productivity while mitigating environmental impacts (Lahlou et al., 2023b).

The State of Qatar, with its arid climate and limited arable land, faces unique challenges in its pursuit of food security. In recent years, Qatar has made significant strides in recycling water, resulting in treated wastewater that is highly purified and enriched with nutrients, including nitrogen. This treated sewage effluent (TSE) is a byproduct of urban water use that, after treatment, could serve as a sustainable irrigation resource. Yet, the potential of TSE as a partial substitute for commercial fertilizers remains largely untapped (Lahlou et al., 2021). Additionally, Qatar's wastewater treatment plants produce a substantial amount of sludge which currently represents an underexplored resource. Through processes such as pyrolysis, sludge can be converted into biochar, a soil amendment known for its nutrient-rich content and carbon sequestration capabilities (Ghiat et al., 2020).. Biochar not only offers a way to recycle waste but also provides a means to improve soil health and fertility, presenting an opportunity to enhance the sustainability of Qatar's agricultural practices.

The transformation of TSE and sludge into valuable agricultural inputs could significantly reduce the reliance on imported commercial fertilizers, decrease the carbon footprint associated with food production, and align with the broader environmental goals of reducing greenhouse gas emissions (Lahlou et al., 2020). The integration of these resources into the agricultural sector may serve as a model for sustainable agriculture in arid regions worldwide. In this context, economic resilience becomes a critical factor. It is essential to ensure that the adoption of alternative fertilizers such as TSE and biochar derived from sludge is not only environmentally sustainable but also economically viable. Economic resilience in this framework refers to the agricultural sector's ability to absorb and adapt to economic shocks, such as fluctuations in global fertilizer prices or changes in trade policies, without significant disruption to agricultural output or profitability.

This study examines the economic resilience of TSE and sludge biochar in Qatar's fertilizer market. It evaluates whether these alternatives can provide a stable and reliable supply of nutrients, offset the need for commercial fertilizers, and withstand market and environmental uncertainties. This research provides insights into the feasibility of these alternative nutrient sources in supporting Qatar's agricultural sustainability and food security ambitions. The findings of this research aim to contribute to the development of informed policies and practices that balance economic, environmental, and regulatory considerations, paving the way for a more sustainable agricultural future.

* 1. Methodology
		1. Study area and scenario description
			1. Base scenario

The State of Qatar relies heavily on commercial fertilizers. For the existing fodder farms, it is estimated that a range of 382-556 kg of N is required every year for optimum fodder yield, of which 89% is supplied through commercial fertilizers while the rest comes from TSE (Lahlou et al., 2023a). For this study, it is assumed that urea produced locally is used as commercial fertilizer, and that the total capacity of N sourced from urea can be calculated using Eq. (1), such that $TC^{Y}$ is the total capacity in year $Y$ [t.y-1], $P\_{u}^{Y}$ designates the urea production in year $Y$, retrieved from QAFCO (2021) [t.y-1], $E\_{u}^{Y}$ is the urea exports in year $Y$ retrieved from (Planning and Statistics Authority, 2021), $Pop\_{Q}^{Y}$ designates Qatar population in year $Y$ [capita], $U\_{fert-use}$ is the average urea usage per capita retrieved from (FAO, 2023) [t.capita-1.y-1], $\%\_{N-urea}$ is the % of N in urea (QAFCO, 2021).

$ TC^{Y}=\left(P\_{u}^{Y}- E\_{u}^{Y}- Pop\_{Q}^{Y} . U\_{fert-use} \right) .\%\_{N-urea}$ ( )

* + - 1. Treated sewage effluent scenario

The State of Qatar has been producing increasingly more TSE over the past few years. While some of the TSE is used for irrigation purposes, important volumes are disposed of, which could, in turn, not only reduce the reliance on the heavily abstracted groundwater resources but also supply Qatar’s irrigated agricultural sector with loads of Nitrogen (N) that can offset the burden associated with commercial fertilizers. With an average N concentration of 6.76 mg.L-1, TSE has the potential to meet the total N fertilization requirement of the agricultural sector in Qatar(Lahlou et al., 2023a). The total capacity of N sourced from urea can be calculated using Eq. (2), such that $C\_{i}^{Y}$ is the capacity of plant $i$ in year $Y$ [million m3.y-1], and $C\_{i}^{N}$ is the N concentration in plant $i$ [mg.L-1]

$ TC^{Y}= \sum\_{i}^{n}C\_{i}^{Y} . C\_{i}^{N}$ ( )

* + - 1. Sludge scenario

Important volumes of sludge are produced every year in the State of Qatar, which can be converted into biochar. When used as soil amendment under the right conditions, biochar can supply a plant’s nutrient requirements (Haider et al., 2020). Aspen Plus is used to simulate the pyrolysis of sludge produced between the year 2017 and 2021 (Figure 1). the proximate and ultimate analysis are retrieved from the literature (AlNouss et al., 2019).



Figure 1: Pyrolysis flowsheet in Aspen Plus.

* + 1. Economic resilience assessment

The redundancy ratio (RR) is used as a measure of the economic resilience of the three scenarios from 2017 to 2021 and is calculated using Eq. (3) and (4) such that $EC$ is the excess capacity, $AD$ is the average demand, and $TC$ is the total capacity.

$RR= \frac{EC}{AD}$ (3) $EC= TC-AD$ (4)

To assess the economic impact of environmental taxation on fertilizer choices, the costs of sludge and urea are compared, incorporating a variable carbon tax. The analysis simulates the introduction of a carbon tax, ranging from $0.03 to $0.1 per kg of CO2, to the price of urea. This is done to reflect the higher carbon emissions from urea production, compared to the lower emissions from sludge. The carbon tax is applied based on the emissions differential per unit of nitrogen, $∆CO2$, given by Eq. (5). Where $E\_{urea}$ and $E\_{sludge}$represent the kg of CO2-eq emissions per kg of nitrogen from urea and sludge, respectively. The adjusted cost of urea, $C\_{urea,adj}$ is then calculated using Eq. (6) such that $C\_{urea}$ is the initial cost of urea per kg of nitrogen and $Tax\_{CO2}$ is the applied carbon tax per kg of CO2-eq. To maintain revenue neutrality for urea production, the carbon tax’s financial impact is directly added to its market price.

 $∆CO2=E\_{urea}-E\_{sludge}$ ( )

 $C\_{urea,adj}=C\_{urea}+ ∆CO2 . Tax\_{CO2}$ ( )

The sensitivity of the cost difference to variations in sludge pricing is also analyzed, considering price changes ranging from a 50% decrease to a 50% increase. This comparison provides insights into how environmental policies, such as carbon taxes, could shift economic preferences between traditional and more sustainable nitrogen sources in agriculture. The price of urea ranges averages 1.51 USD.kg-1, while that of biochar is obtained from the Aspen Plus model considering that raw sludge cost is set to 0.1 USD.t-1 (AlNouss et al., 2021; Quinn, 2023).

* 1. Results
		1. Pyrolysis model results

The results of the Pyrolysis model are demonstrated in Table 1. The volumes of sludge produced in the state of Qatar have been relatively stable over the past few years. The N content in the produced biochar represents on average 11.17% of the total mass. The cost of each kgN ranges between 4.47 and 4.61 USD. In the case where raw sludge is free, the cost would reduce to 1.39, up to 1.53 USD.kgN-1.

Table 1: Biochar N content and cost for different sludge inlets for years 2017-2021.

|  |  |  |  |
| --- | --- | --- | --- |
| Year | Sludge inlet (kg.h-1) | N (kg.h-1) | Cost (USD.kgN-1) |
| 2017 | 41,554.00 | 153.87 | 4.47 |
| 2018 | 37,688.00 | 139.55 | 4.61 |
| 2019 | 39,096.00 | 144.77 | 4.56 |
| 2020 | 40,960.00 | 151.67 | 4.49 |
| 2021 | 41,349.00 | 153.11 | 4.48 |

* + 1. Redundancy Ratio

The RR analysis reveals that TSE and sludge maintain stable surpluses, indicating robust systems against supply shocks (Figure 2). Although TSE's surplus slightly declined in 2021, its overall contribution to resilience remains strong. Conversely, urea's RR displayed volatility, surging in 2017 due to export disruptions from the regional blockade, which suggests a potential for stockpile inefficiency and vulnerability to trade dynamics. The significant RR increase in 2021 for urea might reflect strategic adjustments in response to the Russia-Ukraine conflict's impact on global demands. High RR for urea signals management inefficiencies, reflecting potential overproduction or underuse, rather than economic strength. These inefficiencies underscore the need for a supply strategy attuned to market demands. Conversely, the stable RRs for TSE and sludge indicate reliable, sustainable alternatives. Policy efforts must, therefore, balance urea's output with actual needs and foster the integration of TSE and sludge to safeguard against urea's market uncertainties.



Figure 2: RR values for TSE, Sludge, and Urea from 2017 to 2021.

* + 1. Price comparison under carbon taxation

The introduction of a carbon tax significantly influences the cost competitiveness between sludge and urea-based fertilizers. Figure 3 demonstrates that as the carbon tax increases from $0.03 to $0.10 per kg of CO2, the cost advantage of sludge over urea becomes more pronounced. Each line represents the cost differential between sludge and urea at various levels of carbon taxation, holding the sludge price constant while urea's price adjusts to include the tax, maintaining revenue neutrality. The smallest tax rate, $0.03/kg CO2, presents a modest difference in cost, but as the tax rate escalates, the gap widens consistently. At the highest carbon tax rate, $0.10/kg CO2, the price of urea surpasses that of sludge significantly, indicating a strong economic incentive to shift towards sludge as a more cost-effective and environmentally sustainable nitrogen source. These results suggest that implementing a carbon tax could be an effective policy tool for promoting sustainable agricultural practices through the adoption of lower-emission fertilizers.



Figure 3: Price Difference Between Sludge and Urea with Varying Carbon Tax Rates.

* 1. Conclusions

The RR for urea displayed considerable volatility over the five-year period, with significant peaks in 2017 and 2021 due to geopolitical events that disrupted exports. In contrast, TSE and sludge demonstrated stable RRs, suggesting they are more resilient to external shocks and could serve as sustainable alternatives within Qatar's agricultural sector. The carbon tax simulation showed that as the tax rate increases, sludge becomes progressively more cost-competitive against urea. This reinforces the potential of environmental taxation to influence the adoption of greener agricultural inputs. The limitations of the study include the assumption that biochar derived from sludge could fully meet a plant's nitrogen requirements. In reality, the efficiency of biochar as a complete substitute for conventional nitrogen sources is complex and contingent upon multiple variables, such as soil type, crop needs, and biochar properties. The study's model does not account for these agronomic and environmental subtleties, nor does it incorporate potential future changes in production technology, market dynamics, or agricultural methodologies that might alter nitrogen utilization patterns. Despite these constraints, the findings offer valuable insights for policymakers, and suggest that implementing carbon taxes can effectively incentivize shifts towards more environmentally friendly fertilizers. However, policies should also consider the agronomic suitability of biochar and TSE, promoting research and development to optimize their use in Qatar's unique environmental conditions.

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