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Demography-Driven Assessment of Nitrogen Recovery Potential from Waste for Future Protein Security in Iran

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ABSTRACT

With increasing pressure on water resources, food security, and sustainable development, nitrogen recovery from wastewater and food waste has emerged as a promising source of microbial protein (MP) through the conversion of recovered nitrogen. This study evaluates the potential of MP production in Iran and compares it with conventional protein sources, particularly crude protein supplied by imported soybean meal. Using IIASA– Shared Socio-Economic Pathways (SSP) population projections, annual waste streams and MP yields were estimated under three socioeconomic pathways (SSP1, SSP2, SSP5) for 2025–2050. Results indicate that wastewater-derived MP increases moderately with population growth, reaching 1.59–1.62 × 106 tons by 2050, while crude protein supplied by imported soybean meal-based protein supply ranges from 6.0 to 8.27 × 106 tons. Recovered nitrogen from wastewater could therefore replace approximately 20–27% of crude protein supplied by imported soybean meal demand, with food waste–derived MP contributing an additional 3–5%. The combined substitution potential of 23–32% suggests that integrating nitrogen recovery from wastewater and food waste into a circular bioeconomy framework could reduce dependence on crude protein supplied by imported soybean meal, improve resource efficiency, and enhance long-term protein resilience.

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INTRODUCTION

The growing global population, combined with accelerating urbanization and climate change, has placed unprecedented pressure on natural resources, particularly water, land, and food systems (Hajer et al., 2016). In many regions, these pressures are compounded by environmental degradation, limited arable land, and increasing dependence on food imports (Gomiero, 2016). A key challenge in this context is ensuring long-term food and nutrition security while minimizing ecological footprints and enhancing resource efficiency (Wang et al., 2011). Additionally, agriculture accounts for approximately 70% of global freshwater withdrawals, while food systems contribute over 34% of global greenhouse gas emissions (Crippa et al. 2021). In low-income regions, dependency on food imports has increased by over 80% since 1995, raising concerns about the vulnerability of food systems to market volatility and geopolitical risks (Paterson, 2024). Addressing these interlinked challenges requires integrated strategies, such as shifting toward circular food systems, adopting climate-resilient crops, reducing post-harvest losses, and promoting sustainable intensification that improves yields while preserving ecosystems (Pretty et al., 2018).

In response to these pressures, alternative protein sources have gained increasing attention as a means to reduce the environmental impacts of conventional animal-based protein production. These alternatives include plant-based proteins, insect-derived protein, cultured (cell-based) meat, and microbial protein (MP) (Mehrotra, 2025). Plant-based proteins, derived from crops such as legumes and cereals, generally have lower greenhouse gas emissions and land use requirements but remain constrained by agricultural inputs such as water, fertilizers, and arable land (Detzel et al., 2022). Insect protein offers high feed conversion efficiency and nutritional value, yet faces barriers related to large-scale production, regulatory frameworks, and consumer acceptance (Veldkamp et al., 2022). Cultured meat technologies show long-term promise but are currently limited by high energy demand, technological complexity, and economic feasibility (Treich, 2021). Within this spectrum, MP has emerged as a particularly attractive option due to its high productivity, minimal land use, scalability, and ability to utilize non-food substrates, including waste-derived nutrients.

In traditional waste management approaches, nitrogen present in various feedstocks (e.g. municipal wastewater, agricultural residues, and manure) is typically treated as a pollutant to be removed or disposed of, due to its contribution to environmental issues like eutrophication (Usman et al., 2022). However, within the framework of the circular economy and sustainable resource management, there is a growing shift toward viewing nitrogen as a valuable resource. Instead of eliminating it, nitrogen can be recovered from these waste streams and reintegrated into productive systems such as agriculture (Onukwulu et al., 2022). One promising application of this approach is the recovery of nitrogen from waste for the production of MP. By cultivating specific microorganisms on nitrogen-rich waste streams, it is possible to generate protein-rich biomass, which can serve as an alternative or supplementary source of protein, particularly for animal feed (Yang et al., 2021). MP offers several advantages over conventional protein sources. It can be produced rapidly using minimal land and water, and it is not subject to the same climatic and seasonal limitations as traditional agriculture. Various types of microorganisms (including bacteria, algae, fungi, and yeasts) can be cultivated on waste-derived substrates, such as nitrogen-rich wastewater, agricultural effluents, or industrial byproducts. The resulting biomass is typically high in protein and other valuable nutrients, making it a promising ingredient for sustainable animal feed formulations (Greses et al., 2024).

Iran, as a water-stressed and food-import-dependent country, stands to benefit significantly from innovations in circular nutrient management. Despite generating substantial quantities of wastewater, the country still underutilizes its potential for nutrient recovery and resource valorization. This gap is especially concerning in light of Iran's growing population, rising demand for dietary protein, and exposure to global agricultural market instabilities. Within this context, nitrogen recovery from diverse waste streams and its bioconversion into MP offers a promising opportunity to enhance national food security while mitigating environmental impacts such as eutrophication and greenhouse gas emissions (Matassa et al., 2016). Although several pilot-scale attempts have explored nitrogen recovery or MP production in Iran and parts of the Middle East, these efforts have remained experimental and have not progressed to national-scale assessments (Nasseri et al., 2011; Wada et al., 2023). Importantly, no study has quantified how much of a country's protein demand could realistically be supplied through waste-management-based nitrogen-to-protein pathways.

This study aims to provide a quantitative, national-scale assessment of Iran's potential for converting waste-derived nitrogen into MP. Specifically, it (i) estimates the annual recoverable nitrogen from wastewater and food waste under three future population Shared Socioeconomic Pathways (SSP1, SSP2, SSP5), (ii) converts these nitrogen flows into potential MP yields using established microbial conversion factors, and (iii) compares the resulting MP supply with the crude protein currently obtained from imported soybean meal. By aligning these estimates with projected demographic trends, the study delivers the first systematic evaluation of how waste-derived protein could contribute to Iran's future protein balance and reduce dependency on external feed sources. Beyond the quantitative assessment, the study discusses the strategic implications of integrating nitrogen recovery into national circular-economy and food-security planning.

MATERIALS AND METHODS

Potential Assessment Approach

Potential assessment refers to the theoretical quantification of a system's capacity or yield under defined assumptions and model parameters, rather than direct measurement or pilot-scale observation (Erakca et al., 2024). This method allows the estimation of maximum achievable outputs based on available data, conversion factors, and representative efficiencies reported in the literature (Hasanpour Kashani & Dinpashoh, 2012). By combining demographic projections, waste generation rates, and nitrogen-to-protein conversion coefficients, the study evaluates the potential MP yield that could be obtained without assuming 100% nitrogen recovery but instead applying published recovery efficiencies for wastewater and food waste systems. The results therefore represent an upper-limit estimate of feasible protein recovery under idealized or optimized conditions, providing a benchmark for future experimental and technological evaluations. The variation in total annual waste across SSP1, SSP2, and SSP5 in analyis derives from differences in projected population size and composition rather than assumed changes in per-capita generation.

Population and waste projections

Iran has a population of roughly 87 million (2023 estimate) and is experiencing ongoing urbanization, with more than 75 % of its people living in cities. Rapid population growth in the past decades, coupled with uneven water distribution and recurrent droughts, places significant pressure on water resources and municipal infrastructure (Saatsaz, 2020). These characteristics make Iran an important case study for assessing future waste generation under different demographic and socioeconomic pathways. Population projections for Iran were sourced from the International Institute for Applied Systems Analysis (IIASA) Shared Socioeconomic Pathways (SSP) database derived from the IMAGE Integrated Assessment Model (IAM) (Stehfest et al., 2014), which provides global demographic and economic outlooks under five alternative development trajectories. For this analysis, we selected three contrasting pathways—SSP1 (Sustainability), SSP2 (Middle of the Road), and SSP5 (Fossil-fueled Development)—to capture a plausible range of population growth and sustainability outcomes for the period 2030–2050.

Annual municipal wastewater generation was estimated using United Nations Sustainable Development Goals (UN SDG) global database records. According to the 2022 SDG data, Iran produced approximately 3,893 million cubic meters of municipal wastewater. Using the country's official 2020 population statistics, this corresponds to an average per-capita annual generation rate of 44.75 m^3 $person^{-1}$ $year^{-1}$ (SDG, 2022). The average municipal solid waste (MSW) generation rate in Iran was estimated at 260.49 kg per person per year, with an average food waste of 70.73% (Esmaeilizadeh et al., 2020; Golhosseini & Ghazizade, 2024; Heidari-Maleni et al., 2023). For future projections, this per-capita coefficient was applied as a constant across the selected SSP population scenarios to calculate the total wastewater and food waste volumes expected under each pathway. This approach provides a transparent, reproducible basis for estimating waste trends aligned with Iran's demographic outlooks.

Nitrogen load estimation

To estimate the annual total nitrogen (TN) load in wastewater under each SSP scenario from 2030 to 2050, a consistent TN concentration of 43.47 mg/L was applied. This value was derived as the average TN input concentration based on reported data from various wastewater treatment plants (WWTPs) across Iran, including multiple entries from Tehran, Kerman, Zabol, and other national facilities. Based on values reported in the literature, the total nitrogen (TN) content of food waste is typically around 6 g TN per kg of food waste (Heikkilä et al., 2016; Moonsamy et al., 2024).

Nitrogen Recovery System

The HBI system is an innovative approach developed to produce MP from municipal wastewater (Yang et al., 2022). In the HBI setup, wastewater undergoes primary treatment before being introduced into the bioelectrochemical system. In the anode chamber, organic matter is oxidized by exoelectrogenic microorganisms, releasing electrons and protons. These electrons travel through an external circuit to the cathode, where water electrolysis generates hydrogen gas (H_2). This hydrogen serves as an energy source for hydrogen-oxidizing bacteria (HOB) in the cathode chamber, which assimilate nitrogen and carbon dioxide to form microbial biomass rich in protein. The transfer of nitrogen from the anode to the cathode is facilitated by the energy generated from the oxidation of organic compounds in wastewater. The cell dry weight (CDW) of the produced biomass, containing approximately 64.79% crude protein. The potential annual MP yield was estimated based on the total nitrogen (TN) load calculated for each SSP scenario. To translate TN into microbial biomass, we applied a conversion factor of 8.64 ton of MP per ton of TN, consistent with previous studies that examined microbial conversion efficiencies using hydrogen-oxidizing (Yang et al., 2022). The waste enters the nitrogen recovery systems. The conversion factors applied in the nitrogen recovery system are based on laboratory-scale experimental data generated within an ongoing research program at the Technical University of Denmark (DTU), where the process is currently being scaled up toward pilot-scale operation.

The bioelectrochemical system (BES) represents an emerging and sustainable technology designed to convert food waste into MP while simultaneously recovering nutrients and reducing organic pollution (Das, 2024). Nitrogen cycling in the BES involves both ammonium recovery and assimilation. During the hydrolysis and fermentation of food waste, proteins and amino acids are mineralized to ammonium (NH_4^+). Instead of being lost via nitrification-denitrification, this ammonium can migrate through the ion-exchange membrane and be directly incorporated into microbial cells at the cathode. The recoverable ammonium–nitrogen (NH_4-N) from food waste was estimated as 74.71% × 0.92 × 83.7% of the total nitrogen (TN), representing the fraction of nitrogen hydrolyzed, retained, and mineralized during pretreatment and hydrolysis stages (Singh et al., 2024). Because these efficiencies originate from laboratory-scale systems, extrapolating them to national scale introduces uncertainty; therefore, the results should be interpreted as upper-limit potentials rather than realizable near-term outputs.

Avoided crude protein supplied by imported soybean meal

To assess the potential contribution of MP to Iran's protein supply chain, we compared the estimated annual MP yield with the protein content supplied by crude protein supplied by imported soybean meal, which currently represents a major source of animal feed protein in Iran. Substitution estimates reflect only crude-protein mass; therefore, the results indicate protein-equivalent substitution rather than nutritional equivalence. According to FAO and national agricultural statistics, Iran's annual crude protein supplied by imported soybean meal meal consumption ranges between 1.2 to 6.2 million tons (FAO, 2022), with an average protein content of approximately 43% (Banaszkiewicz, 2011). This comparison provides context for evaluating MP as a partial substitute or complementary source in domestic feed or food systems.

RESULTS AND DISCUSSION

Projected Population Dynamics of Iran

Figure 1 illustrates the historical and projected population trends of Iran from 2010 to 2050 under three SSP (SSP1, SSP2, and SSP5). The data show a consistent historical growth from approximately 75.4 million in 2010 to 87.9 million in 2020, representing the observed demographic expansion before scenario divergence. From 2020 onwards, projections diverge slightly among the three SSPs. Under SSP1, population growth slows moderately, reaching about 101.5 million by 2050, reflecting lower fertility rates and sustainability-oriented development. SSP2 projects a somewhat higher value of 102.6 million, indicating continuation of current demographic trends. SSP5 yields the highest population estimate, around 103.7 million by 2050, due to higher economic growth and slightly elevated fertility assumptions. Overall, despite minor variations across scenarios, all pathways indicate that Iran's population will stabilize near 100 million by mid-century, suggesting a demographic plateau that could significantly influence future food and protein demand, as well as waste generation potential relevant to nitrogen recovery assessments.

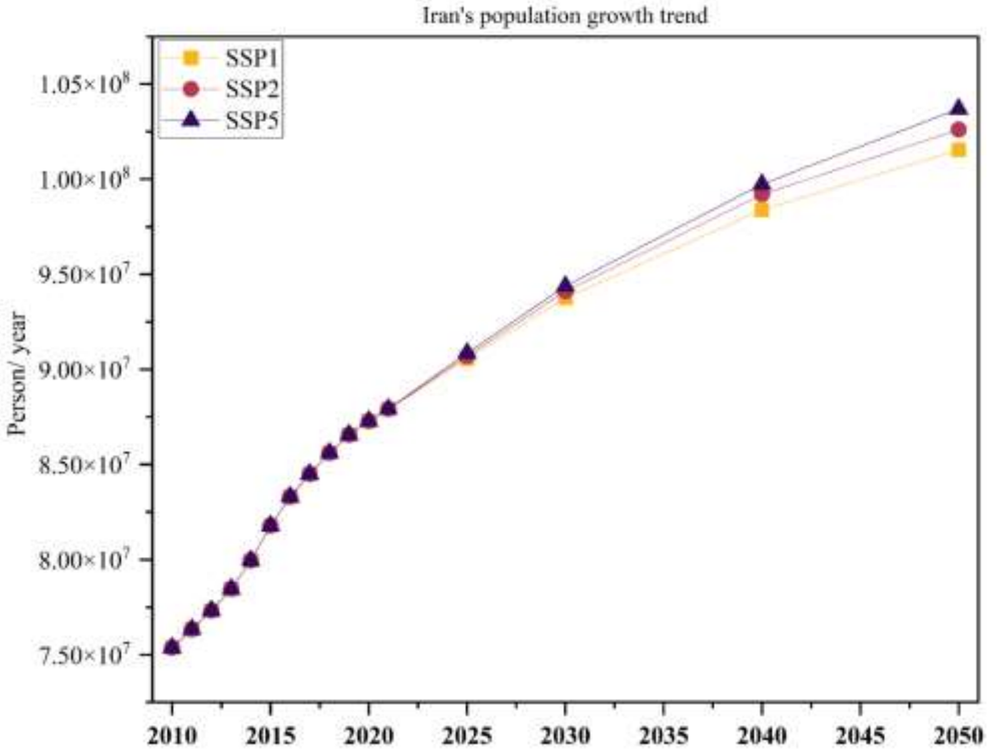

Figure 1. Projected population trends in Iran under SSP1, SSP2, and SSP5 scenarios (2010–2050).

Protein Potential from Waste-Derived Nitrogen

Figure 2 presents the temporal comparison between the projected MP yield derived from nitrogen recovery in wastewater and the crude protein supplied by imported soybean meal supply for Iran under the SSP1, SSP2, and SSP5 scenarios from 2010 to 2050. The MP potential follows a gradual but steady increase across all scenarios, directly driven by population growth and corresponding wastewater generation rates. In contrast, crude protein supplied by imported soybean meal shows a sharper increase, reflecting agricultural expansion and import-based supply dynamics captured by the IMAGE model. From 2010 to 2020, MP production remains almost constant at around 1.18–1.36×10^6 tons, while crude protein supplied by imported soybean meal ranges between 1.2–2.1×10^6 tons. The two trajectories diverge more noticeably after 2025, when agricultural productivity and demand acceleration cause crude protein supplied by imported soybean meal projections to grow faster than MP yields. By 2050, MP production is estimated to reach approximately 1.59×10^6 tons (SSP1), 1.60×10^6 tons (SSP2), and 1.62×10^6 tons (SSP5), whereas crude protein supplied by imported soybean meal availability rises to 6.00×10^6, 6.92×10^6, and 8.27×10^6 tons, respectively.

Overall, MP recovered from wastewater nitrogen could theoretically substitute between 20% and 27% of the crude protein supplied by imported soybean meal supply by 2050, depending on the socioeconomic pathway. Under the sustainability-oriented SSP1, the substitution potential reaches ≈26.5%, while in the high-growth SSP5 pathway, despite higher absolute MP output, the larger crude protein supplied by imported soybean meal base reduces the relative share to ≈19.6%. These results suggest that even under optimistic demographic and technological assumptions, wastewater-based nitrogen recovery could offset one-fifth to one-quarter of national crude protein supplied by imported soybean meal demand, significantly reducing reliance on imported plant protein sources and contributing to Iran's long-term protein security and circular bioeconomy strategies. This stronger growth in soybean-meal-derived protein supply reflects the IMAGE model's assumptions regarding livestock-sector intensification, rising animal-protein consumption, and increased reliance on imported feed, which together expand feed-protein demand at a rate exceeding population growth.

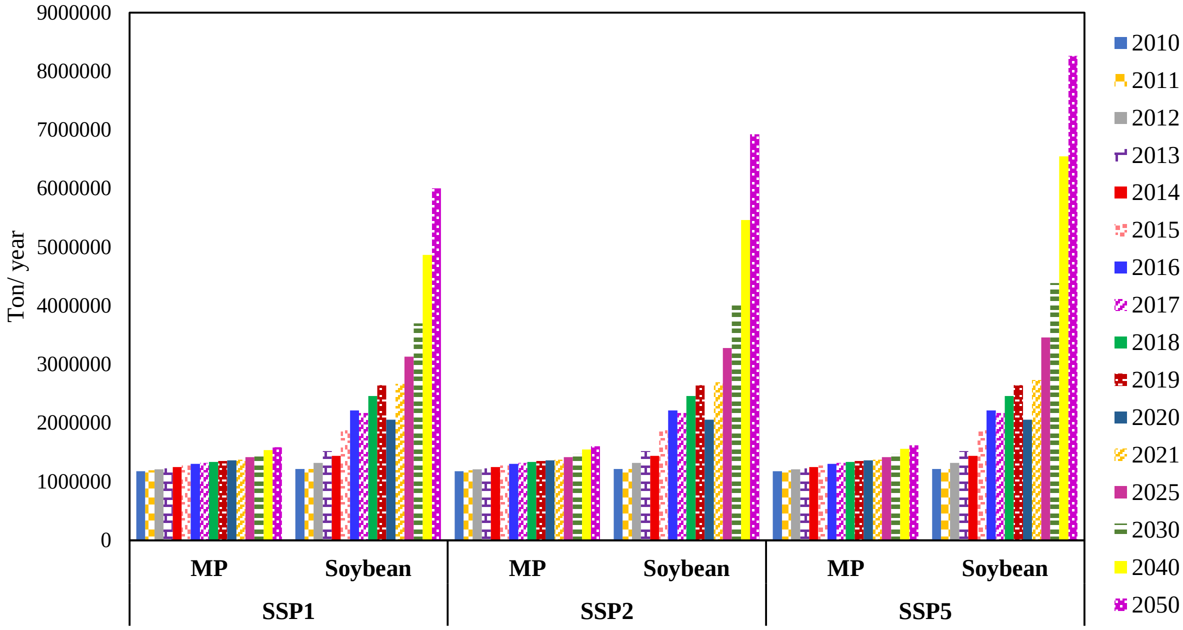

Figure 2. Comparison of estimated MP production from wastewater nitrogen recovery and crude protein supplied by imported soybean meal supply in Iran under SSP1, SSP2, and SSP5 scenarios.

Figure 3 illustrates the projected evolution of MP generation derived from nitrogen recovery in food waste in comparison with crude protein supplied by imported soybean meal availability in Iran across three SSP pathways between 2010 and 2050. The simulated MP potential exhibits a continuous but moderate increase over time, largely reflecting population growth and the consequent expansion of municipal solid waste production. During the period 2010–2020, the estimated MP yield remains relatively stable, ranging between 2.0×10^5 and 2.3×10^5 tons, while crude protein supplied by imported soybean meal fluctuates from 1.2×10^6 to 2.1×10^6 tons. After 2025, both trajectories begin to diverge more noticeably. The crude protein supplied by imported soybean meal curve accelerates more sharply, consistent with higher consumption and production projections, whereas MP growth maintains a slower, linear trend linked to waste generation and nitrogen recovery efficiency. By 2050, total MP output from food waste is estimated to reach 2.72×10^5 tons under SSP1, 2.75×10^5 tons under SSP2, and 2.78×10^5 tons under SSP5, while the corresponding crude protein supplied by imported soybean meal availability reaches 6.00×10^6, 6.92×10^6, and 8.27×10^6 tons, respectively.

Based on these estimates, MP obtained from food waste nitrogen could substitute approximately 3–5% of national crude protein supplied by imported soybean meal demand by 2050, depending on the socioeconomic pathway. The highest replacement potential (≈4.5%) occurs under the sustainability-oriented SSP1 scenario, whereas in the high-growth, resource-intensive SSP5, the relative share declines to around 3.4% due to the larger crude protein supplied by imported soybean meal base.

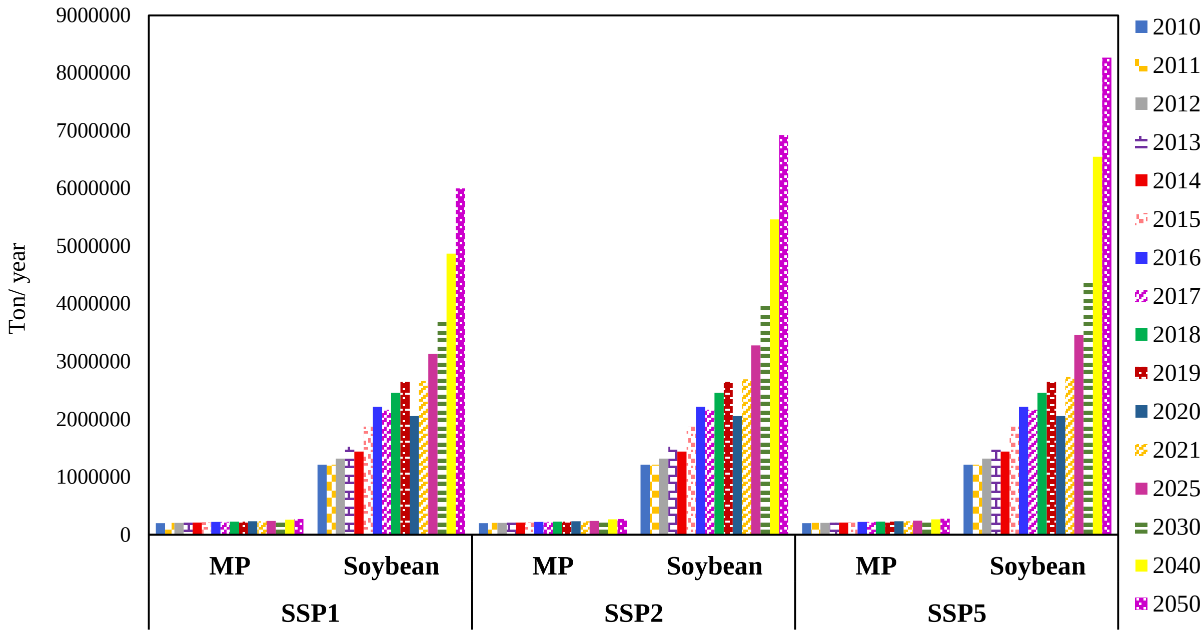

Figure 3. Comparison of estimated MP production from food waste nitrogen recovery and crude protein supplied by imported soybean meal supply in Iran under SSP1, SSP2, and SSP5 scenarios.

Altogether, these two urban waste streams could collectively offset approximately 23–32% of Iran's crude protein supplied by imported soybean meal requirement by mid-century, depending on the socioeconomic trajectory (SSP1–SSP5). These finding highlights that although current waste-derived nitrogen recovery technologies alone cannot fully replace conventional protein sources, they represent a significant complementary pathway toward national protein security. By integrating both wastewater and solid waste valorization into a unified circular bioeconomy framework, Iran could substantially reduce its dependency on crude protein supplied by imported soybean meal, lower nutrient losses, and enhance environmental sustainability through nitrogen recycling.

However, given that nearly two-thirds of national organic nitrogen remains embedded in other underutilized waste streams (such as livestock manure, agricultural residues, and food processing by-products) future strategies should aim to expand nitrogen recovery beyond municipal sources. For context, studies in comparable agricultural systems indicate that livestock manure contains 3–5 times more recoverable nitrogen than municipal wastewater (Ohimain, 2025), suggesting that inclusion of agricultural residues and manure could significantly expand the total theoretical nitrogen-recovery potential.

Discussion and future projection

The demographic projections presented in this study jointly highlight the emerging role of wastewater-derived MP as a complementary protein source in Iran's future food system. This demographic plateau creates a strategic window for enhancing resource efficiency and developing alternative protein systems such as MP production from nitrogen recovery. These findings emphasize the importance of integrating demographic foresight into circular bioeconomy planning (Schipfer et al., 2024). The coupling of population growth, urban wastewater generation, and nutrient recovery potential suggests that urban centers (particularly Tehran, Isfahan, and Mashhad) could become key hubs for sustainable protein production. Beyond mitigating nutrient losses, nitrogen recovery systems provide environmental co-benefits, including reduced eutrophication, lower greenhouse gas emissions, and decreased dependence on agricultural imports (Andersen & Bonnis, 2021). In a broader context, the ability to convert waste-derived nitrogen into high-quality MP can partially decouple Iran's protein security from agricultural constraints such as water scarcity, land degradation, and climate-induced yield instability. It is important to emphasize that the substitution percentages reported in this study are quantitative and based solely on crude protein mass. Microbial protein differs from soybean meal in amino-acid composition, digestibility, and the presence of anti-nutritional factors, meaning that functional or nutritional equivalence cannot be assumed. Therefore, the reported substitution values should be interpreted as mass-based offsets. While the substitution potential of one-fifth to one-quarter of crude protein supplied by imported soybean meal may not fully satisfy future protein requirements, it represents a meaningful complementary contribution within a diversified and resilient food system. Continued investment in nitrogen recovery technologies, coupled with supportive regulatory frameworks and public acceptance, could thus enhance transition toward a circular, low-emission protein economy (Shahzad et al., 2024). However, realizing this potential requires overcoming several challenges, including the absence of clear regulatory pathways for wastewater-derived protein products and stringent safety requirements regarding contaminants, as well as public perception barriers linked to the waste-origin of such proteins. Addressing these issues through transparent safety assessment, certification, and communication strategies will be essential for broader societal acceptance.

CONCLUSIONS

The findings of this study demonstrate that nitrogen recovery from wastewater and food waste can serve as a significant complementary pathway for sustainable protein production in Iran. While wastewater-based MP could replace up to 27% of crude protein supplied by imported soybean meal demand, food waste-derived MP accounts for an additional 5%. Together, these waste streams could supply nearly one-third of the crude protein currently supplied by imported soybean meal by 2050. However, since a large share of organic nitrogen remains in underutilized streams such as livestock manure, agricultural residues, and food processing by-products, future strategies should aim to integrate these sources into microbial or biotechnological conversion systems. Expanding nitrogen recovery beyond municipal waste could further enhance Iran's protein self-sufficiency, reduce dependency on imports, and contribute to circular economy and climate mitigation goals.

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