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Multicriteria Suitability Index for Prioritizing Early-Stage Deployments of Wastewater-Derived Fertilizers in Sub-Saharan Africa

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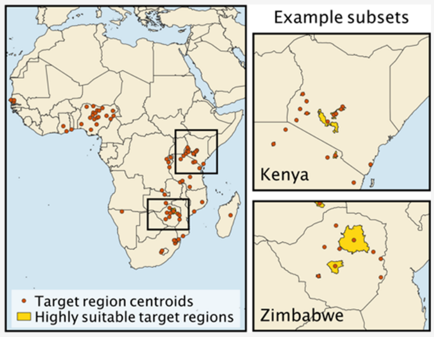
ABSTRACT: Recycling nutrients from wastewater could simultaneously decrease the carbon intensity of traditional ammonia supply chains and increase the accessibility of local fertilizer. Despite the theoretical potential, techno-economic viability of wastewater nutrient recovery in sub-Saharan Africa has been poorly characterized at subnational scales. This work proposes a multicriteria suitability index to describe techno-economic viability of wastewater-derived fertilizer technologies with district-scale resolution. This index, with a range from 0 to 1 (highest suitability), incorporates key drivers, including population density, soil conditions, sanitation levels, and fertilizer prices. We found that suitability varies widely within and across countries in sub-Saharan Africa and that the primary limiting factor is the absence of sanitation infrastructure. Regions with a minimum of 10% cropland area and a suitability index of at least 0.9 were identified as highly suitable target regions for initial deployment. While they comprise only 1% of the analyzed area, these regions are home to 39 million people and contain up to 3.7 million hectares of cropland. Wastewater-derived fertilizer technologies could deliver an average of 25 kg of nitrogen per hectare of cropland, generating additional food equivalent to the annual consumption of 6 million people. Screening for high suitability can inform selection of effective lighthouse demonstration sites that derisk technology deployment and promote the transition to a more circular nutrient economy.



KEYWORDS: *nitrogen recovery, sanitation, pollution, sustainable development, food security, lighthouse demonstrations*

1. INTRODUCTION

While the global ammonia market is expected to increase at a rate of 6.4% per year in the next decade to meet the demands of a growing population, accessibility to synthetic nitrogen fertilizers for agriculture varies widely and remains critically low in sub-Saharan Africa.[1−4] Fertilizer application rates in sub-Saharan Africa are 6.5 times lower than the global average, primarily due to high imported fertilizer prices and transportation costs associated with long transport distances between ports and fields.[5,6] Political instability and conflict can also contribute to fertilizer inaccessibility and price spikes through supply chain disruptions.[7,8] Nitrogen is often the primary limiting nutrient in agricultural production and is critical for improving low-yielding cereal systems in sub-Saharan Africa.[8−10] Reported ecological yield gaps are considerable and estimated to be 7800 and 10,200 kg of rainfed maize per harvested hectare in Kenya and Zambia, respectively.[11] Increasing local fertilizer accessibility would improve food security for the estimated 70% of the population in sub-Saharan Africa experiencing moderate-to-severe food insecurity.[12−15]

The Haber−Bosch process is currently used to produce most inorganic nitrogen in fertilizers. While pivotal to revolutionizing agricultural production in the past century, the Haber−Bosch process is energy and carbon-intensive—accounting for 1.2% of the world's annual anthropogenic CO_2 emissions.[16] In addition, around 90% of countries in Africa are net importers of synthetic nitrogen fertilizers, and as a result, are sensitive to supply chain shocks that impact food security.[17] Nevertheless, the urgent need to increase crop productivity across the region has driven major efforts to increase fertilizer accessibility through fertilizer subsidy programs (e.g., Malawi, Zambia, and Tanzania) and improved fertilizer management practices.[6,12,13,18,19]

An alternative approach is to pursue nutrient recovery from urine, wastewater, or polluted waters. Local recovery of nitrogen using waste streams decreases reliance on carbon feedstocks, which are vulnerable to global supply chain volatility, while also decreasing nutrient pollution in the environment.[6,20,21] Production and reuse of nutrients locally can increase resilience to imported fertilizer and natural gas shortages and decrease prohibitively high transportation

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costs.[17] A significant potential cobenefit of this approach is improved sanitation coverage through increased adoption of distributed collection systems. These distributed collection systems are promising alternatives to centralized systems in regions where sanitation infrastructure is limited and capital costs for installing new piped sewer systems are cost-prohibitive.[21,22] While the product costs of nitrogen fertilizer from early-stage technologies may be more expensive than those of traditional industrial ammonia production, lower carbon emissions, and decreased transportation costs may lead to an overall net benefit. Identifying opportunities with high techno-economic viability for initial deployment and continued technological development may facilitate future deployments at scale and reduce product costs.

Technologies to cost-effectively realize local production of fertilizers from source-separated urine and other wastewater streams are rapidly advancing. Processes such as ion exchange, ammonia stripping, biological nitrification, and electrochemical systems have made nutrient recovery from urine, which contains the majority of excreted nitrogen, a viable technology.[21,23−25] Ammonia stripping is most feasible for large-scale applications, while ion exchange requires resin regeneration materials that may face accessibility challenges similar to imported fertilizers.[24] Electrochemical systems are feasible for small-scale and distributed systems and could be integrated with renewable energy sources such as solar but are still in the early stages of development.[24]

Tarpeh et al.[21] successfully demonstrated the production of ammonium sulfate fertilizer from urine at $0.85/kg nitrogen (N) from an ion exchange pilot installation in Kenya. Compared to the reported government subsidized prices for fertilizers, such as urea ($4.29/kg of N), local nutrient recovery may become cost-effective in these scenarios, but longer-term studies are still needed. Larsen et al.[24] further expands upon the current state-of-the-art nitrogen recovery technologies for urine, highlighting adsorption and electrochemical processes as active areas of research that have made significant progress in the past decade. Many of these technologies are reported to be nearing industrial optimization, and local nutrient recovery is recommended to reduce transport costs.[24] While cost-effective technology innovations for nutrient recovery continue to be developed, the maturity of all these technologies is largely still at the pilot-scale stage and has not yet been deployed at scale in sub-Saharan Africa.[26,27]

While there is no single pathway for moving technologies from the laboratory to the mainstream, many technology transitions have included lighthouse deployments, which act as leaders and guides for driving innovation adoption, across diverse socio-technical and economic settings.[28] In particular, taking a spatial approach to assessing sustainable technology transitions is critical due to the uneven geographical landscape of technological change and the impact of site-specific interactions.[29] Regardless of the ultimate nitrogen recovery technology, early-stage demonstration and deployment in favorable markets are necessary for establishing an initial understanding of the limiting factors and key techno-economic criteria that may constrain feasibility. The issue is that identifying these markets is challenging, considering the various factors that may determine successful adoption. As a result, characterizing and spatially integrating key factors can facilitate the identification of these favorable first markets.

Generally, small-scale and distributed nutrient recovery technology is expected to be most economically feasible in regions like sub-Saharan Africa where fertilizer prices can be two to three times greater than in the U.S., and production is limited by accessibility of raw input materials (e.g., methane feedstocks).[3,12,17] Distributed systems are also not reliant on the existing infrastructure and are advantageous for reducing fixed infrastructure costs. Across this vast region, however, there are few tools for identifying specific locations with key factors such as high fertilizer prices, agronomically suitable soils, and a high density of sanitation infrastructure for wastewater collection. Prior assessments in sub-Saharan Africa have identified fertilizer prices, farmer profitability, soil-fertilizer constraints, and urban-cropland proximity as major constraining factors either for nutrient accessibility or potential recovery and application.[30−32] Other studies have established viability of ion exchange wastewater nutrient recovery for local case studies and assessed general nutrient recovery potential for several highly populated cities.[21,32] Those examining suitability across larger areas typically focus on the spatial distribution of individual criteria, such as soil suitability or colocation of population and cropland, but do not account for other pertinent factors such as variability in sanitation coverage.[31,33]

Scaling technically detailed suitability analysis to broader regions is essential to supporting early technology implementation. Multicriteria assessments are needed over regional extents to capture geographic variability but must also be resolved at local scales to ensure operational feasibility. The current work proposes a simple yet flexible framework for informing the targeted deployment of local wastewater nutrient recovery technologies. We leverage recent subcountry data sets to study suitability across thousands of districts in sub-Saharan Africa and consider multiple feasibility criteria by calculating an integrated suitability index. Our study aims to demonstrate the heterogeneity of suitability at subnational scales, characterize the main drivers that constrain suitable areas, identify promising target regions for initial deployment, and quantify nutrient recovery potential.

2. METHODS

This section describes the data sets used (Section 2.1), the formulation of the suitability index (Section 2.2), the thresholds determined for each of the suitability parameters (Section 2.3), and the screening analysis used to determine the relative contribution of each parameter toward determining suitability (Section 2.4).

2.1. Data Sets. Various subnational data sets in sub-Saharan Africa were used to determine district-level techno-economic suitability and nutrient recovery potential. Detailed descriptions of each data set and subsequent processing are included in the Supporting Information (SI Section 1.1).

2.1.1. Administrative Boundaries. Administrative-level 2 boundaries (Admin2, districts) were the smallest units available for the entire study region and were used in this analysis as the basis of our suitability calculations. We considered the district level to be sufficiently spatially resolved and easily identifiable for the local targeting, recovery, and reuse of nutrients. For instance, discussions with local truck-serviced sanitation companies revealed that they typically operate within a single district because of the high transportation costs of serving larger areas.

2.1.2. Cropland, Population, Sanitation, and Fertilizer Economics. Two recent worldwide data sets were used to calculate cropland within the districts: European Space Agency

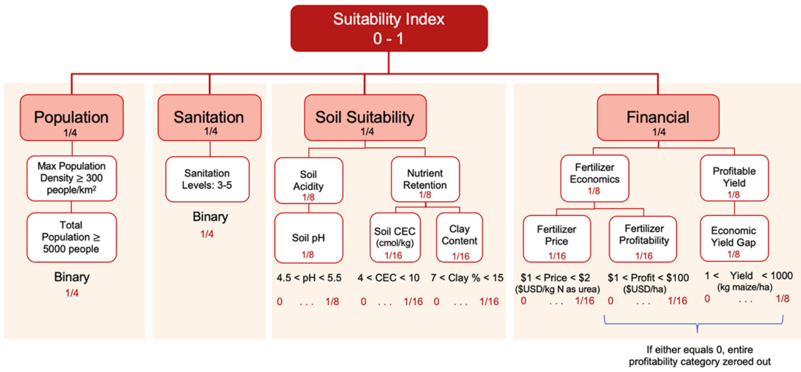

Figure 1. Suitability index weighting and calculations. The main categories are population (population density and total population), sanitation levels, soil characteristics (soil pH, soil CEC, and clay content), and financial parameters (fertilizer price, fertilizer profitability, and economic yield gap). Our analysis equally weights all four categories equally to ensure full transparency in their respective contributions. However, this can be tailored in subsequent assessments of specific regions based on local information. Sensitivity analysis on alternative thresholds and weights are included in the Supporting Information (SI Figures 1 and 3).

(ESA) World Cover 2020[34] and Environmental Systems Research Institute (ESRI) 2020 Land Cover.[35] To account for uncertainties from individual crop masks, both data sets were used to provide a range of estimated cropland area.

We also computed population metrics and sanitation coverage quality over each district.[36,37] Soil characteristics (soil pH, cation exchange capacity (CEC), and clay content) were extracted over cropland areas.[31] Last, we account for fertilizer economics and potential yield by including fertilizer price, profitability, and economic yield gap data across sub-Saharan Africa.[30]

2.1.3. Nitrogen Recovery and Potential People Fed. Using the most recent FAO (Food and Agriculture Organization of the United Nations) protein supply per capita by country[38] and Trimmer and Guest[32] methods for determining total nitrogen supply, we calculated the potential nitrogen recovered based on population totals within each Admin2 region (detailed descriptions in SI Section 1.1). To account for how much recovered nitrogen could then be taken up by crops after field fertilizer application, we incorporated estimates of the nitrogen use efficiency (NUE). Then, using methods from Rosa and Gabrielli,[17] we estimated the additional people that could be fed from the additional fertilizer availability through calculations of nitrogen recovered and per capita nitrogen consumed. We also computed the fraction of the population that could be fed from recovered nutrients to assess the potential for self-sufficient and local food production. While we compute the potential additional people fed as a metric to contextualize the regional nitrogen recovery potential, the additional food generated from the increased production could be used to improve the existing population's diet, which is particularly relevant in sub-Saharan Africa, where high levels of food insecurity are a critical concern.

2.2. Suitability Index. The computed suitability index in this study ranges from 0 to 1, with 1 considered the highest suitability. Suitability calculations incorporated equally weighted contributions from four main categories believed to drive nutrient recovery technology viability: local population levels, sanitation levels, soil suitability, and local agricultural and fertilizer economics (hereafter termed the financial category). Population and sanitation primarily relate to the resource and collection feasibility, whereas soil and fertilizer economics account for the agronomic suitability of the recovered fertilizer product and price competitiveness with traditional synthetic fertilizers. Detailed weighting and individual parameter contributions are shown in Figure 1.

The development of the suitability index stemmed from the need to capture diverse yet equally pertinent criteria for determining the suitability of nutrient recovery technology. We designed our index to be simple and interpretable, on a scale from 0 to 1, to ensure that the weighting and attribution of each criterion were transparent. We acknowledge that in local and regional contexts, some criteria may become more relevant than others, demonstrating the flexibility of this approach; each criterion can be easily adjusted to be weighted differently, providing tailored suitability assessments on a regional or technological basis. We assess the impact of each individual parameter on our suitability assessment in the Supporting Information (SI Figure 4).

While we have carefully incorporated key criteria with known thresholds that constrain the techno-economic suitability of nutrient recovery technologies, we acknowledge that this suitability index captures only a subset of the many potential factors that may influence suitability. For example, while cropland area or density is an important characteristic in ensuring that the produced fertilizer can be applied locally, there is no well-defined cutoff for a minimum cropland amount (either within the district or within some neighboring regional extent) where local nutrient recovery begins to be viable. To identify top target regions for initial deployment, we imposed a 10% cropland density filter to ensure that these identified areas had considerable local cropland. However, regions with lower cropland density or coverage may still have sufficient cropland or may be surrounded by nearby regions with high cropland coverage to be considered viable. These situations would thus be most suited to receiving subsequent input from local decision-makers once regions have been screened for the other criteria with known thresholds. As a result, this index is intended to be applied as an initial screening tool for identifying regions that meet major criteria, but subsequent country- or local-level assessments of techno-economic viability should still be implemented.

2.3. Selecting Thresholds. Thresholds for each parameter were required to assign relative parameter suitability scores before arriving at our final index (Figure 1). We chose thresholds that currently best fit the parameter type and context for our analysis but also conducted a sensitivity analysis to explore the impact of alternative thresholds (SI

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Figure 1). Additional details on specific threshold suitability calculations, rationale, and parameter threshold sensitivity are included in SI Section 1.2, along with maps of the spatial distribution of each parameter (SI Figure 2).

2.3.1. Population Density. While distributed nutrient recovery systems can operate on small scales and do not typically have a minimum population requirement, some level of infrastructure and density of people (e.g., peri-urban areas) are needed for sanitation collection to be viable on a local scale.

2.3.2. Sanitation Levels. Sanitation levels (defined in SI Section 1.1) between 3 and 5 were chosen to be considered suitable for the sanitation binary suitability variable. A sanitation level of 3 represents a basic level of collection, which is necessary for the initial deployment of nutrient recovery technology.

2.3.3. Soil Characteristics. Soil conditions are potentially important for determining the appropriateness of specific fertilizers retrieved from wastewater treatment.[31] Soil parameters were considered to have fuzzy logic relationships where the suitability would increase relative to certain parameter ranges. We based our soil suitability calculations on insights from Trimmer et al.[31] and also assumed that our fertilizer products are acidifying, which is a common property of most fertilizers used globally (e.g., urea, ammonium nitrate, ammonium sulfate).[39] We note that other nutrient recovery products that are alkaline, such as struvite or stored urine, may be considered as a potential alternative in regions where pH conditions for acidic products are not met.[31,40] Since struvite recovery may require more centralized facilities, stored urine may be more suited for decentralized systems. In addition to soil pH, we considered adequate soil nutrient retention as an important factor for deployment. Specifically, we used soil CEC and clay content to capture nutrient retention capabilities. Suitability function equations are included in the Supporting Information (SI eqs 1−6).

2.3.4. Financial (Agricultural and Fertilizer Economics). Financial viability was assessed through a combination of data on fertilizer price, profitability, and the potential economic yield gap. Average synthetic nitrogen fertilizer prices for each district were compared to wastewater-derived fertilizer prices to determine if nutrient recovery would be price competitive.[21,22] Since potential competitive prices could differ from the bounds used in our primary analysis, we conducted various threshold analyses of different suitable price ranges to assess these alternative scenarios (SI Figures 1 and 3).

Higher values of fertilizer profitability and economic yield gap as estimated by Bonilla-Cedrez et al.[30] were considered more suitable. Fertilizer profitability was defined as the maximum potential farmer-side profit under optimal fertilizer application conditions (estimated using the average of both empirical and mechanistic model approaches). Economic yield gap estimates identify the maximum potential additional yield under the profit-maximizing fertilizer application scenario compared with current yield levels.

2.4. Parameter Inclusion Analysis. We conducted a screening analysis to identify the relative contribution of each parameter to determining suitability. To do so, we screened out the contribution of each parameter to the suitability calculation and recalculated suitability such that fully suitable regions are still equal to 1. We then calculated the difference in suitable cropland area from our base case (no parameters screened out) to each of the screening scenarios. The observed difference represents the area no longer fully suitable as a result of the screened variable alone. This identifies the degree to which an individual variable restricts the suitable cropland area. Population and sanitation constraints were by far the most relevant parameters in determining suitable cropland area, with potential increases of over 200,000 km^2 of suitable cropland area when removing either parameter (SI Figure 4).

3. RESULTS

3.1. Spatial Heterogeneity within and across Countries in Sub-Saharan Africa. Our suitability estimates exhibit substantial spatial variation both within and between countries (Figure 2). We observe that regions with high suitability

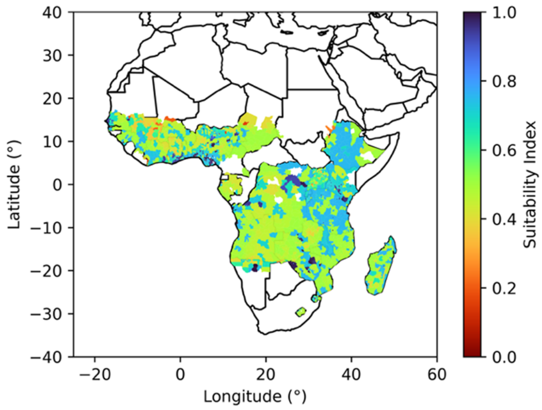

Figure 2. Total suitability map: suitability index (0−1) with 1 set to highest suitability. Suitability maps for each of the four categories (sanitation, population, soil, and financial) are included in SI Figure 5.

(suitability index ≥ 0.9) are present in multiple countries across Africa such as Kenya, Nigeria, and Zimbabwe. There is no single country where most of its area is highly suitable, demonstrating the value of conducting this analysis at a subnational level. A number of these highly suitable regions also share borders, highlighting the geospatial autocorrelation of the parameters of interest. Category-specific suitability maps are included in Figure 5.

To demonstrate both a cross-country and within-country comparison, Figure 3 illustrates subcountry variation in suitability indices for four different countries, with each dot representing one Admin2 region (SI Figure 12 contains all countries). We include these four countries as examples of the different types of variations in the distribution of suitability indices and the number of districts that can be observed at the country level. Kenya and Nigeria have a relatively large number of districts, with Nigeria having a larger number of districts in the 0.8 to 1.0 range compared to Kenya. Zimbabwe is an example of a country with a smaller overall number of districts but with some districts in the higher suitability range (0.8−1.0). In contrast, Uganda is an example that does not have a cluster of districts in the higher suitability range.

For targeted technology deployment, both country-level comparisons and regional assessments are essential for identifying regions with favorable levels of suitability. Assessing country-level distributions can also highlight what the current unmet criteria are for certain districts and the expected challenges they would need to address before nutrient recovery would be viable. For example, both Kenya and Nigeria have three large distinctive clusters, each cluster within the low,

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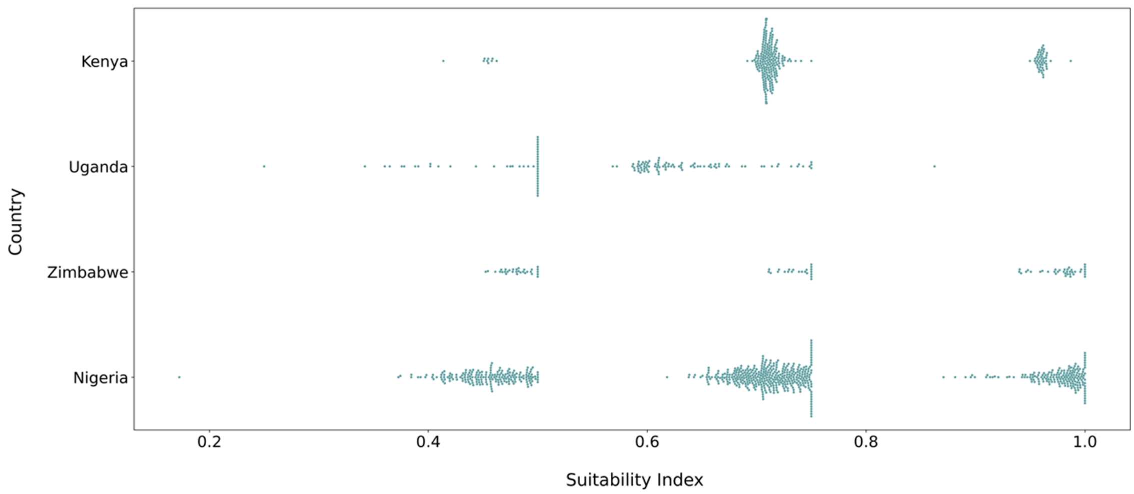

Figure 3. Range of Admin2 region suitability indices for four different countries. Each individual point in the figure represents one Admin2 region in its respective country.

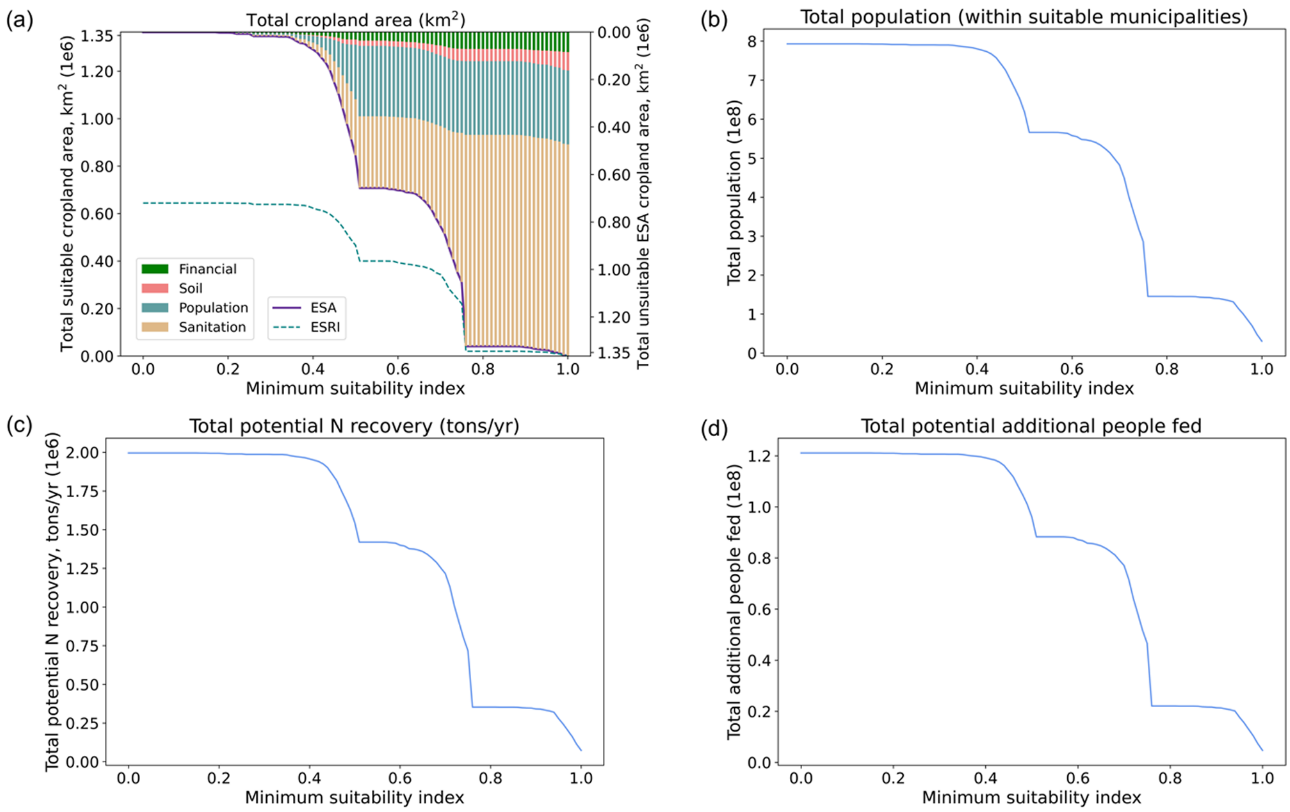

Figure 4. Resulting totals within suitable areas as a function of the minimum suitability threshold level used to define suitable regions. (a) Total cropland area, where the left *y*-axis corresponds to the line plots of total suitable cropland area (ESA and ESRI cropland estimates) and the right *y*-axis corresponds to the bars displaying the total unsuitable ESA cropland area that was filtered out, color coded by the categorical fraction that disqualified these areas (this fraction is district dependent and therefore the same for ESRI), (b) population, (c) estimated nutrient recovery, and (d) total additional people fed if all potential recovered nutrients were used for crop production.

medium, or high suitability index range. To assess what distinguishes these clusters from each other, we averaged the category-based suitability scores for each of the 3 main clusters. We found that the low-index cluster consisted primarily of regions that did not meet the sanitation and population criteria (the two most restrictive categories). The medium-index cluster primarily had regions where the sanitation criterion was not met. The high-index cluster had both population and sanitation criteria met along with most of the soil and financial criteria. These assessments highlight that for Kenya and Nigeria, increases in sanitation coverage in the districts in the middle cluster would increase this cluster's suitability to the high suitability range.

3.2. Higher Suitability Index Values Increasingly Constrain Suitable Areas. Since suitability is defined on a scale from 0 to 1, we can also examine in detail how total cropland within suitable regions changes as a function of the minimum suitability index threshold used to define suitable

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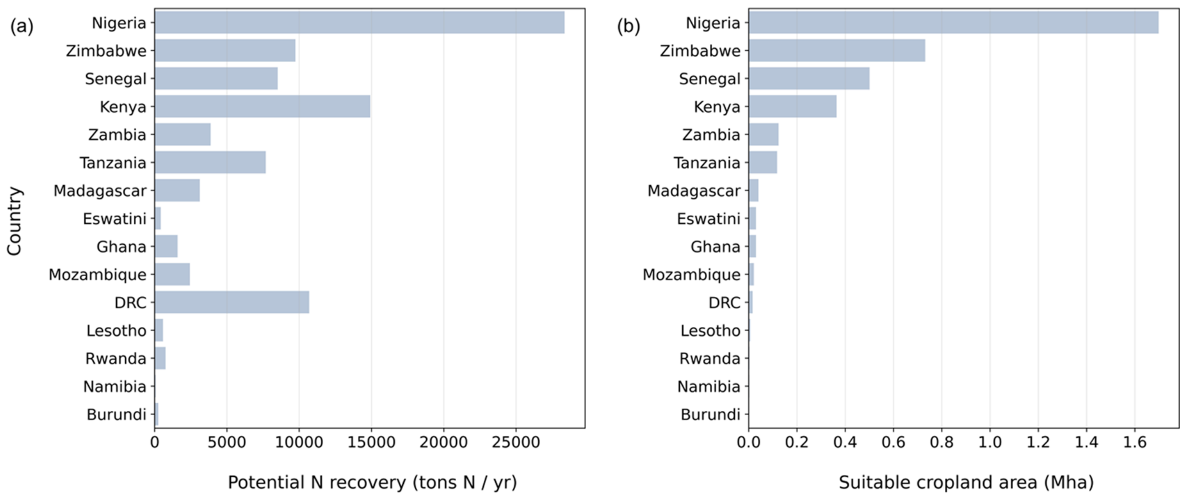

Figure 5. Country-level totals for highly suitable target regions. Highly suitable target regions were determined by selecting suitable regions (suitability index ≥ 0.9) that contained at least 10% cropland and aggregating any areas that shared a common border. (a) Total potential recovered nitrogen available within the target regions. (b) Corresponding total cropland area by country within these target regions.

areas (Figure 4). We can further calculate the total population, potential nitrogen recovery, and potential additional people fed within these suitable regions. Above suitability indices of 0.5, we observe notable declines in suitable areas as a result of the two most restrictive categories: population density and sanitation. When assessing the relationship between population density and sanitation levels, we do not observe a noticeable correlation (SI Figure 6). When examining changes in the 0.8−1.0 range, there are comparatively much smaller decreases, and a threshold choice within this range is expected to be relatively insensitive. Alternative threshold sensitivities as a function of the suitability index suggest that the largest influence on the suitable cropland area for higher suitability index thresholds (e.g., 0.9) is the sanitation criteria threshold (SI Figure 1). This finding highlights the considerable opportunity for significant increases in suitable regions, given that nutrient recovery and sanitation infrastructure could be implemented simultaneously within regions with low levels of sanitation.

3.3. Target Regions for Informed Initial Deployment.

Successful initial technology deployment is critical for future development and increased adoption. We further constrain our search criteria to include only highly suitable regions, which we defined as regions with a suitability index ≥ 0.9 and a cropland density of at least 10% (using the highest cropland area from ESA and ESRI cropland estimates). We select 0.9 as our threshold to ensure that all the main criteria and the first level of subcriteria in the current weighting scheme are nonzero to be considered suitable. Figure 4 allows further insight into how these restrictions impact suitable areas and can be useful for decision-makers to potentially define their own acceptable thresholds. We also note that as demonstrated in Figure 4a, we would not expect large changes in overall suitable cropland area from 0.8 to 0.9 as the curve is mostly flat in that region. The average area of these highly suitable regions was 760 km^2, which was well within a rough estimate of typical truck coverage for transporting waste, estimated at 2830 km^2 assuming a 30 km travel radius and circular coverage area.[21] To account for local movement of recovered fertilizer products within the highly suitable areas since there are many shared borders, we aggregated any bordering regions into contiguous subnational areas for further analysis. After performing the aggregation step on the 139 highly suitable Admin2 areas, we obtained a total of 72 target regions that are highly promising for initial technology deployment. Figure 5 demonstrates, on a country-level basis, the relationship between the total potential N recovered per year within the highly suitable target regions and the available cropland area within each respective region. Note that not all countries contained highly suitable target regions and thus were not included in Figure 5. We observe that Nigeria and Zimbabwe contain over half of the highly suitable cropland area and that five countries—Nigeria, Zimbabwe, Senegal, Kenya, and Zambia—contain over 90% of the total highly suitable cropland area (Figure 5b).

3.4. Recovered Nutrient Potential in Target Regions.

Within these 72 target regions, the resulting potential fertilizer application rate, when weighted by total cropland area in each region, is 25 kg of nitrogen per hectare of cropland (kg N/ha). In comparison, the raw average of the application rates is 101 kg of N/ha, highlighting the differences in available cropland areas in each suitable region. As a conservative estimate of the nitrogen application potential, we used the highest cropland area for each region (from ESA or ESRI) to compute the total cropland area. The range of potential recovered nitrogen per hectare of cropland by country for the target regions is shown in SI Figure 8. The overall range is 3−2041 kg of N/ha, with a median of 30 kg N/ha. One region in the Democratic Republic of the Congo (DRC) had a much higher fertilizer rate potential at 2041 kg N/ha due to a low total cropland area (9 out of 74 km^2) and a high total population of over 700,000 people. Upon removing this data point from the average calculation, we obtain a weighted average potential fertilizer application rate of 25 kg N/ha and a raw average of 74 kg N/ha. For context, current fertilizer application rates are on average 22.5 kg N/ha in sub-Saharan Africa,[41] although it has been demonstrated that this value can be highly variable within and across countries, with household survey data reporting 8−94 kg N/ha for some countries.[42] In comparison, the world average fertilizer application rate is still much higher at 146.4 kg N/ha.[41]

For these identified target regions, we estimate the total potential nitrogen contribution from the deployment of nutrient recovery technology (Figure 5a). Over 3 million hectares of cropland could receive an average of 25 kg N/ha of nitrogen fertilizer (SI Figure 9). If all potential recovered

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fertilizer is used for crop production, we estimate that 5.9 to 8.9 million people could be fed as a result of the additional crop yield from recycled fertilizers (range based on lower and upper bound NUE values). We also compute the fraction of people fed from recovered nutrients within these target regions to demonstrate potential increased opportunities for improved food security through local and circular nutrient management (SI Figure 7). With region-specific NUE estimates, around 10−20% of the population in these highly suitable target regions could be fed using recycled nutrients. If NUE values were to approach the current global NUE, the fraction approaches 25%, demonstrating that a quarter of the population in these regions could potentially be sustained through food produced using recovered fertilizer. Some potential advances for increasing NUE in sub-Saharan Africa include improved crop varieties, water management interventions, and lime application to increase pH on acidic soils.[43,44] However, low adoption rates and resource constraints faced by smallholder farmers remain barriers to improving NUE.

3.5. Parameter Threshold Value Sensitivity. Performing threshold sensitivity analysis reveals that our suitability estimates are most sensitive to the sanitation parameter (Figure 6). This finding highlights the need for careful selection of sanitation requirements when tailoring this analysis for specific locales and tracking areas with improved sanitation development. If population density thresholds were further relaxed, many regions may become suitable as seen from the amount of area with lower population density levels (SI Figure 2). In the screening analysis, we observed that the population criterion was the most restrictive (SI Figure 4); however, since the periurban threshold was our most reasonable lower bound, due to the lack of truck-serviced sanitation and limited individual household nutrient recovery potential in rural regions, we did not test threshold sensitivity for a lower population criterion. We tested less restrictive soil parameter thresholds compared with the original thresholds to account for potential improvements in soil conditions (e.g., through added amendments) but did not observe high sensitivities to these parameters (Figure 6).

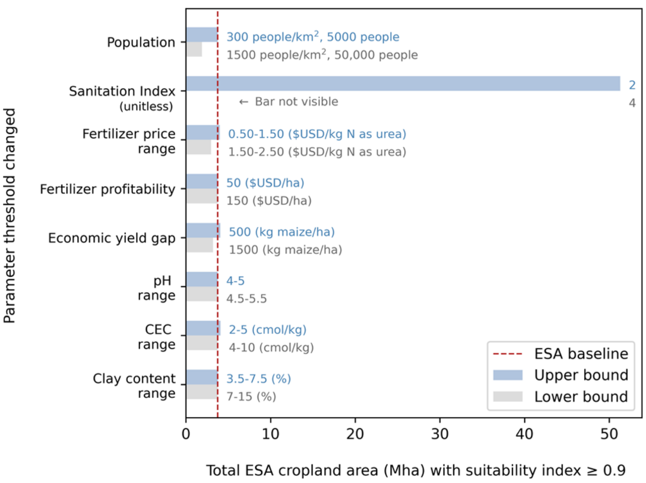

Figure 6. Sensitivity to threshold selection for suitability parameters using the baseline result of total suitable ESA cropland area from the original threshold values as a reference (dashed line). Total suitable cropland area was calculated based on regions with suitability index values of 0.9 or above for the ESA cropland data sets (sensitivities for the ESRI cropland data set are included in SI Figure 11). The values next to each bar represent the parameter ranges and values used to determine the upper and lower bounds of the total suitable cropland area. Rationale for the tested thresholds is discussed in SI Section 1.2.

4. DISCUSSION

Our analysis identifies from over 3000 subnational regions in sub-Saharan Africa, some of the most promising regions for initial deployment of nutrient recovery technology. We found considerable heterogeneity of suitability both within and across countries, quantified the substantial impact of future sanitation development for increasing suitable areas, and spatially located and quantified nutrient recovery potential of the most promising regions for targeted technology deployment.

The promising target regions that we identified comprise only about 1% of the total analyzed area and 3% of the total cropland area. Despite implementing considerable restrictions such as population criteria, sanitation levels, and soil characteristics, we still find substantial opportunities for high agricultural and sanitation potential within these regions. To the best of our knowledge, nitrogen recovery technology has not been implemented at scale in these target regions. However, some of these target regions, such as in Kenya, do have considerable pre-existing infrastructure for source-separated wastewater collection, which may further facilitate nutrient recovery technology deployment.[45]

Prior work by Trimmer and Guest[32] assessed the nutrient recovery potential and colocation of urban nutrients with surrounding agriculture for 56 of the largest cities in the world. However, only 6 of these cities were located in sub-Saharan Africa, providing a partial view of the true potential that may exist in this region. As we demonstrate in our study, there are many regions beyond major cities across sub-Saharan Africa where cropland and nutrient recovery potential are still highly localized and may be considered suitable. In particular, for the 4 cities in the Trimmer and Guest analysis that overlapped with our analysis extent (Kano and Lagos in Nigeria, Kinshasa in Democratic Republic of the Congo, and Abidjan in the Ivory Coast), all were identified to have suitability indices of 0.9 or above. One of these cities, Kano in Nigeria, contained highly suitable target regions since cropland density was sufficiently high.

Overall, the estimated nitrogen application per hectare of cropland for the suitable target regions was 25 kg of N/ha, which exceeds the current average fertilizer application rate in sub-Saharan Africa (estimated at 22.5 kg N/ha). There are also a considerable number of regions with nitrogen potential above 100 kg of N/ha (SI Figure 7). These regions highlight that some areas have the potential to have local fertilizer application rates approach global levels solely by using recycled nutrients. These potential fertilizer application rates, however, are based on wastewater collection and recovery occurring for the entire region, so the nitrogen recovered value should be viewed as a theoretical maximum. Bonilla-Cedrez et al.[30] estimated that the fertilizer required for maximum profitability in sub-Saharan Africa ranged from 15 to 245 kg N/ha with an average of 93 kg N/ha (empirical model) and 0−400 kg N/ha with an average of 72 kg N/ha (mechanistic). While the weighted average of 25 kg N/ha of fertilizer application potential is generally lower than the plausible cropland demand, this recovered fertilizer potential could still meet a large fraction of current fertilizer use or augment current application. Since this subnational analysis has prioritized identifying areas for local reuse, we also

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expect that fertilizer transport distances would be reduced from the presence of this technology.

Even for target regions with lower available nitrogen per total cropland area, the minimum available nitrogen potential was still above 29,000 kg N/year. While we assume fertilizer to be evenly applied throughout the region when calculating nitrogen application potential, it is reasonable to expect that distribution and allocation will be uneven. As a result, decision-makers can use the fertilizer magnitude in kilograms of N/year to easily compute the amount of cropland served within each region for a given target fertilizer application rate (SI Figure 8). This approach would further allow plausible cropland requirements to be met as locally as possible by applying fertilizer to cropland starting closest to the nutrient recovery site.

This study focused on nitrogen recovery, as nitrogen is one of the main nutrients present in wastewater and is often the most limiting nutrient in agricultural production. Nitrogen mining (where more nitrogen is taken up by crops than is applied to soil) and issues of soil fertility are prevalent in sub-Saharan Africa.[46] Nitrogen inputs are estimated to need to increase by 9- to 15-fold to reach self-sufficiency in 2050 for maize in nine countries in sub-Saharan Africa.[10] Nitrogen is also critical for reliably improving crop production in low-yield agricultural systems (e.g., cereal systems in sub-Saharan Africa).[8] While nitrogen is a predominant limiting factor, other nutrients like phosphorus, potassium, and micronutrients can also limit yield production.[47] Future work may extend the current framework to assess the techno-economic viability of other wastewater recovery technologies focusing on other nutrients such as phosphorus.

Since our suitability restrictions could be relaxed to accept lower sanitation levels, which was identified as the most restrictive parameter in the threshold sensitivity analysis, the realized impact has the potential to be considerably larger. We assessed the sensitivity of total cropland area within regions with suitability indices $\geq$ 0.9 as a function of changing the sanitation level criteria (SI Figure 10). If regions with sanitation levels below 3 were treated as suitable for coupled installation of sanitation infrastructure and nutrient recovery, these regions would add 35−60 million hectares of suitable cropland. This considerable addition to total suitable cropland area characterizes the substantial opportunities for extending nutrient recovery systems beyond the currently suitable regions and also highlights the potential cobenefits gained through increased sanitation coverage.

Since sanitation status could improve and fertilizer prices can fluctuate, the inherent limitation of this analysis is that many parameters are based on current static estimates. To address this limitation, we performed sensitivity analysis on different suitability parameter thresholds to reflect how technology requirements, economic factors, population, and sanitation levels might change over time. We also assessed the sensitivity of different parameter weighting scenarios and parameter inclusion through parameter screening analysis. We found that sanitation levels are a key factor in determining suitability and emphasize that detailed and accurate estimates of current sanitation levels are critical for informed deployment. While our sanitation data are based on comprehensive household-level survey information, these data are compiled across over 10 years of survey data collection.[37] While there are indications that proxy variables may provide strong sanitation coverage prediction value (e.g., basic hygiene facilities), this work has not yet been scaled to the broad area of our analysis.[48]

Another important limitation of our analysis is that we assume the Bonilla-Cedrez et al.[30] fertilizer response estimates for maize capture the general potential agronomic response in a given region and are representative of other crops. A meta-analysis of millet, sorghum, and maize in sub-Saharan Africa found that relative yield increases from fertilizer application were independent of the crop type.[49] We also note that while the district selection for our analysis is limited to regions where maize was grown (since the fertilizer price, profitability, and yield data were only available for maize-growing areas in sub-Saharan Africa), we account for all crop types when computing total cropland area.

To the best of our knowledge, this is the first effort to analyze the suitability of nutrient recovery technology at subnational scales while accounting for sanitation and fertilizer profitability across a multinational region. Since this analysis was limited to regions where we had data coverage for all parameters assessed, we excluded countries such as South Africa and Sudan where sanitation data were unavailable. As these excluded countries include substantial populations and cropland areas and likely include some highly suitable regions for nutrient recovery technology, our assessment can be considered as a reasonable lower bound of nutrient recovery potential in sub-Saharan Africa. Furthermore, the high spatial variation observed both within and across countries demonstrates the advantage of using subnational data sets for localized targeting. Country-specific analyses with higher-resolution administrative boundaries could benefit from even more detailed findings. While suitability potential is difficult to validate, future work should include collaborators on the ground in these identified suitable target regions to test the success of initial deployment and further identify site-specific factors that influence suitability. The suitability index can be further refined and tailored for specific locations based on locally relevant thresholds and factors. Our targeted spatial analysis method could also be applied to different scales and to other technologies that aim to contribute to sustainable development.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.3c05435.

Detailed data set and threshold descriptions; equations for calculated suitability index values; figures showing suitability index sensitivity analyses, potential fraction of people fed, nitrogen recovery potentials, and country level suitability distributions; and maps of input data sets, highly suitable target regions, and categorical suitability indices (PDF)

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Notes

The authors declare no competing financial interest.

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