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Integration of environmental, social and governance (ESG) into the supply chain of ammonia: Case study of Africa

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ABSTRACT

Ammonia is a cornerstone of global agricultural productivity, yet its traditional production and distribution systems remain highly centralised, carbon-intensive, and often inaccessible in under-resourced regions. An integration of ESG factors into a decentralised ammonia supply chain model, using Africa as a case study to highlight broader global relevance and overcoming a research gap in financial engineering and business strategies. The research investigates the feasibility of deploying small-scale, locally distributed production facilities as an alternative to conventional large-scale models, particularly in regions facing high transport costs and limited infrastructure. Innovative, low-emission technologies, such as high thermal plasma, mini-Haber-Bosch systems and others are evaluated for their techno-economic potential, including the application of environmental credits and future carbon tax scenarios. A comprehensive supply chain simulation demonstrates that decentralised ammonia production can achieve competitive costs of USD 232 per tonne when ESG-aligned strategies are applied. Beyond cost-efficiency, the study offers a strategic framework to operationalise ESG integration in global fertiliser supply chains, with implications for climate resilience, local economic development, and long-term food security in emerging markets.

1. Introduction

Ammonia is one of the world's most essential platform chemicals with major use as a nutrient to provide the necessary nitrogen levels to promote agricultural productivity for human food production. Ammonia can be added directly to soils or as ammonia-based fertilisers in various shapes, including urea, to provide essential nutrients for plants [1–3]. In recent years, there's been a proposal for small-scale ammonia plants utilizing renewable materials and energy, aiming for distributed production at local sites with optimal renewable energy sources [4–7]. However, these concepts remain largely theoretical. This study aims to bridge this gap by assessing the feasibility of such plants through cost internalization of carbon credits and considering social factors [8–10]. The African continent, with its significant capacity for fertilizer production yet high dependency on imports, serves as a case study. With Africa's anticipated agricultural growth, its fertilizer consumption is expected to rise dramatically, highlighting the need for local production to reduce dependency on imports [11–13].

Fertilizer usage in Africa remains low due to its high cost and limited accessibility, especially for rural farmers in Sub-Saharan Africa (SSA). Farmers in SSA typically use only 8 kg/ha of fertilizer per year, compared to the global average of 93 kg/ha and 200 kg/ha in East Asia [14–16]. The current ammonia supply chain in Africa is restricted to a few centralised production plants on the continent and the remainder is

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imported from other areas and transported, via ship and truck, to local markets [17–19]. Current ammonia production in Africa relies heavily on the conventional Haber-Bosch (HB) process, benefiting from economies of scale but facing limitations due to the long distances to rural markets and poor infrastructure [14,15,20–22]. This results in high transport costs and significant environmental impacts from fossil fuel usage during transportation as shown in Fig. 1. This results in very high market prices for smallholder farmers in rural areas, limiting the uptake and regular use of fertiliser. Consequently, many agricultural regions in Africa achieve poor crop yields and suffer from very high food insecurity [20,23,24]. The Covid-19 pandemic has also had a significant impact on transportation costs and lead times, exposing the vulnerability of global trade under current supply models and has raised concerns for food security, particularly in developing countries [1,25,26].

In order to achieve a self-sustaining food supply, Africa aims to raise nitrogen consumption from 35 kg N/ha/year to 181 kg N/ha/year to support its growing population [17,27–29]. Increasing the availability of affordable ammonia-based fertilizer in rural areas is crucial for reaching this target. While subsidy programs have been implemented in many Sub-Saharan African countries to promote fertilizer use, they are unsustainable due to financial limitations and implementation challenges faced by African governments [15,30–35]. Alternative long-term solutions should be investigated to improve the uptake of ammonia-based fertilisers in Africa.

This paper proposes the implementation of decentralised ammonia production plants to serve local African markets, aiming to reduce both production and supply costs. Emerging processes utilizing sustainable technologies for hydrogen and ammonia production offer promising opportunities to transform the supply chain to regional scales. These include water electrolysis and high thermal plasma (HTP) methane pyrolysis for hydrogen production, which can feed mini-Haber-Bosch (HB) processes [1,36–39]. Another option is nonthermal plasma (NTP) for ammonia production. A study completed by Tran et al. 2021 suggests that decentralised production of ammonia through renewable technology could compete with conventional processes, provided benefits such as reduced environmental impact and lead time are considered [1].

This study also proposes integrating ESG factors into a decentralised ammonia supply chain concept aforementioned particular for developing and underdeveloped region like Africa, aiming to enhance its economic potential. A preliminary framework for selecting plant locations based on ESG criteria has been developed. Leveraging existing Regional Economic Communities (RECs) in Africa, ammonia supply will benefit from tariff reductions within the same alliance, enhancing fertilizer affordability. Cost simulations will compare decentralised and centralized models using different technologies. ESG factors will be quantified, and corresponding indexes established to measure the model's impact. Future work will include cost internalizations based on ESG indexes to determine ammonia supply costs when considering credits for ESG-aligned solutions.

2. Literature review & problem identification

2.1. Current fertiliser situation in Africa

Food security is a pressing issue in Africa, particularly in SSA, where rural communities face severe poverty, with approximately one in four people estimated to be malnourished [40,41]. Rural households in Africa obtain approximately three-quarters of their income from agriculture [42], which shows the dependence of regional communities, particularly in SSA, on agriculture as their primary income source [41, 43]. Thus, agricultural growth will be fundamental in alleviating poverty and food insecurity in SSA. Countries that have seen improvements in food security are those that have increased agricultural productivity which has also demonstrated indirect positive effects in stimulating the overall economy [40]. A combination of factors has restricted the agricultural potential of rural areas in Africa. Poor soil fertility and land degradation have significantly impacted the suitability of agricultural land [42,43]. Nutrient-deficient soils along with expensive fertiliser prices has contributed to low attainable crop yields [20]. The high cost and limited accessibility of fertilisers, especially in rural areas, hinder their widespread use in Africa. Supply chain constraints, such as irregular deliveries and high transportation costs due to inadequate infrastructure, further compound these challenges [15]. Africa's transportation costs are significantly higher than the global average and 136 % higher than in other developing countries [21,44]. Inadequate road and railway networks, along with high handling costs at ports and

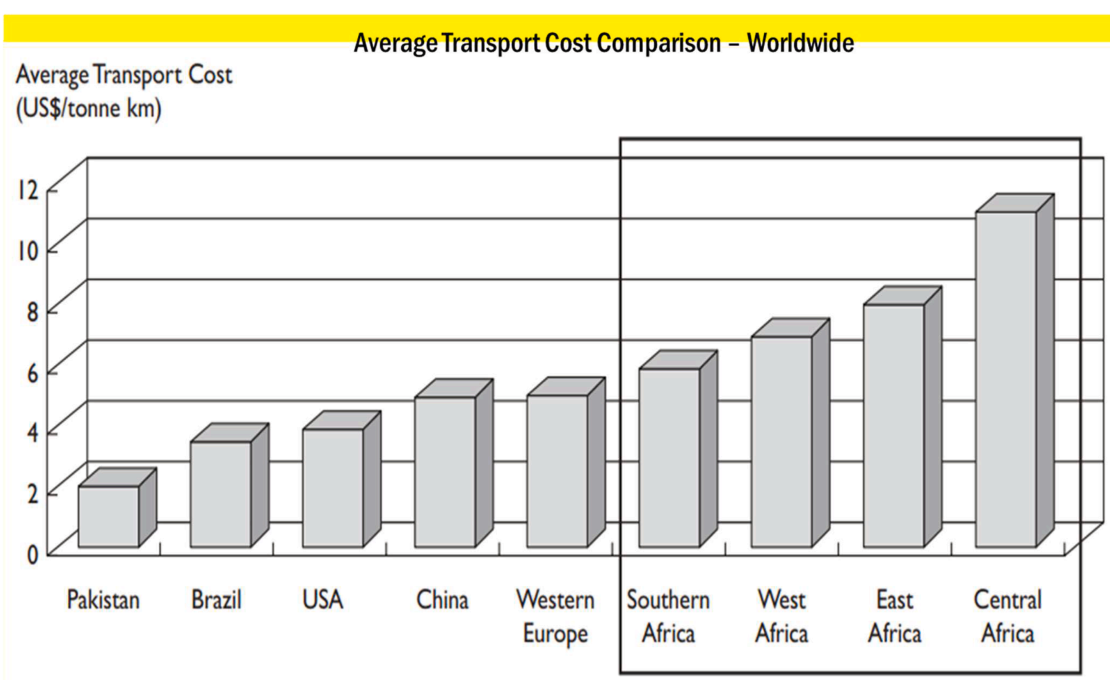


Fig. 1. A global comparison of average transportation costs (reproduced with permission of SAGE Publications) [21].

distribution centres, drive up market prices. The infrastructure limitations have been further exacerbated by the COVID-19 pandemic [1].

Several approaches have been employed to promote fertiliser uptake in SSA, including input subsidy programs (ISPs). Malawi's Agricultural Inputs Subsidy Programme was among the first successful implementations, leading to improved food security and making the country a grain exporter. Following this success, by 2010 another 10 countries had implemented similar ISPs [15,32]. While these ISPs have encouraged increased fertiliser uptake initially, evidence suggests that these will not be sustainable long-term solutions due to the significant costs and reliance on government and external funding. For instance, Nigeria established a fertiliser voucher program through public-private partnership funding, offering fertiliser at a 40 % discount to 300,000 farmers [31]. Despite initial success, challenges such as political differences and funding withdrawals undermined the program's long-term feasibility. These examples highlight the limitations of subsidy programs, which rely heavily on external funding and fail to address the inefficiencies in the fertiliser supply chain. This program exposes the limitations of subsidy programs due to the reliance on external funding rather than focusing on the failure of the fertiliser supply chain in reaching remote areas. While these programs can increase fertiliser use, African governments cannot sustain them due to financial constraints and implementation complexities [30]. Thus, suggesting that alternative long-term solutions should be investigated to improve the uptake of ammonia-based fertilisers.

The centralised nature of fertiliser production in Africa results in high shipping and transportation costs due to poor infrastructure, leading to expensive retail prices in rural areas [17]. Farmers closer to markets have higher fertiliser use due to reduced transportation costs, while those in remote areas have lower uptake [14,15]. Therefore, localised production plants offer a long-term solution to reduce transportation costs across large distances, making fertiliser accessible and affordable in regional areas. Regional production would allow for the implementation of small-scale plants supported by renewable hydrogen and ammonia technologies, offering environmental benefits [17].

2.2. Regional economic communities (RECs)

The ammonia supply chain in Africa is affected by the existing Regional Economic Communities (RECs) between countries. Africa has small and isolated markets which increases the complexity of trade, so RECs have potential to overcome these associated challenges. There are eight RECs that are considered the foundation of the African Economic Communities which are shown in Fig. 2 [45]. Many RECs have overlapping memberships which can complicate trade relationships rather than simplifying them and often significantly influences market prices [45]. These include the East African Community (EAC), the Common Market for Eastern and Southern Africa (COMESA), the Economic Community of West African States (ECOWAS), the Intergovernmental Authority on Development (IGAD), the Economic Community of Central African States (ECCAS), the Arab Maghreb Union (AMU), the Southern African Development Community (SADC), and the Community of Sahel-Saharan States (CEN-SAD). African countries are working towards integrating trade under the Continental Free Trade Area (CFTA) framework and reduce the negative impacts of overlapping trade agreements. Unified trade will encourage goods and services to come from within the continent which will reduce costs and thus increase accessibility to local communities [45]. RECs are vital considerations, as established trade agreements affect market prices through factors like tariffs, transport corridors, and political and social relationships between member states [46]. Exporting within a shared alliance may lead to lower market prices due to reduced or disregarded tariffs [45]. These RECs work towards economic integration, free trade, infrastructure development, and regional peace, and their efforts have had a significant impact on rural Sub-Saharan Africa. Through the adoption of innovative technologies like biogas-fuelled aqua-ammonia absorption refrigeration, solar-powered irrigation systems, wind energy for rural electrification, and biogas digesters, they have enabled off-grid solutions that reduce post-harvest losses and improve energy access in remote areas [47]. Additionally, advancements in precision agriculture, mobile farming apps, and low-cost cold storage systems have empowered farmers to preserve their produce, boost yields, and minimize waste [46,48]. These sustainable solutions not only support net-zero and climate goals but also enhance agricultural productivity, food security, and rural

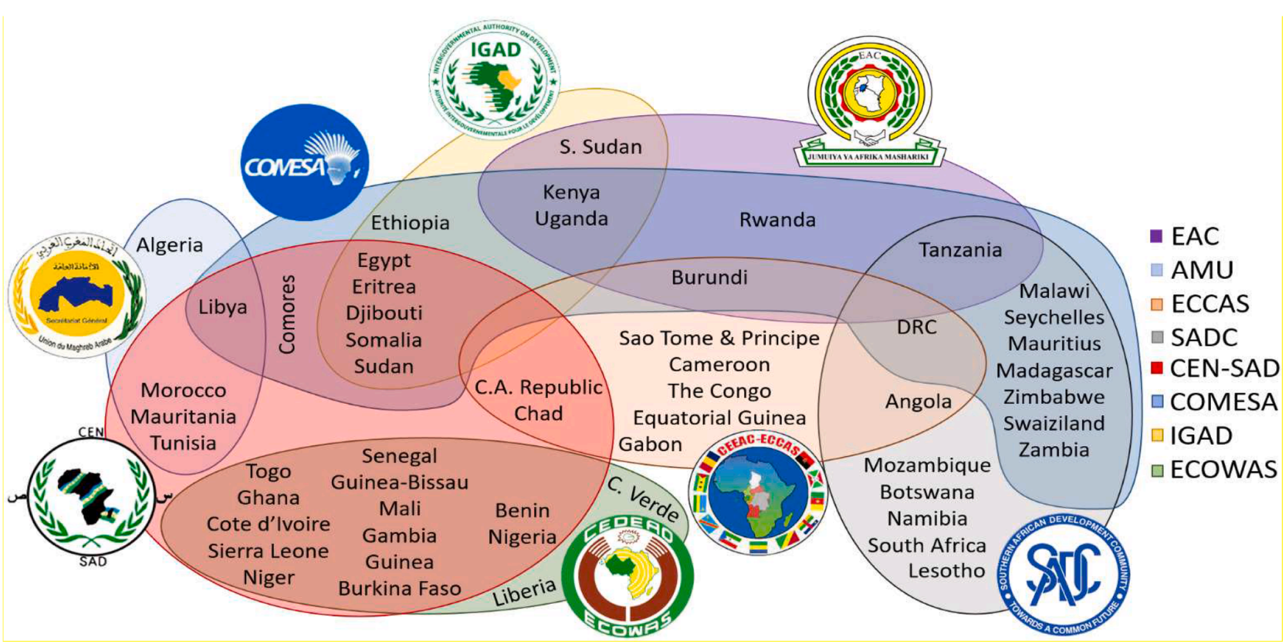


Fig. 2. Overview of the eight RECs in Africa and the member states in each alliance [45]. (EAC - East African Community; AMU - Arab Maghreb Union; ECCAS - Economic Community of Central African States; SADC -Southern African Development Community; CEN-SAD - Community of Sahel-Saharan States; COMESA - Common Market for Eastern and Southern Africa; IGAD - Intergovernmental Authority on Development; ECOWAS - Economic Community of West African States).

economic development, driving Africa's regional integration, economic resilience, and long-term growth while contributing to global climate targets [45,49,50]. However, further work is required on ammonia as a key fertilizer source to meet food security targets, given its crucial role in agricultural productivity. These efforts align with several United Nations Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger), SDG 7 (Affordable and Clean Energy), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action), promoting sustainable agricultural practices, clean energy, and climate resilience [15,51–53].

The EAC is considered the most advanced as tariff rates have been disregarded between members. Fig. 3 shows how the current tariff liberalisation differs between REC's. It compares two critical aspects of intra-REC tariff rates on imports and the share of fully liberalized tariff lines. Intra-REC tariff rates reflect the level of trade barriers between member countries within each REC. CEN-SAD has the highest intra-REC tariff rate, indicating relatively higher trade barriers, followed by ECOWAS, suggesting some restrictions on internal trade. SADC and AMU show moderate tariff rates, indicating partial trade liberalization, while COMESA, ECCAS, and IGAD present similar tariff rates. EAC stands out with the lowest intra-REC tariff rate, reflecting a highly liberalized trade environment. On the other hand, the share of fully liberalized tariff lines shows the extent to which tariff barriers have been removed within each REC. EAC leads with the highest share of fully liberalized tariff lines, signalling strong economic integration. COMESA and AMU also show considerable liberalization, while SADC and ECCAS have moderate levels of tariff line liberalization. IGAD and ECOWAS lag behind, with ECOWAS having the lowest share of liberalized tariff lines, suggesting that, despite low intra-REC tariffs, trade liberalization is still limited within the region. The varying levels of economic integration across Africa's RECs, with some regions like EAC making significant strides toward deeper integration, while others like ECOWAS and CEN-SAD still face substantial trade barriers. Future work could focus on examining the impact of these barriers on regional trade flows and economic development, as well as the alignment of these efforts with the CFTA, which aims to further integrate the continent's economies. The other RECs show various reductions in tariffs for member states but are yet to completely eliminate tariffs [44] as many countries are fearful of economic loss by removing tariff revenues [45]. However, eliminating tariffs across all RECs could stimulate economic growth, provide affordable products, and help achieve the SDGs across the continent [45]. RECs have the potential to significantly improve trade networks, uniting member states for economic and social benefits [54]. These factors are carefully integrated into the analysis of localized ammonia production plants, as African RECs will play a pivotal role in providing affordable ammonia-based fertilizers and strengthening food security across the continent.

2.3. *Technologies for hydrogen and ammonia production*

2.3.1. *Conventional Haber-Bosch*

The Haber-Bosch (HB) process, developed in the early 20th century, enables large-scale ammonia production for fertiliser manufacturing, boosting global agricultural productivity [1,55]. Over 90 % of the 170 million metric tonnes of global ammonia is produced using HB [36,55,56]. This process catalytically reacts hydrogen and nitrogen under high temperatures and pressures, with hydrogen primarily derived from fossil fuels like methane or coal via steam reforming [1,36,55,56]. Natural gas is primarily used as steam methane reforming (SMR) systems are more energy efficient and have lower carbon emissions. Ammonia production emits approximately 1.8 % of global emissions, primarily due to its reliance on fossil fuels [56].

The conventional HB process, reliant on natural gas or coal, has led to centralized ammonia production in countries with abundant fossil fuel resources, increasing carbon emissions and transportation costs [1,36]. The Covid-19 pandemic has further disrupted global connectivity, impacting shipping costs and lead times, exacerbating the challenge of accessing affordable ammonia-based fertilisers. In many SSA countries, limited natural gas resources make local HB-based production impractical [52]. Encouraging the uptake of ammonia-based fertilisers in SSA could significantly enhance agricultural productivity and food security [20,30]. Adopting state-of-the-art, sustainable production technologies at smaller scales offers a feasible solution to improve the affordability and accessibility of ammonia in Africa.

2.3.2. *New small-scale technology*

New technologies for cleaner ammonia production are viable for small-scale plants, strategically located near farming areas to reduce transportation costs and enhance sustainability, making them competitive alternatives to the conventional HB process. Multiple studies have evaluated alternative processes as potential replacements for existing HB plants. Advance technologies for cleaner ammonia production are

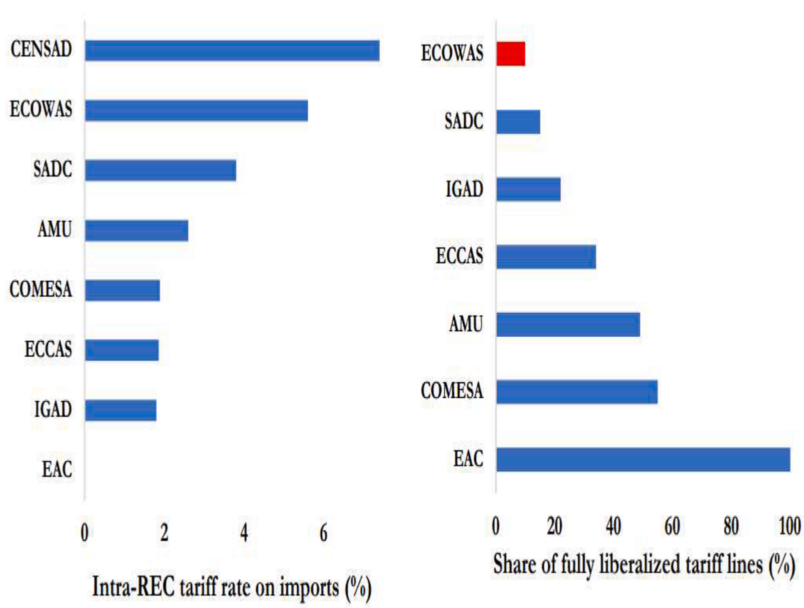


Fig. 3. Tariff rates applied for members within each REC show the percent of tariff liberalisation [44] (reproduced with permission of World Bank).

viable for small-scale plants, strategically located near farming areas to reduce transportation costs and enhance sustainability, making them competitive alternatives to the conventional Haber-Bosch (HB) process. Numerous studies have evaluated alternative processes as potential replacements for existing HB plants. Among many alternatives, water electrolysis has emerged as a promising pathway for hydrogen production to fuel mini-HB systems. When powered by renewable sources, such as wind or solar energy, the resulting hydrogen is considered green. Lin et al. (2020) investigated this approach and determined that the resulting facility could be significantly smaller than a large-scale HB process hile still being economically viable [36]. For instance, Monolith's pilot plant at Redwood City Seaport, California, operational since 2014, showcased successful performance. Expanding on this achievement, Monolith inaugurated a commercial plant with a capacity of 580–660 kg H_2/h in Olive Creek, Nebraska, in 2020. This facility is expected to co-produce 200,000 tons of carbon black, bolstering its economic viability [1].

3. Methodology

In current study, the methodology applies an integrated ESG–Techno-Economic Analysis (TEA) framework to assess the feasibility of a decentralised ammonia supply chain, using Africa as a case study due to its growing agricultural demand and limited local fertilizer production. The process aligns an investigation of the possibilities of these renewable technologies using a decentralised supply chain model for local ammonia production. Conventional and renewable production technologies, including steam methane reforming, water electrolysis, and high thermal plasma, are evaluated through cost-optimized simulations using real-world data on infrastructure, demand, and pricing. These simulations are conducted on the Agile supply chain optimization platform developed by the Tele-traffic Research Centre at the University of Adelaide. ESG metrics are developed and incorporated into a multi-criteria location assessment. This will offer a scalable, data-driven approach to identifying decentralised ammonia production strategies that are both economically viable and aligned with broader sustainability goals. The study discovered that a decentralised renewable supply chain could compete with existing networks if benefits like environmental effect and lead time were considered [1,57]. As a result, the purpose of the current study is to expand on previous research by proposing an ESG strategy that may help add value to the decentralised renewable supply chain in order to compensate for economic shortfalls caused by greater investment and operation expenses when compared to traditional procedures.

3.1. Optimisation software

Based on the location assessment, several scenarios were developed and run through the supply chain optimisation software on the Agile platform developed by the Tele-traffic Research Centre (TRC) at the University of Adelaide. This section describes the mathematical model developed, process assumptions and calculation of input parameters for the different scenarios investigated.

3.1.1. The mathematical model

Ammonia supply costs in Africa are calculated using a modified version of the cost minimisation model developed by author previous work as Tran et al. (2021) [1], implemented within the Agile optimisation platform by the Tele-traffic Research Centre (TRC) at the University of Adelaide. This model adopts a mixed-integer linear programming (MILP) framework to minimise total ammonia supply costs by optimising capital investment (CAPEX), operational expenditure (OPEX), transportation (including tariffs and carbon taxes), and warehousing. Decision variables include facility locations, technology options (e.g., SMR+HB, HTP + Mini-HB), supplier-market linkages, and logistics flows. The current study enhances the original model by integrating ESG-based site selection, decentralised production structures, intra-REC tariff mechanisms, and environmental credit internalisations. Constraints ensure demand satisfaction, production and storage limits, and trade compliance. Fig. 4 illustrates the complete cost structure, comprising fixed investment costs for plants and warehouses, transportation costs across the supply chain (from suppliers to plants, plants to warehouses, warehouses to markets, and plants to markets), and operating costs at each facility. This enhanced MILP framework supports scenario testing across multiple technologies and policy interventions, serving as the computational backbone for evaluating the ESG-aligned, decentralised ammonia supply chain's techno-economic feasibility as the novel work for ammonia new business strategy and financial engineering combination in Africa. Further information and calculations are available in the appendix 1,2,3.

3.1.2. Process assumptions and data required

The optimization software determined the supply cost of ammonia based on the decentralised ammonia supply chain developed from ESG factors and compared the cost with the centralized conventional supply chain. The decentralised model considers renewable technologies including HTP and electrolysis for hydrogen production and NTP and mini-HB for ammonia production, alongside the conventional SMR and HB process for comparison. The centralized model was simulated using only conventional SMR and HB. Carbon tax and environmental credits were introduced into the simulation, and a future scenario was considered by incorporating a carbon tax at a rate of US $8/tonne CO_2, based on anticipated rates in South Africa, the first country in Africa to implement carbon tax [53]. Carbon tax was included into the SMR and HB technology to assess its impact on supply costs. Environmental credits were introduced for the renewable technologies, utilizing conservative estimates. Carbon credits were applied for the production of carbon black in HTP at a rate of US $1/kg, and oxygen credits for the coproduction of oxygen in water electrolysis were applied at a rate of US $0.7/kg [1]. Table 1 presents the variables considered in the optimization software to calculate the ammonia supply cost. It was assumed that hydrogen production was integrated with the ammonia production plant, locating the supplier at the same site as the plant. Table 1 presents the core decision variables embedded in the MILP framework of the optimisation model, each playing a critical role in determining the minimum total supply cost of ammonia within the decentralised and centralised system configurations. The variable X_1 governs the selection of hydrogen and ammonia production technologies, incorporating five distinct technological pathways: (i) conventional Steam Methane Reforming coupled with Haber-Bosch (SMR + HB), (ii) High Thermal Plasma with Mini-Haber-Bosch (HTP + Mini-HB), (iii) HTP with Non-Thermal Plasma (HTP + NTP), (iv) Water Electrolysis with Mini-HB, and (v) Water Electrolysis with NTP. These combinations allow the model to compare conventional and renewable routes under varying investment, operational, and environmental cost assumptions. The variable X_2 defines supplier allocation, where hydrogen production is assumed to be co-located with ammonia plants to eliminate inter-site transportation costs and reflect modular plant configurations. The variable X_3 specifies candidate plant locations across five high-demand African regions, Egypt, Algeria, Nigeria, Kenya, and South Africa, identified through a geospatial ESG-informed location assessment. X_4 denotes the presence and location of warehouses, which are essential in smoothing seasonal demand variations and maintaining supply reliability during off-peak production periods. Lastly, X_5 accounts for operating expenditure (OPEX), which is endogenously linked to the selected production technology and plant configuration. These variables form the structural input space for the MILP solver, enabling robust scenario testing and cost optimisation under constraints such as production capacities, warehouse limits, market demand satisfaction, REC-based tariff regimes, and environmental credit internalisation. Further information and calculations are available in the appendix 1.

Several assumptions were made regarding warehouse and market

$$\underbrace{\sum_{f}\sum_{p}\sum_{c} F_{fpc}Y_{fpc}}_{\text{Fixed cost investment at a specific location}} + \overbrace{\sum_{w} f_w y_w}^{\text{Fixed cost investment for warehouse}} + \underbrace{\sum_{f}\sum_{s}\sum_{p}\sum_{t}\sum_{v} \alpha_{fspv} x\alpha_{fsptv}}_{\text{Transportation cost from suppliers to plants}}$$

$$+ \underbrace{\sum_{f}\sum_{p}\sum_{w}\sum_{t}\sum_{v} \beta_{fpwv} x\beta_{fpwtv}}_{\text{Transportation cost from plants to warehouses}} + \underbrace{\sum_{f}\sum_{p}\sum_{m}\sum_{t}\sum_{v} \mu_{fpmv} x\mu_{fpmtv}}_{\text{Transportation cost from plants to market}}$$

$$+ \underbrace{\sum_{f}\sum_{w}\sum_{m}\sum_{t}\sum_{v} \gamma_{fwmv} x\gamma_{fwmtv}}_{\text{Transportation cost from warehouses to market}} + \underbrace{\sum_{f}\sum_{p}\sum_{c}\sum_{t} o\alpha_{fpct}}_{\text{Operation cost at a specific plant + location}}$$

Fig. 4. Mathematical model developed by Tran et al. 2021 that was coded and built into the Agile platform provided by the Tele-traffic Research Centre at the University of Adelaide [1].

Table 1
Variables considered in the optimisation software to minimise supply cost of ammonia.

Variable	Coded Variables	Possible Values Considered
Hydrogen and ammonia production technologies	X_1	SMR + HB HTP + Mini HB HTP + NTP Electrolysis + Mini HB Electrolysis + NTP
Supplier Location	X_2	Hydrogen production near ammonia plants i.e., suppliers in same location as plants
Plant Location	X_3	5 plant locations; Egypt; Algeria; Nigeria; Kenya; South Africa
Warehouse	X_4	Yes
Operating Cost	X_5	Dependent on technology

locations in the simulation. A 100 km radius was assumed for the distance from the plant to the warehouse and from the warehouse to the market, while a 200 km radius was assumed for the distance from the plant to the market. Additionally, a distance matrix was created to input into the optimization software, considering straight-line distances from each plant location to various suppliers and markets across Africa. Warehouse capacities were estimated based on fertiliser use throughout the year, determined by the growing season of crops in each market location [48,58].

It was assumed all fertiliser demand would be throughout the growing season. Thus, the proportion of the year where fertiliser was not used could be calculated to determine the storage capacity required for the warehouses to store fertiliser in low-demand periods. Real-world production data was used to calculate capital costs and operating costs of the plants under each technology which were scaled-up to the required plant capacities. Transportation rates in Africa were obtained through literature review and analysis, determining the cost for shipping to be US $0.005/tkm, rail to be US $0.05/tkm and truck to be US $0.14/tkm. Using all the collected data, the scenarios were run through the cost optimisation simulation to determine the corresponding ammonia supply costs.

3.2. Development of ESG metrics and assessment

Four primary ESG factors were developed to assess the feasibility of the selected plant locations after determining the ammonia supply costs, with the possibility of incorporating additional factors in future iterations. The selection of these ESG metrics was informed by globally recognized frameworks, including the Global Reporting Initiative (GRI), Sustainability Accounting Standards Board (SASB), and Corruption Perceptions Index (CPI). These frameworks were chosen for their well-established, reliable methodologies in assessing key sustainability, social, and governance factors [7,59,60]. The MSCI ESG Ratings were also considered, providing a comprehensive evaluation of a company's exposure to long-term ESG risks and opportunities, with ratings ranging from AAA (highest) to CCC (lowest), helping to quantify and compare the sustainability performance of various locations [61,62]. Furthermore, Refinitiv ESG Ratings were integrated into the analysis, offering insights into a company's sustainability performance across environmental, social, and governance dimensions, with a scale of 0 to 100 indicating overall ESG performance [63–66]. The use of these established metrics and rating systems ensures a thorough, consistent, and globally recognized evaluation process. The inclusion of ratings such as MSCI and Refinitiv provides additional layers of insight, helping to assess risks and opportunities, while enabling comparison across different regions and sectors, ultimately contributing to a more comprehensive and sustainable approach to ammonia production. However, available frameworks and standards are not duly applicable due to complex nature of existing case studies comprising of supply chain, location and financial engineering. Modified novel metrics are adopted and factors are introduced.

The environmental factor focused on evaluating the proportion of renewable energy used in ammonia production, providing a clear gauge of sustainability. Social considerations included the availability of skilled labor, crucial for plant implementation, as well as the potential of localized plants to improve food security by supplying affordable fertilizers locally, which could alleviate malnutrition in high-risk areas. Governance was assessed by evaluating national stability, especially its impact on intra-REC trade for ammonia distribution and the potential for transport delays along shared routes [47] (Table 2).

Indexes were subsequently devised as essential performance metrics within these factors to facilitate assessment and comparison of plant locations. Table 3 explains the factors, and their corresponding indexes developed. Data pertaining to each plant location was gathered to gauge their alignment with the identified indexes. Initially, the feasibility of selected plant locations was evaluated using a color-coded system, categorizing them as green, yellow, or red. Green indicates locations that would significantly enhance the African ammonia supply chain under the respective ESG factor, while yellow denotes a medium impact, and red signifies little to no impact. It mainly includes integrating cost internalization of these ESG metrics to quantitatively measure the value added to this supply chain based on ESG factors.

3.3. Data collection

The analytical scope of this study is primarily delineated by the current spatial distribution of ammonia demand across the African continent. To quantify this demand, country-level data on ammonia-based fertiliser production, imports, and exports were systematically compiled from authoritative sources, including *Key Statistics and Trends in Regional Trade in Africa* UNCTAD-2019 [49], the Food and Agriculture Organisation (FAO) *Global Information and Early Warning System*,GIEWS – 2020 [40,67], and additional techno-economic analyses on decentralised ammonia production systems [68,69]. The net demand for each country was computed using a standard material balance equation:

$$Demand = production + import - export \quad (1)$$

Further data were collected from a major literature review of [1,4, 36,52,55,56,59,68–96] to calculate the socio-economic parameters, location indices, carbon tax, life cycle costing and associated financial cost at different plant capacities for hydrogen production technologies such as SMR, HTP and water electrolysis as well as for ammonia production technologies including conventional HB, mini-HB and NTP.

3.4. Location assessment

A location assessment was developed to evaluate the most suitable plant locations for decentralised ammonia production. Africa was divided into geographic regions; North, West, Central, and South to develop a continental plant distribution. Various criteria exist in the literature; however, the modified model necessitates a specific integration of financial and ESG metrics aligned with location selection [97–103]. The four countries with the highest ammonia demand in each of these regions were considered in the location assessment. Novel criteria were developed to rank the countries in each of the geographic regions to select the optimal plant locations across Africa. This was the first introduction of ESG factors into the decentralised supply chain. Table 3 presents the criteria, and a description of the metrics used to assess each location under the corresponding criterion.

Table 2
ESG factors and corresponding metrics developed to assess the feasibility of plant locations.

	Factor	Index
Environment	Renewable energy	Energy provided by renewables in each location
Social	Availability of skilled labour	Number of university graduates
	Potential to improve food security	Malnutrition rates Agricultural land use
Governance	National stability	Corruption index Current conflict

Table 3
Description of the unranked criteria and metrics used to measure them in the location assessment.

Criteria	Description
1. Ammonia Demand	• Demand based on import, export, and production values averaged from 2016 to 2019 • Agriculture land use estimates as an indicator of potential future fertiliser use
2. Access to Transport	• Type of transportation available (e.g. ship, rail, truck) • Cost of transportation
3. Feedstock Availability	• Water and methane availability. Measured using water scarcity index and methane reserves and availability in each country.
4. Renewable Energy	• Renewable energy sources available and associated reliability.
5. REC Membership	• Number of REC memberships. Higher ranking was given to countries with memberships in multiple alliances as greater potential for reduced export tariffs to more countries

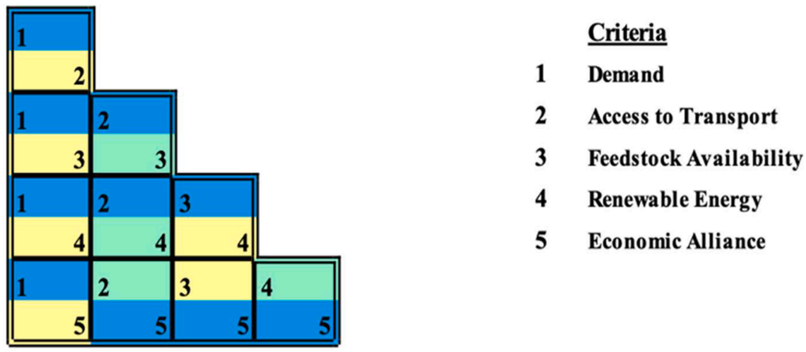
The criteria were compared using a head-to-head comparison of competing criteria to determine their relative weightings when ranking the plant locations. Each criterion was compared against the other criteria to determine which would be considered most influential in selecting plant locations. A score was given to each criterion based on the number of times it was considered more important in the head-to-head allowing the criteria to be ranked from most to least influential. An arbitrary weighting was then applied to each criterion to reflect these rankings. Fig. 5 summarises the process and results of the head-to-head analysis showing the final weightings of each criterion that would be used to rank each location. The dark blue squares represent when the criterion “won” against the other criteria. A score was given to each criterion based on the number of times it was weighted more important. The criteria were then ranked based on these scores with 1 being the criterion with the highest score (i.e. “won” the most times) and 5 being the criterion with the lowest score. An arbitrary weighting was then given to each criterion to reflect these rankings. For example, criterion 1 (ammonia demand) was ranked the highest so was given the greatest weighting of 30 %.

The weighted criteria were applied to assess the suitability of the four countries within each geographic region based on each criterion. This facilitated a comparative analysis of locations within the region to establish an optimal plant distribution across the continent. Each country received a rank from 0 to 3 for each criterion, with a score of 3 indicating the best option, 2 representing an intermediate position, 1 denoting the least favourable option, and 0 indicating inapplicability or unattainability. If countries were indistinguishable or impossible to rank differently for any criterion, they were assigned the same score. Subsequently, a score was computed for each country using Eq. (2), which aggregated the relative weighting of each criterion, and the corresponding rank assigned to the country. A maximum score of 300 could be attained if a country ranked as the best option (i.e., received a rank of 3) across all criteria. This quantitative scoring mechanism facilitated a comprehensive assessment of countries based on the weighted criteria, and the highest-scoring country within each geographic region was designated as the final plant location.

$$\sum_{i}^{n} (criterion\ weighting)_i \times (rank\ of\ country)_i \quad (2)$$

4. Results and discussion

An ESG-based approach is implemented to identify suitable locations across Africa for renewable ammonia plants in a decentralised supply chain and an optimisation framework is utilised to simulate the potential



Criteria	1	2	3	4	5
Score	4	2	1	0	3
Rank	1	3	4	5	2
Weighting (%)	30	20	15	10	25

Fig. 5. Head-to-head comparison of criteria, with dark blue squares indicating preference wins. Criteria were scored by frequency of selection, ranked from 1 (most preferred) to 5 (least), and assigned weightings accordingly.

market price of ammonia. A continental ammonia supply was developed based on the selected plant locations to ensure production capacities would meet demands of the continent. The surrounding countries that each plant would supply to be determined based on the existing Africa RECs to benefit from tariff reductions when countries receive goods from members of the same REC. Therefore, the total capacity of each plant was determined based on the ammonia demand in the plant locations and the countries it would supply to in the same RECs. Tariff rates for intra-REC trade were obtained in the literature review and were utilised to estimate adjusted ammonia supply costs once simulations were complete.

A decentralised ammonia supply chain was formulated for Africa based on a comprehensive location assessment integrating ESG factors. This assessment prioritized areas with the highest demand for ammonia-based fertilizers, considering factors like resource availability, transportation infrastructure, and regional demand. Table 4 displays the outcomes of this assessment, indicating the total scores assigned to countries within the identified geographic regions. The highest-scoring countries in each region were designated as the final plant locations. Given the significantly higher demand for ammonia in the north region, two countries were chosen to meet this demand effectively and minimize transportation costs. The recommended plant locations, namely Egypt, Algeria, Nigeria, Kenya, and South Africa, establish a balanced continental distribution network.

Another consideration was plant capacity constraints, based on the assumption that the maximum feasible capacity for renewable technologies would be 1 million tonnes per annum. As the demand for the Egypt and Algeria plants was greater than this maximum capacity, these locations were divided into multiple plants to meet the demand and maintain feasible plant capacities. Table 5 shows the final plant locations and the associated plant capacities that would be used in this ammonia supply chain model.

Table 5
Final plant locations and associated plant capacities for continental ammonia distribution across Africa.

Location	Plant Location (city)	Plant Capacity (tonnes/year)
P0	Egypt (Cairo)	950,000
P1	Egypt (Alexandria)	950,000
P2	Egypt (Port Said)	950,000
P3	Egypt (Suez)	950,000
P4	Algeria (Algiers)	850,000
P5	Algeria (Arzew)	850,000
P6	Nigeria (Abuja)	19,000
P7	Kenya (Nairobi)	43,000
P8	South Africa (Cape Town)	108,000

4.1. Ammonia supply costs

Simulations were run through the supply chain optimisation software on the Agile platform developed by the Adelaide TRC to investigate ammonia supply costs using different renewable technologies for a decentralised ammonia supply chain. This was compared to a centralised model using conventional technology as a benchmark. Fig. 6 shows the supply costs of ammonia associated with the different scenarios investigated.

The centralised model using conventional SMR and HB, as shown in Fig. 7, was used as a benchmark for ammonia supply costs. In this model, all ammonia is produced at a single mega plant in Egypt and supplied to markets across Africa. In this case (scenario 1), ammonia can be produced at US $181/tonne, demonstrating the benefit of economy of scale for this centralised supply model. A future scenario has also been simulated by incorporating carbon tax at a rate of US $8/tonne CO_2. It is anticipated for the near future whereby major CO_2 emitters must pay a

Table 4
Results obtained from location decision matrix, indicating the total score obtained for each country in the four geographic regions. Blue shading indicates the final plant locations.

North		West		Central/East		South	
Country	Score	Country	Score	Country	Score	Country	Score
Algeria	275	Cameroon	145	Ethiopia	180	South Africa	220
Egypt	250	Côte D'Ivoire	200	Tanzania	230	Namibia	185
Libya	215	Senegal	250	Kenya	275	Zimbabwe	140
Morocco	205	Nigeria	275	The Democratic Republic of Congo	235	Zambia	170

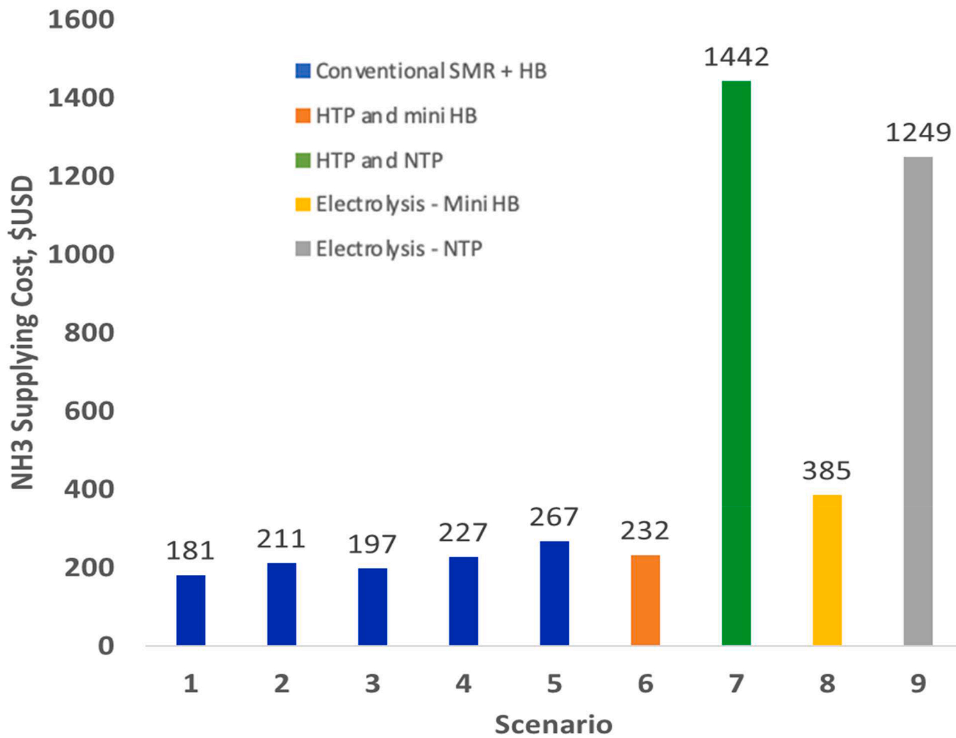


Fig. 6. Supply costs of ammonia produced by different technologies. Scenario 1: Centralised production in Egypt. Scenario 2: Decentralised production in 5 locations. Scenario 3: Centralised production in Egypt considering carbon tax. Scenario 4: Decentralised ammonia production in 5 locations considering carbon tax. Scenario 5–9: Decentralised ammonia production in 9 locations under the different technologies.

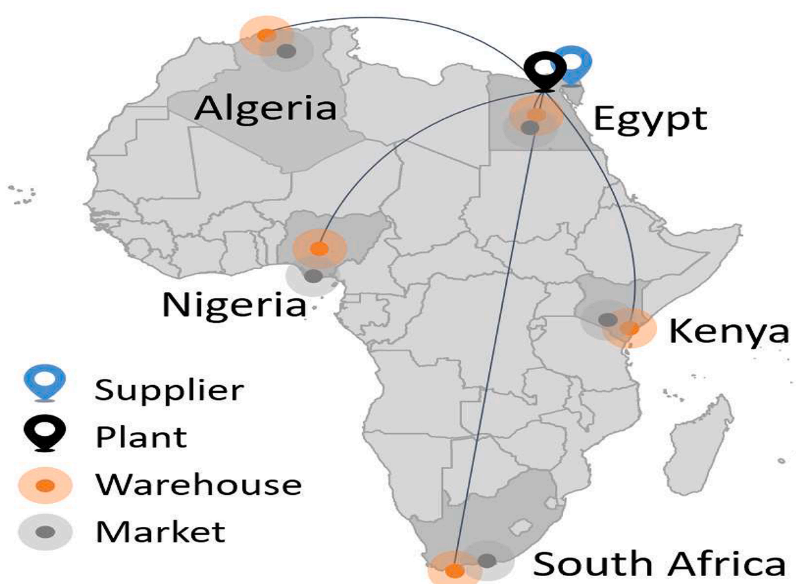


Fig. 7. Diagram of the centralised ammonia supply chain with a mega plant in Egypt supplying ammonia across the continent.

price per tonne of greenhouse gases produced which will be essential, especially to the current ammonia industry which is one of the biggest contributors to global CO_2 emissions, in acting against climate change. Many countries, such as South Africa, have made plans or have commenced implementation of carbon taxes and many more will likely follow [104]. The introduction of carbon taxes will assist in making renewable technologies economically viable. Incorporating carbon tax for conventional SMR and HB under a centralised model (scenario 3), increased the supply cost of ammonia to US $197/tonne.

Ammonia supply costs were assessed across various technologies for the decentralised ammonia supply chain, illustrated in Fig. 8. This model was constructed based on ESG considerations, and ammonia distribution across the continent was determined through existing RECs. For a decentralised supply chain employing conventional technology (scenario 2), the ammonia supply cost is estimated at US $211/tonne. With the inclusion of a carbon tax (scenario 4), this cost rises to US $227/ton. The increased cost compared to the centralized model reflects the presence of multiple smaller-capacity plants, resulting in higher

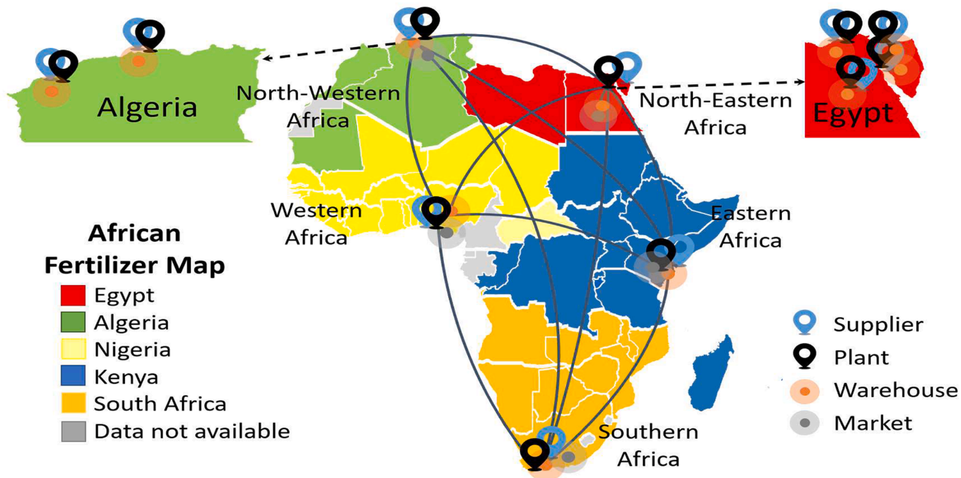


Fig. 8. Diagram of the decentralised ammonia supply chain showing the distributed ammonia plants based on the selected locations across Africa. Egypt and Algeria locations have been magnified to show that multiple plants have been implemented to meet the market demands and ensure plant capacities are within current feasible limits. The countries each plant would supply to have also been grouped by colour.

investment expenses. Among renewable technologies, the integrated HTP and mini-HB (scenario 6) offer the most cost-effective option, supplying ammonia at US $232/ton. While the price for water electrolysis and mini-HB (scenario 8) is the next best renewable option, supplying ammonia at US $385/tonne, the feasibility of water electrolysis is limited as Africa is a water-stressed continent, with water scarcity increasing across many countries, as identified through literature review and technology assessment. The cost is still approximately 1.7 times higher than HTP and mini-HB with oxygen credits being incorporated at US $0.7/kg. This is because the plant investment costs are greater as well as higher energy consumption [1]. As anticipated, ammonia production through NTP proved to be the most costly option. The scenario employing HTP and NTP (scenario 7) exhibited the highest supply cost at US $1442/tonne, while the utilization of water electrolysis and NTP (scenario 9) similarly incurred a high supply cost of US $1249/tonne. Presently, NTP technology for ammonia production remains feasible only at laboratory-scale plants, unlike the other technologies assessed in this study, which are all either at or near production scale. Further development is imperative for NTP technology to evolve into an economically viable option for ammonia synthesis in the future [1].

These findings indicate that the decentralised model utilizing HTP and mini-HB (scenario 6) can compete effectively with conventional technology. The supply cost is only 10 % higher than conventional technology within the decentralised supply chain, and a mere 2 % higher when factoring in the carbon tax. The supply cost for HTP and mini-HB includes environmental credits due to the co-production of carbon black, assuming a conservative sale price of US $1/kg. In comparison to the traditional approach of a centralised mega plant employing conventional processes, the supply cost is 28 % higher, and 18 % higher when factoring in the carbon tax. When both environmental credits and potential carbon taxes are considered, the economic competitiveness of the HTP and mini-HB process notably improves, presenting an appealing solution for transforming the ammonia supply chain in Africa. Further exploration into environmental credits should be contemplated; if higher credits can be anticipated in the future, it could enhance the competitiveness of this technology even further. Ultimately, these results underscore the potential of HTP and mini-HB to provide ammonia at a highly competitive price, particularly when additional cost internalisations are integrated to augment the value of the ammonia supply chain based on ESG factors.

4.2. Centralised conventional model vs decentralised renewable model

The impact of the REC-based approach, as utilized in the decentralised model, underwent scrutiny to assess potential reductions in tax barriers affecting ammonia supply costs. This investigation involved determining adjusted ammonia supply costs based on estimated tariff rates for both the centralised and decentralised models. In the centralised supply chain, a single mega plant in Egypt serves as the export hub to the five primary markets dispersed across Africa. Consequently, Egypt exports to countries that may not necessarily belong to the same REC, potentially subjecting them to higher tariff rates compared to if they received goods from a fellow REC member. An average tariff rate was computed considering the REC memberships of both importing and exporting countries. Table 6 provides a glimpse into the adjusted ammonia supply costs calculated to account for the impact of export tariffs. For the decentralised renewable model, the supply cost for the HTP and mini-HB technology was used as the basis. The decentralised model utilised intra-REC trade to develop a continental ammonia supply. Lower tariff rates can be achieved through intra-REC trade [45].

In the centralised model, when tariff rates on exports are factored in, the average ammonia cost across Africa rises to US $195/tonne, and

Table 6
Adjusted ammonia supply costs incorporating the average tariff rate for export from the mega plant in Egypt to the five main markets considered across Africa. The base cost for conventional technology without carbon tax is US $181/tonne and for the case with carbon tax US $197/tonne. Tariff rates were obtained from UNCTAD 2019 [45].

Plant Location	Market Location	REC	Average Tariff Rate (%)	Adjusted Ammonia Supply Cost (US $/tonne)	
				No Carbon Tax	With Carbon Tax
Egypt	Egypt	COMESA CEN-SAD	-	181	197
	Algeria	AMU/UMA	15	208	227
	Nigeria	ECOWAS CEN-SAD	12	204	222
	Kenya	IGAD CENSAD COMESA EAC	4	189	206
	South Africa	SADC	7	194	211

when including carbon tax, it reaches US $212/tonne. This represents approximately a 7.8 % increase compared to the base cost where tariffs were not considered. For the decentralised model incorporating renewable technology, the cost of ammonia, accounting for tariff rates, stands at US $245/tonne, marking roughly a 5.5 % increase from the base cost. This suggests that the decentralised model holds potential for reducing the supply cost of ammonia through intra-REC trade. While this simplifies trade relationships and associated tariffs, it provides an indication that intra-REC trade can indeed mitigate supply costs. The value added to the supply chain through intra-REC trade could be integrated into the subsequent ESG assessment. It's worth noting that ammonia supply through the traditional centralised model could incur additional tariffs if countries receive fertilisers through indirect pathways, especially for landlocked countries lacking sea-port facilities [45]. Table 7 outlines the adjusted ammonia supply cost with tariff rates incorporated when the plants supply ammonia to surrounding countries within the same REC.

A key advantage of the decentralised model is that with multiple exporters of ammonia-based fertiliser, countries can opt to import from those with the lowest tax rates, thus reducing fertiliser costs. Further exploration into tariff rates and trade agreements between countries would be necessary to fully assess the potential of the intra-REC trade approach in alleviating tariff barriers. Beyond its cost implications, the decentralised ammonia supply model presents a strategically superior alternative to conventional centralised systems, offering enhanced operational flexibility, regional adaptability, and long-term resilience, particularly within the African context. Centralised models are inherently susceptible to systemic disruptions such as port congestion, infrastructure failures, political instability, and global trade shocks, which can significantly hinder fertiliser accessibility. In contrast, decentralised systems distribute production capacity across multiple nodes, thereby reducing reliance on singular export hubs and increasing the robustness of the supply chain. This distributed structure allows for better alignment with local agricultural calendars, climatic variations, and fertiliser usage practices, improving responsiveness to regional demand. The decentralised systems reduce both logistical distances and costs by situating production closer to demand centres, yielding estimated transport savings of 20–30 % in comparison with centralised systems [69,84,105].

Moreover, decentralised facilities can be optimally sized and timed to align with regional planting cycles and fertiliser application windows, enhancing the efficiency of input delivery. Furthermore, decentralised plants benefit from preferential intra-REC trade arrangements, effectively minimising tariff-related costs and streamlining cross-border logistics, particularly in landlocked and infrastructure-constrained regions. The model also enables seamless integration with decentralised renewable energy systems, such as solar, hydro, and wind power, supporting a transition toward low-carbon and locally powered fertiliser production. From a socio-economic perspective, decentralised production facilitates local job creation, skills development, and the establishment of green industrial clusters, contributing to broader development goals and strengthening national food sovereignty. Socio-economically, the localisation of fertiliser production through decentralised plants is projected to support the creation of 5–8 full-time jobs per 10,000 tonnes of ammonia produced annually, spanning operations, maintenance, logistics, and agronomic support as compared by Davide et al. [71]. In addition, the development of regional decentralised supply chains fosters technological capacity, knowledge transfer, and rural industrialisation. The attributes collectively highlight the decentralised model as not only a viable alternative but also a crucial element of a future-oriented, climate-resilient, and socially inclusive ammonia supply framework duly when compared with as centralised major planetary boundary work [90]. Current decentralised model approach has proved to be capable of promoting regional self-sufficiency and advancing global sustainability objectives [55], particularly from an ESG and financial perspective.

Table 7
Adjusted ammonia supply costs incorporating the average tariff rate for export based on the decentralised supply chain exporting to surrounding countries. The base cost for the thermal plasma and mini-HB technology was US $232/tonne. Tariff rates were obtained from UNCTAD 2019 [45].

Plant Location	REC	REC Tariff Rate (%)	Adjusted Ammonia Supply Cost (US$/tonne)
Egypt	COMESA	2.6	238
Algeria	AMU/ UMA	16.6	271
Nigeria	ECOWAS	5	244
	CEN-SAD	9.0	253
Kenya	EAC	0.1	232
	IGAD	1.3	235
	COMESA	2.6	238
	CENSAD	9.0	253
South Africa	SADC	2.7	238

4.3. ESG assessment and cost internalisation

A preliminary methodology has been created to assess the additional value generated by including ESG aspects in the implementation of a decentralised ammonia supply chain in Africa. These indicators were used to assess the practicality of the selected plant locations and their contribution to the supply chain in terms of ESG factors. Appendix 1 displays the results of the ESG evaluation, where each plant site is assigned, a score using a system that uses different colours. For example, in Kenya, where 77 % of the energy is presently obtained from renewable sources, there are ample resources available to sustain an ammonia manufacturing facility. In contrast, the present use of renewable energy in Algeria is far lower, indicating that obtaining electricity from renewable sources in this area may be less viable. As a result, Kenya is categorized as green and Algeria as red for this particular aspect. In terms of food security, Nigeria experiences elevated levels of malnutrition and utilizes a significant amount of agricultural land. These findings indicate that implementing a decentralised supply chain that produces ammonia-based fertilizer locally and on-demand might enhance agricultural production. This, in turn, would lead to increased nitrogen consumption and improvements in food security and malnutrition rates within the country. Consequently, Nigeria was classified as "green" based on this criterion. According to this evaluation, it is noted that every factory location would contribute to the supply chain, while certain locations would have a greater impact than others. In the future, this framework will incorporate more ESG indices as the project progresses. A thorough analysis of literature produced critical performance indicators that may be effectively measured. These indicators are included in Appendix 2. These factors will be included in the ESG evaluation to initially evaluate the suitability of the plant sites based on a binary assessment for each criterion, as done for the existing indices. They will subsequently be utilised to establish the overall feasibility. The primary objective is to convert these ESG measures into a factor that can be employed to modify the ammonia supply cost in order to accurately reflect the value that can be contributed to the ammonia supply chain by utilizing decentralised renewable technology. An evaluation of ESG aspects is now in progress, and the associated costs will be incorporated into future articles. The inclusion of ESG elements in the ammonia supply prices for the decentralised model utilizing HTP and mini-HB technologies is expected to enhance its economic competitiveness compared to traditional routes employing conventional methods.

5. Conclusions

This study emphatically underscores the transformative potential of incorporating Environmental, Social, and Governance concerns into the ammonia supply chain, particularly in Africa. Through the application of an ESG-driven framework, this research confronts the persistent inefficiencies of traditional, centralised ammonia production systems, which have long hindered access to affordable fertilizers, particularly in remote and underdeveloped regions. By strategically evaluating plant locations based on weighted ESG criteria, the study identifies Egypt, Algeria, Nigeria, Kenya, and South Africa as optimal sites for decentralised ammonia production. The economic analysis further reveals those innovative technologies, such as high thermal plasma (HTP) and mini-Haber-Bosch (mini-HB), hold the potential to effectively compete with conventional ammonia production methods, especially when paired with renewable energy sources and environmental credits. This approach offers a critical challenge to traditional systems, which remain entrenched in carbon-intensive processes. ESG based supply chain integration and computational optimisation provide systematic results that intra-Regional Economic Community trade presents an invaluable opportunity for reducing fertilizer costs via tariff reductions, making localized production models more feasible and sustainable. While centralized systems may still offer lower base prices for ammonia, their inherent inefficiencies, marked by high transport costs, poor infrastructure, and extended lead times, continue to hinder accessibility, particularly for small-scale farmers in remote areas. In light of these challenges, the study advocates for the strategic incorporation of ESG factors into global ammonia supply chains. This shift ensures that environmental sustainability, social equity, and economic considerations are not merely complementary but central to the operationalization of ammonia production systems. The development of ESG indexes tailored to assess plant locations and their potential contributions to the supply chain establishes a robust framework for future research. The critical next step lies in quantifying these ESG indexes, enabling cost internalizations that better reflect the value added through sustainable practices. This approach paves the way for further exploration into scalable, decentralised systems that align with global sustainability targets. By adopting this comprehensive, ESG-aligned model, ammonia production can be redefined as a more resilient, equitable, and sustainable process. This study asserts that decentralised ammonia production is not only an economically viable alternative but also a crucial solution to pressing environmental and social challenges. It calls for a paradigm shift in the way ammonia is produced, distributed, and consumed globally, particularly in Africa. The incorporation of ESG factors elucidates strategies to develop a more resilient and sustainable ammonia supply chain that fortifies local economies, promotes environmental sustainability, and guarantees enduring solutions for hunger and malnutrition. Ultimately, this strategy will facilitate create a fair global food system, promote a future resilient to climate change, and greatly aid in the accomplishment of the UN SDG's.

6. Implication, limitations and future directions

The innovative, advanced, and multidisciplinary paradigm study has incorporated ESG factors into techno-economic analyses of decentralised ammonia production in Africa. The findings have provided a significant advancement towards achieving more sustainable and inclusive supply chains. The viability of renewable technologies like high thermal plasma and mini-Haber-Bosch can be effectively demonstrated, especially when considering carbon pricing and environmental credits. However, the methodology would gain from more thorough critical enhancement. The application of ESG metrics in site selection is significant, however, they have not been completely integrated into the cost optimisation model, which restricts their strategic impact on economic decision-making. Furthermore, the dependence on fixed assumptions and the nascent development of specific technologies imposes limitations on evaluating their scalability over the long term. Variations in infrastructure, governance, and data accessibility across regions pose significant obstacles to consistent implementation. On the other hand, our study established a significant foundation for subsequent multidisciplinary investigations. Another approach, like enhancing this model through dynamic systems analysis, quantitative risk ESG valuation, and pilot-scale deployment is crucial for unlocking the full potential of a decentralised, low-carbon, and socially responsive ammonia supply chain designed to meet the varied development needs across the globe.

CRediT authorship contribution statement

Nam Nghiep Tran: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Lucy Kate Penna:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology. **Isla May Heath:** Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Data curation, Conceptualization. **Muhammad Yousaf Arshad:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Marc Escribà Gelonch:** Writing – original draft, Funding acquisition, Formal analysis, Data curation. **Jose Luis Osorio Tejada:** Writing – review & editing, Writing – original draft, Validation, Software. **Mohammad Mohsen Sarafraz:** Writing – review & editing, Supervision, Software, Methodology, Formal analysis. **John Suberu:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Funding acquisition. **Martin Fregene:** Writing – original draft, Formal analysis, Conceptualization. **Bernard Rolfe:** Writing – original draft, Project administration, Funding acquisition, Data curation. **Volker Hessel:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.sftr.2025.100893.

Data availability

Data will be made available on request.

References

[1] N.N. Tran, et al., Economic optimization of local australian ammonia production using plasma technologies with green/turquoise hydrogen, ACS Sustain. Chem. Eng. 9 (48) (2021) 16304–16315.
[2] F. Tahir, et al., Integrated process for simulation of gasification and chemical looping hydrogen production using artificial neural network and machine learning validation, Energy Convers. Manage 296 (2023) 117702.
[3] H. Gul, M.Y. Arshad, M.W. Tahir, Production of H2 via sorption enhanced auto-thermal reforming for small scale applications-a process modeling and machine learning study, Int. J. Hydrog. Energy 48 (34) (2023) 12622–12635.
[4] E. Morgan, J. Manwell, J. McGowan, Wind-powered ammonia fuel production for remote islands: a case study, Renew. Energy 72 (2014) 51–61.
[5] M. Reese, et al., Performance of a small-scale Haber process, Ind. Eng. Chem. Res. 55 (13) (2016) 3742–3750.
[6] F. Saleem, et al., Decomposition of benzene as a biomass gasification tar in CH4 carrier gas using non-thermal plasma: parametric and kinetic study, J. Energy Inst. 102 (2022) 190–195.

[7] A.M. Yousaf, R. Aqsa, Integrating circular economy, SBTI, digital LCA, and ESG benchmarks for sustainable textile dyeing: a critical review of industrial textile practices, Glob. NEST J. 25 (2023) 39–51.
[8] H. Fekete, et al., The role of green hydrogen in a just, Paris-compatible transition. 2023.
[9] M.A. Saeed, et al., Combustion and explosion characteristics of pulverised wood, valorized with mild pyrolysis in pilot scale installation, using the modified ISO 1 m3 dust explosion vessel, Appl. Sci. 12 (24) (2022) 12928.
[10] A. Yar, et al., Machine learning-based relative performance analysis of monocrystalline and polycrystalline grid-tied PV systems, Int. J. Photoenergy 2022 (1) (2022) 3186378.
[11] D. Malpass A transformed fertilizer market is needed in response to the food crisis in Africa. 2022 [cited 2023 1/7]; Available from: https://blogs.worldbank.org/voices/transformed-fertilizer-market-needed-response-food-crisis-africa#:~:text=The20continent20produces20approximately2030,mostly20from20outside20the20continent.
[12] M.Y. Arshad, et al., Integrating life cycle assessment and machine learning to enhance black soldier fly larvae-based composting of kitchen waste, Sustainability 15 (16) (2023) 12475.
[13] M.Y. Arshad, et al., Maximizing hydrogen-rich syngas production from rubber wood biomass in an updraft fluidized bed gasifier: an advanced 3D simulation study, J. Taiwan Inst. Chem. Eng. 156 (2024) 105365.
[14] P.P. Marenya, C.B. Barrett, Soil quality and fertilizer use rates among smallholder farmers in western Kenya, Agric. Econ. 40 (5) (2009) 561–572.
[15] R.M. Ogeto, G. Jiong, Fertilizer underuse in Sub Saharan Africa: evidence from Maize, J. Agric. Econ. Dev. 7 (2019) 11–28.
[16] Y. Arshad, et al., Optimization of acid-assisted extraction of pectin from banana (Musa Acuminata) peels by central composite design, Glob. NEST J. 24 (2022) 752–756.
[17] M.D. Mukelabai, U.K. Wijayantha, R.E. Blanchard, Renewable hydrogen economy outlook in Africa, Renew. Sustain. Energy Rev. 167 (2022) 112705.
[18] M.Y. Arshad, et al., Pioneering the future: a trailblazing review of the fusion of computational fluid dynamics and machine learning revolutionizing plasma catalysis and non-thermal plasma reactor design, Catalysts 14 (1) (2024) 40.
[19] M.Y. Arshad, et al., Metal (II) triazole complexes: synthesis, biological evaluation, and analytical characterization using machine learning-based validation, Eur. J. Chem. 14 (2023) 155–164.
[20] T. Benson, T. Mogues, Constraints in the fertilizer supply chain: evidence for fertilizer policy development from three African countries, Food Secur. 10 (2018) 1479–1500.
[21] I.N. Kessides, Regionalising infrastructure for deepening market integration: the case of East Africa, J. Infrastruct. Dev. 4 (2) (2012) 115–138.
[22] M.A. Rafique, et al., Green synthesis of copper nanoparticles using Allium cepa (onion) peels for removal of disperse yellow 3 dye, Desalin. Water Treat. 272 (2022) 259–265.
[23] M. Rafique, et al., Effective removal of direct orange 26 dye using copper nanoparticles synthesized from Tilapia fish scales, Glob. NEST J. 24 (2022) 311–317.
[24] S. Saeed, M.Y. Arshad, A.S. Ahmed, Advancing circular economy in industrial chemistry and environmental engineering: principles, alignment with United Nations sustainable development goals, and pathways to implementation, Eur. J. Chem. 14 (3) (2023) 414–428.
[25] A. Mehmood, et al., Optimization of gasifying agents in 3D downdraft gasification for enhanced gas composition, combustion, and CO2 utilization, Fire 6 (9) (2023) 361.
[26] M.Y. Arshad, et al., Advancing sustainable decomposition of biomass tar model compound: machine learning, kinetic modeling, and experimental investigation in a non-thermal plasma dielectric barrier discharge reactor, Energies 16 (15) (2023) 5835 (Basel).
[27] S. Saeed, et al., Influence of thermal and chemical treatment on biosorbent from rice husk and its application in removal of resorcinol from industrial wastewater, Processes 11 (12) (2023) 3344.
[28] M.Y. Arshad, et al., Role of experimental, modeling, and simulation studies of plasma in sustainable green energy, Sustainability 15 (19) (2023) (2071-1050).
[29] M. Tahir, et al., Modelling and simulation of an integrated coupled reactor for hydrogen production and carbon dioxide utilisation in an integrated fuel cell power system, J. Taiwan Inst. Chem. Eng. 167 (2025) 105857.
[30] M. Sheahan, J. Ariga, T.S. Jayne, Modeling the effects of input market reforms on fertiliser demand and maize production: a case study from Kenya, J. Agric. Econ. 67 (2) (2016) 420–447.
[31] B. Kiger and K. Adodo, Getting fertiliser into farmers' hands'. Grain de Sel, 2010. 51.
[32] T.S. Jayne, S. Rashid, Input subsidy programs in sub-Saharan Africa: a synthesis of recent evidence, Agric. Econ. 44 (6) (2013) 547–562.
[33] M.Y. Arshad, D. Lewis, N.N. Tran, Empowering sustainability: integrating ESG principles for a net-zero future through decentralised process plant design, in: Proceedings of the International Conference on Environmental, Social, and Governance (ICESG 2024), Atlantis Press, 2025.
[34] M.Y. Arshad, A. Halog, Life cycle assessment of various process routes including biological processes for renewable fuel production. Sustainable and Green Catalytic Processes for Renewable Fuel Production with Net-Zero Emissions, Elsevier, 2025, pp. 377–428.
[35] A. Modzelewska, et al., Sustainable production of biohydrogen: feedstock, pretreatment methods, production processes, and environmental impact, Fuel Process. Technol. 266 (2024) 108158.
[36] J. Osorio-Tejada, N.N. Tran, V. Hessel, Techno-environmental assessment of small-scale Haber-Bosch and plasma-assisted ammonia supply chains, Sci. Total Environ. 826 (2022) 154162.
[37] H. Hussain, et al., Kinetic and thermodynamic parameter optimization of an anode-supported solid oxide fuel cell: a computational fluid dynamics study, J. Electrochem. Sci. Technol. (2024).
[38] T.K. Pham, et al., Developing microfluidic purification techniques for biodiesel production from recycled grease trap waste, Sustain. Energy Fuels (2024).
[39] M.Y. Arshad and M. Azam. Environmental friendly specialty chemical plants for developing world: a roadmap for economic development and sustainability with waste reduction. in BOOK OF ABSTRACTS. 2021.
[40] S. McGuire, FAO, IFAD, and WFP. The state of food insecurity in the world 2015: meeting the 2015 international hunger targets: taking stock of uneven progress. Rome: FAO, 2015, Adv. Nutr. 6 (5) (2015) 623–624.
[41] S. Gomez y Paloma, L. Riesgo, K. Louhichi, The Role of Smallholder Farms in Food and Nutrition Security, Springer Nature, 2020.
[42] B. Davis, S. Di Giuseppe, A. Zezza, Are African households (not) leaving agriculture? Patterns of households' income sources in rural Sub-Saharan Africa, Food Policy 67 (2017) 153–174.
[43] E. Donkor, et al., Fertiliser adoption and sustainable rural livelihood improvement in Nigeria, Land Use Policy 88 (2019) 104193.
[44] W. Kassa, P.N. Sawadogo, Trade Creation and Trade Diversion in African RECs, World Bank, 2021.
[45] UNCTAD, Key Statistics and Trends in Regional Trade in Africa, UNCTAD, Geneva, 2019, pp. 2263–7960.
[46] U.O. Uzodike, The role of regional economic communities in Africa's economic integration: prospects and constraints, Afr. Insight 39 (2) (2009) 26–42.
[47] B. Warf, B. Warf, Geographies of Sub-Saharan African corruption, Glob. Corrupt. Geogr. Perspect. (2019) 111–141.
[48] A. Vrieling, J. De Leeuw, M.Y. Said, Length of growing period over Africa: variability and trends from 30 years of NDVI time series, Remote Sens. 5 (2) (2013) 982–1000 (Basel).
[49] UNCTAD, U.O.A., Key Statistics and Trends in Regional Trade in Africa, UNCTAD, Geneva, 2019, pp. 2263–7960.
[50] M.C. Udeagha, M.C. Breitenbach, Can fiscal decentralization be the route to the race to zero emissions in South Africa? Fresh policy insights from novel dynamic autoregressive distributed lag simulations approach, Environ. Sci. Pollut. Res. 30 (16) (2023) 46446–46474.
[51] D. Tenaw, A.D. Beyene, Environmental sustainability and economic development in sub-Saharan Africa: a modified EKC hypothesis, Renew. Sustain. Energy Rev. 143 (2021) 110897.
[52] C. Smith, L. Torrente-Murciano, The potential of green ammonia for agricultural and economic development in Sierra Leone, One Earth 4 (1) (2021) 104–113.
[53] D. Nong, Development of the electricity-environmental policy CGE model (GTAP-E-PowerS): a case of the carbon tax in South Africa, Energy Policy 140 (2020) 111375.
[54] Y. Wang, et al., State-of-the-art review on evaluation indicators of integrated intelligent energy from different perspectives, Renew. Sustain. Energy Rev. 189 (2024) 113835.
[55] C. Smith, A.K. Hill, L. Torrente-Murciano, Current and future role of Haber–Bosch ammonia in a carbon-free energy landscape, Energy Environ. Sci. 13 (2) (2020) 331–344.
[56] R. Society, Ammonia: Zero-Carbon Fertiliser, Fuel and Energy Store: Policy Briefing, Royal Society, 2020.
[57] M.M. Sarafraz, et al., Tri-fold process integration leveraging high-and low-temperature plasmas: from biomass to fertilizers with local energy and for local use, J. Adv. Manuf. Process. 3 (2) (2021) e10081.
[58] FAO, GIEWS-Global Information and Early Warning System. United Nations, 2020.
[59] L. Yu, et al., ESG assessment methodology for emerging technologies: plasma-versus conventional technology for Ammonia production, RSC Sustain. (2025).
[60] Y. Yousfi and J. Thewissen, Challenges and opportunities in the development of ESG structured products: an analysis of the financial industry.
[61] M. Singhania, D. Gupta, Impact of environmental, social and governance (ESG) disclosure on firm risk: a meta-analytical review, Corp. Soc. Responsib. Environ. Manage 31 (4) (2024) 3573–3613.
[62] R. Seth, S. Gupta, H. Gupta, ESG investing: a critical overview, Hans Shodh Sudha 2 (2) (2021) 69–80.
[63] M. Pompella, L. Costantino, ESG disclosure and sustainability transition: a new metric and emerging trends in responsible investments, TalTech J. Eur. Stud. 13 (1) (2023) 8–39.
[64] A. Panagopoulos, I. Tzionas, The use of sustainable financial instruments In relation to the social impact investment: ESG policies, capital markets' approach and investors' protection: an innovative perspective for a global surveillance authority, Int. J. Bus. Adm. (2023).
[65] E. Palmieri, E.F. Geretto, ESG Innovation in the Financial industry. Adapting to Change: ESG and Alternative Finance in Shaping the Bank-Firm Relationship, Springer, 2024, pp. 63–95.
[66] O.I.K. Olanrewaju, G.O. Daramola, O.A. Babayeju, Transforming business models with ESG integration: a strategic framework for financial professionals, World J. Adv. Res. Rev. 22 (3) (2024) 554–563.
[67] FAO, G., GIEWS-global information and early warning system. 2020.
[68] N.N. Tran, et al., Economic optimization of local Australian ammonia production using plasma technologies with green/turquoise hydrogen, ACS Sustain. Chem. Eng. 9 (48) (2021) 16304–16315.

[69] J. Osorio-Tejada, et al., Sustainability analysis of methane-to-hydrogen-to-ammonia conversion by integration of high-temperature plasma and non-thermal plasma processes, Energy Convers. Manage 269 (2022) 116095.
[70] L.R. Winter, J.G. Chen, N2 fixation by plasma-activated processes, Joule 5 (2) (2021) 300–315.
[71] D. Tonelli, et al., Cost-competitive decentralized ammonia fertilizer production can increase food security, Nat. Food 5 (6) (2024) 469–479.
[72] X. Tang, et al., Ultra-low pressure membrane-based bio-purification process for decentralized drinking water supply: improved permeability and removal performance, Chemosphere 211 (2018) 784–793.
[73] J. Sun, et al., A hybrid plasma electrocatalytic process for sustainable ammonia production, Energy Environ. Sci. (2021) 14.
[74] R.J. Stoklosa, et al., Techno-economic comparison of centralized versus decentralized biorefineries for two alkaline pretreatment processes, Bioresour. Technol. 226 (2017) 9–17.
[75] N. Srivastava, et al., Prospects of solar-powered nitrogenous fertilizers, Renew. Sustain. Energy Rev. 187 (2023) 113691.
[76] R.K. Sharma, et al., Plasma activated electrochemical ammonia synthesis from nitrogen and water, ACS Energy Lett. 6 (2) (2020) 313–319.
[77] M.M. Sarafraz, et al., Thermodynamic potential of a novel plasma-assisted sustainable process for co-production of ammonia and hydrogen with liquid metals, Energy Convers. Manage 210 (2020) 112709.
[78] C.R. Santhosh, R. Sankannavar, A comprehensive review on electrochemical green ammonia synthesis: from conventional to distinctive strategies for efficient nitrogen fixation, Appl. Energy 352 (2023) 121960.
[79] S. Samipour, M.R. Rahimpour, Chapter two - nonthermal plasma-assisted ammonia synthesis technologies, in: A. Basile, M.R. Rahimpour (Eds.), Progresses in Ammonia: Science, Technology and Membranes, Elsevier, 2024, pp. 33–62.
[80] K.H. Rouwenhorst, et al., Plasma-driven catalysis: green ammonia synthesis with intermittent electricity, Green Chem. 22 (19) (2020) 6258–6287.
[81] P. Peng, et al. Current situation of non-thermal plasma (NTP) ammonia synthesis and its potential to build a sustainable nitrogen fixation industry. 2018.
[82] B.S. Patil, et al., Plasma N2-fixation: 1900–2014, Catal. Today 256 (2015) 49–66.
[83] D. Panchal, et al., Advanced cold plasma-assisted technology for green and sustainable ammonia synthesis, Chem. Eng. J. 498 (2024) 154920.
[84] J.L. Osorio-Tejada, E. Rebrov, V. Hessel, Internalisation of environmental costs of decentralised nitrogen fertilisers production, Int. J. Life Cycle Assess. 28 (11) (2023) 1590–1603.
[85] E.R. Morgan Techno-economic feasibility study of ammonia plants powered by offshore wind. 2013.
[86] C.F. Guerra, et al., Technical-economic analysis for a green ammonia production plant in Chile and its subsequent transport to Japan, Renew. Energy 157 (2020) 404–414.
[87] C.A. Fernández, et al., Achieving decentralized, electrified, and decarbonized ammonia production, Environ. Sci. Technol. 58 (16) (2024) 6964–6977.
[88] M. Fasihi, et al., Global potential of green ammonia based on hybrid PV-wind power plants, Appl. Energy 294 (2021) 116170.
[89] J.W. Erisman, et al., How a century of ammonia synthesis changed the world, Nat. Geosci. 1 (10) (2008) 636–639.
[90] S.C. D'Angelo, et al., Planetary boundaries analysis of low-carbon ammonia production routes, ACS Sustain. Chem. Eng. 9 (29) (2021) 9740–9749.
[91] H. Chen, et al., Review of low-temperature plasma nitrogen fixation technology, Waste Dispos. Sustain. Energy 3 (3) (2021) 201–217.
[92] J. Brightling, Ammonia and the fertiliser industry: the development of ammonia at Billingham, Johns. Matthey Technol. Rev. 62 (1) (2018) 32–47.
[93] A. Boretti, Reviewing the progress toward an ammonia energy storage ecosystem, Int. J. Hydrog. Energy 63 (2024) 472–479.
[94] I. Barnosell, C. Pozo, The impacts of the European chemical industry on the planetary boundaries, Sustain. Prod. Consum. 44 (2024) 188–207.
[95] A. Anastasopoulou, et al., Environmental impact assessment of plasma-assisted and conventional ammonia synthesis routes, J. Ind. Ecol. 24 (5) (2020) 1171–1185.
[96] H.S. Ahmed, et al., Sustainable pathways to ammonia: a comprehensive review of green production approaches, Clean Energy 8 (2) (2024) 60–72.
[97] D. Vázquez, G. Guillén-Gosálbez, Process design within planetary boundaries: application to CO2 based methanol production, Chem. Eng. Sci., 246 (2021) 116891.
[98] K. Sahoo, et al., GIS-based biomass assessment and supply logistics system for a sustainable biorefinery: a case study with cotton stalks in the Southeastern US, Appl. Energy 182 (2016) 260–273.
[99] E. Ojetunde, et al., Integrating Environmental, Social, and Governance Criteria in Corporate Auditing: A Multiple Criteria Decision Making, World Scientific News, 2024.
[100] K. Narine, et al., Climate smart process design for current and future methanol production, J. CO2 Util. 44 (2021) 101399.
[101] K. Im-orb, A. Arpornwichanop, Process and sustainability analyses of the integrated biomass pyrolysis, gasification, and methanol synthesis process for methanol production, Energy 193 (2020) 116788.
[102] A. Azadeh, S.A Zadeh, An integrated fuzzy analytic hierarchy process and fuzzy multiple-criteria decision-making simulation approach for maintenance policy selection, Simulation 92 (2015).
[103] A. Arias, G. Feijoo, M.T. Moreira, Biorefineries as a driver for sustainability: key aspects, actual development and future prospects, J. Clean. Prod. 418 (2023) 137925.
[104] V. Agarwal, A. Hingne, S. Gupta, Internal carbon pricing: aligning business priorities with climate action, Obs. Res. Found. (2023) 22.
[105] J.L. Osorio-Tejada, et al., The sustainability impact of nobel prize chemistry: life cycle assessment of C–C cross-coupling reactions, Green Chem. 25 (23) (2023) 9760–9778.