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Catalytic innovations in fertilizer production from agricultural waste: Enhancing soil health and sustainability☆

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A B S T R A C T

Catalytic technologies facilitate the conversion of agricultural waste into high-value fertilizers, enhancing nutrient recovery efficiency while mitigating environmental impacts through reduced greenhouse gas emissions and improved soil management. Selective catalytic reduction (SCR), hydrothermal carbonization (HTC), catalytic pyrolysis, and electrochemical nutrient recovery raise plant-available N, P, and K while reducing life-cycle greenhouse-gas emissions by up to 30 %. These processes support decarbonization efforts and advance circular-economy principles. The article examines catalyst design, process optimization, and the integration of catalytic biomass conversion with renewable-energy systems. Innovative waste-derived fertilizers enhance soil health, lower contamination risks, and strengthen agricultural resilience. Case studies document economic and environmental gains, such as higher nutrient-use efficiency and lower pollutant loads. The review also evaluates regulatory hurdles linked to standardizing and adopting bio-based fertilizers. Future work should explore data-driven catalyst design, microbially assisted nutrient recovery, and the scale-up of promising pilot systems. An integrated catalysis-materials-green-chemistry framework for fertilizer production is presented, advancing food security, improving energy efficiency, and strengthening environmental stewardship.

1. Introduction

The agricultural sector faces increasing pressure to improve food production sustainability amid rising demand and environmental concerns. Conventional fertilizers derive from non-renewable phosphate rock and natural gas and, in excess, contribute to soil degradation, water pollution, and greenhouse-gas emissions [1–5]. Sustainable alternatives are essential. Ammonia synthesis through the Haber-Bosch process represents a major industrial source of CO_2 emissions, responsible for roughly 1.8 % of global totals and approximately 2 % of global energy consumption, due to high operating pressures (200–300 bar) and temperatures (400–500 °C) [6,7]. Excess nitrogen fertilization accelerates eutrophication and raises emissions of ammonia (NH_3) and nitrous oxide (N_2O), the latter having a GWP almost 300 times that of CO_2 [8]. Current policy frameworks endorse renewable feedstocks; agricultural biomass is now recognized as a viable nutrient reservoir [9–11]. The European Union prioritizes waste valorization to improve resource efficiency [12]. Nutrient-enriched biomass serves as a feedstock for organic and slow-release fertilizers [11,13]. Efficient stabilization and recovery of nitrogen, phosphorus, and potassium are crucial for expanding these technologies.

Modern biomass-fertilizer technology rests on interdisciplinary research integrating process engineering, catalytic chemistry, materials science, and agronomy [14]. This interdisciplinary approach fosters the development of advanced catalytic solutions that enhance nutrient recovery, decrease reliance on non-renewable inputs, and lower environmental footprint. Catalytic processes are central to converting agricultural biomass because they enable efficient nutrient recovery while reducing emissions of harmful substances [13]. Selective Catalytic Reduction (SCR) minimizes nitrogen oxide (NO_x) emissions during biomass combustion, simultaneously enabling controlled ammonia (NH_3) recovery for fertilizer synthesis [15]. Moreover, the implementation of catalytic technologies allows optimization of industrial processes, which consequently translates into economic benefits. The literature indicates that the use of modern catalysts makes it possible to achieve high efficiency with relatively low energy use [16].

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Catalytic processes enable innovative biomass conversion methods, for example, catalytic pyrolysis, hydrothermal carbonization (HTC) [17], electrochemical recovery [18] and thermochemical gasification of biomass [19]. Catalytic pyrolysis decomposes waste biomass into bio-oil, syngas, and biochar, each with potential fertilizer applications. Particularly relevant in the fertilizer context is biocarbon, which has a positive effect on soil properties, increasing water retention [20] or its microbial activity [21]. Enriched with nutrients, it can also be used as controlled-release micronutrient fertilizers [22]. Biochar-based formulations enhance carbon sequestration and mitigate greenhouse gas emissions, improving soil health and long-term sustainability [23]. Catalysts in pyrolysis lower activation energy, enhance reaction efficiency, and increase carbon content in the final product [24,25]. The use of ZnO or CuO catalysts enables the selective removal of undesired substrates while enhancing reaction efficiency [26,27]. Catalytic hydrothermal carbonization of biomass is also an alternative [17]. Wang et al. in their study showed that CaO used in microwave-assisted hydrothermal carbonization promotes phosphorus accumulation in hydrochars and improves their combustion properties [17]. Recent studies indicate that iron- and cobalt-based catalysts can recover up to 90 % of nitrogen as ammonia, enhancing fertilizer production efficiency [28,29].

This article examines the theoretical foundations and experimental validation of catalytic processes in biomass conversion. This review describes technological, economic, and regulatory challenges in fertilizer production from renewable feedstocks and provides research directions for process optimization. Given the increasing market and environmental demands, advancing catalytic technologies is not just an alternative, but a necessity for global agriculture.

The agricultural sector must adopt strategies that strengthen the food-energy-water nexus and promote sustainable development. Catalytic technologies offer an alternative to fertilizers synthesized from non-renewable resources that reduce soil degradation, reduce greenhouse gas emissions, and support decarbonization goals. This review examines advanced catalytic approaches for biomass conversion, focusing on their role in reducing greenhouse gases, improving fertilizer quality, and circular economy practices. Converting agricultural residues into fertilizers recovers critical nutrients while mitigating emissions, aligning with efforts in the hydrogen economy and water treatment catalysis. A holistic catalyst design can drive low-carbon development across multiple sectors.

2. Agricultural waste: transforming residues into valuable resources

Agricultural waste arises throughout the production cycle, including crop harvesting, post-processing, and livestock management [30]. It can be classified into the following categories [31]:

- Crop residues - cereal straw, corn stalks, rice husks, wheat, and barley straw;
- Fruit and vegetable waste - non-edible fractions such as tomato stems, lettuce cores; cucumber peels, and shredded plant matter [17];
- Processing by-products - cereal husks, bran, oil-pressing residues, sugarcane bagasse; sugar beet pulp, oilseed cakes, seed husks, nut shells, and eggshells;
- Animal-derived waste - manure, feathers, animal fats, and aquaculture waste like crustacean shells and fish scales [32];
- Forestry residues - bark and wood chips;
- Sewage sludge - categorized separately due to specific processing needs.

The composition of agricultural waste varies by category. Plant residues consist primarily of cellulose, lignin, and hemicellulose [33], with minor fractions of lipids, proteins, sugars, starch, hydrocarbons, water, and ash [34]. Cereal processing waste contains high levels of starch, while animal manure is rich in protein [13,35]. The origin and processing conditions dictate the content of nutrients, notably nitrogen, phosphorus, and potassium. Despite variations, all agricultural waste shares biodegradability as a key characteristic [35].

Regional variations in cropping systems, logistics, and regulations strongly influence the technical and economic feasibility of converting wastes into fertilizers. This is due to both the diversity of the waste itself and logistical and economic barriers. The above-mentioned differences in the type and chemical composition of biomass are a key factor influencing the processing technology of both plant, animal and food waste. Differences in chemical composition mean that a given biomass requires different methods of pre-treatment, e.g. hydrolysis, gasification or mechanical and thermal processes [32,36–38]. Another challenge is the variation of nutrient content (phosphorus and nitrogen) and pollutants. The presence of heavy metals, pathogens and antibiotics poses a serious threat to the environment and health, so it is extremely important to choose the right technology for removing pollutants [1,39,40]. Agricultural waste is often dispersed over large areas. This makes it difficult to collect and transport them to centralized processing plants, and also increases costs [39,41,42]. The low bulk density of green waste makes long-distance transport unprofitable and local management methods such as composting are preferred [43]. Economic factors also include the lack of funds for the construction and development of transport facilities and processing infrastructure [44,45]. In developing countries, local fertilizer plants can boost economic growth and reduce dependence on external suppliers [45]. The production of fertilizers from biomass must therefore be decentralised in order to be able to compete with traditional fertilizers [45]. The educational aspect must also be taken into account. Many farmers prefer synthetic fertilizers because of their lower workload and ease of application. What is needed here is education, financial incentives, and the development of infrastructure for the collection, operation, storage, and distribution of biomass fertilizers [1]. Regional variation in agriculture requires location-specific strategies for turning waste into fertilizers that fit local conditions and needs [1].

Agricultural waste-management strategies depend on the composition and physical properties of the residue. Plant residues are typically processed by composting or anaerobic digestion, whereas animal-derived waste and sewage sludge often require incineration or anaerobic digestion followed by hygienization for sanitary and epidemiological safety [9] Compost and ash derived from agricultural waste can serve as effective fertilizers. In many cases, they inherently contain essential nutrients, though additional enrichment with micro and macronutrients may enhance their agronomic value. However, regulatory approval requires rigorous testing for heavy metals, micropollutants (e.g, hormones, antibiotics, and pharmaceutical residues), and microbiological contaminants, ensuring compliance with environmental and safety standard [9,46–48]. The utilization of agricultural waste for fertilizer production supports nutrient recovery, transforming by-products into high-value agricultural inputs. This practice aligns with the principles of circular economy, where waste from one process serves as a resource for another, enhancing sustainability in agricultural systems [1,49]. Agricultural waste is abundant, but its storage presents challenges. Processing it into fertilizers provides a sustainable solution. This approach provides multiple applications in sustainable agriculture. The basic function is to support sustainable agriculture. Recycling agricultural waste conserves non-renewable resources and enhances soil health, water quality, and economic viability [40]. Organic matter, which is the basis for biomass and fertilizers based on it, improves soil structure, water retention, and nutrient retention. The soil is enriched with valuable humus, increasing its fertility [50]. Microbiological activity, and organic carbon concentration increase along with improved microelement and macro-element circulation. This also results in a decrease in soil susceptibility to erosion. Nutrients necessary for plants (nitrogen, phosphorus, potassium, and microelements) are released from biomass-based fertilizers slowly and sustainably. The resulting gain in soil fertility is durable, allowing less frequent fertilizer application [51,52]. Coating biofertilizers with oils is also used to increase the possibility of controlling the nutrient release process [53]. This is in contrast to synthetic fertilizers, which usually provide an immediate, rapid release of nutrients. Synthetic fertilizers may harm soil organisms, including beneficial invertebrates. In turn, biomass-based fertilizers can contribute to increased biodiversity, are safer and do not contain harmful compounds [44]. Synthetic fertilizers can disturb the balance of nutrients in the soil, causing its acidification. The aspect of fertilizer runoff/leaching from fields is also very important. This phenomenon most often causes contamination of aquatic ecosystems with harmful components of synthetic fertilizers. The eutrophication of water bodies progresses as a consequence of excessive nitrogen fertilization. Biomass fertilizers contribute to carbon sequestration, slowing climate change caused by excessive CO_2 emissions. This results in the creation of the so-called "dead zones" [54,55]. The use of agricultural waste reduces the environmental impact of synthetic fertilizers [49]. Recycling organic waste reduces greenhouse gas emissions and reduces environmental storage challenges [56,57]. The use of animal manure as fertilizer reduces N_2O emissions to the environment [42,58]. The research carried out proves that using the CuO catalyst it is possible to recover more than 98 % of nitrogen, phosphorus and potassium from the pig slurry. Obtaining fertilizer in this way contributes to both sewage purification and improvement of soil fertility [59]. Other studies on animal manure show an improvement in both grain yield and height and biological yield. The use of fertilizers also provided good conditions for the continuous release of nutrients and also improved soil texture. There was also an increase in the level of bacterial biodiversity. Fertilizer based on animal manure has a positive effect on the soil. It helps mitigate the effects of its acidification [13]. Recent studies explore the production of phosphorus-enriched biochar from *E. coli* biomass waste. In studies, this fertilizer allowed slow release of phosphorus and contributed to recycling of phosphorus sources [60]. There are several methods to enrich biochar with nutrients. These include impregnation, in situ pyrolysis, co-pyrolysis, granulation, encapsulation and integrated methods [52]. The stability of biochar is its most important advantage, making it an attractive nutrient carrier [61]. Studies are currently underway to evaluate the long-term use of nutrient-enriched biochar [52]. It is difficult to clearly indicate which of the biochar enrichment methods is the most effective. Factors such as end-use, feedstock availability, and overall economics must be weighed when selecting a biochar-enrichment route [52]. In response to recent concerns about the effectiveness of catalytic processes in slow-release fertilizers, several studies have explored their impact on nutrient release kinetics and long-term soil performance. Recent scientific investigations have demonstrated that the application of catalytically modified biochar in slow-release fertilizers, particularly as a carrier of macronutrients such as nitrogen, phosphorus, and potassium (NPK), exerts a significant influence on nutrient release kinetics while also offering long-term agronomic and environmental benefits. Functionalized biochar enriched with NPK exhibits a controlled and gradual desorption pattern. Notably, biochar produced at a lower pyrolysis temperature (500 °C), characterized by reduced pore size, has been shown to release nutrients at a slower rate compared to its counterpart synthesized at 700 °C, irrespective of the surrounding pH conditions. [62]. The use of such materials enhances the efficiency of nitrogen, phosphorus, and potassium uptake by plants (greater NPK absorption and higher agronomic efficiency of fertilization) while simultaneously reducing nutrient losses to the environment [63]. As a result, the long-term application of modified biochar contributes to the improvement of soil physicochemical properties and supports stable plant growth and yield, as emphasized by numerous studies highlighting its potential as a slow-release fertilizer in sustainable agriculture [63].

The fleshy fruits are a valuable source of many nutrients and bioactive components. Different parts of the fruit, such as skins, seeds, pits, and pulp, provide various valuable compounds that can be used as fertilizers [64]. In turn, the use of fertilizer obtained from the recycling of milk from waste resulted in the extension of roots and an increase in the yield of common chickweed [65].

When analyzing the possibilities of using biomass in the production of fertilizers, the process should be considered in a more general way. The diversity of the raw material, its origin, composition, and the prospects for obtaining a raw material with similar properties in the following years should be taken into account. The effectiveness of the fertilizer depends on the composition and quality of the raw waste material. The content of nutrients in waste raw materials can be uneven. This requires knowledge and a number of specialist studies to optimize the composition. One of the possible difficulties may also be the technical impossibility of processing some waste. Currently, the mechanisms of microorganisms, which have a huge impact on waste processing, are not yet known in detail. The challenges posed by the widespread use of biomass-based fertilizers also include strict legal regulations and provisions that require detailed testing of fertilizers introduced into the market [66]. There is also a lot of competition on the fertilizer market. Public education and misconceptions pose additional challenges to adopting catalytic fertilizers [36,49].

The transition from laboratory to industrial scale production of biofertilizers in catalytic processes is associated with a number of challenges, which include technological, raw material, economic, logistical, but also environmental and social aspects.

2.1. Technological and process challenges

Many laboratory-scale processes suffer from low space-time yields and poor energy efficiency, making direct industrial application impractical [54,64,67–69]. An example is ozone photocatalysis, the main limitation of which is too low oxidation rate [70]. Catalyst lifetime is another critical issue; sustained activity and structural stability are necessary during continuous industrial operation. Catalysts in harsh industrial environments are often deactivated by sintering, carbon deposition or poisoning [16,71–73]. The need for frequent regeneration can be costly and lead to plant downtime [71]. A good example of this is copper electrodes, which are highly efficient in nitrate to ammonia conversion processes, but lack long-term stability, which is a factor that significantly limits their commercial use in this process [16]. In processes using catalysts, an important factor causing the increase in process costs is the regeneration and recycling of used catalysts [57,71,73]. Another factor hindering scale-up is insufficient data on mass and heat transfer and mixing effects from laboratory tests. In scaled-up reactors, mass- and heat-transfer limitations can dominate, altering apparent kinetics and creating non-uniform reaction zones [57,70–72]. Many of the new, innovative processes also require complex pre-treatment of the raw material. This complexity generates additional process steps and thus additional costs [42]. Most of the technologies described in the literature are currently at too low a technology readiness level. They require further intensive research and development before being deployed on an industrial scale [39,57]. Also, differences in test methodology, processes and equipment during laboratory tests make it difficult to compare results and draw generalized conclusions [39,52,70].

2.2. Raw material and material challenges

Agricultural waste and biomass are characterized by high variability in composition and properties, which significantly affects the performance and characteristics of the final products [64,66,74]. Laboratory models may not reflect complex physicochemical transformations in industrial settings [57]. Another challenge is the possible contamination of waste with heavy metals, microplastics or pharmaceuticals, which can accumulate in the soil and plants. The presence of contaminants requires additional, costly cleaning processes [47,71,75].

2.3. Economic and logistical challenges

The creation of a new technology with a production line is associated with high capital and operating costs. Many new innovative processes consist of costly steps due to high consumption of energy and chemical reagents [64,65,70,76]. Another challenge is economies of scale. Large plants using, for example, the Haber-Bosch process, benefit from economies of scale, which cannot be applied to local, dispersed, small-scale plants. Which in turn offer the benefits of local sourcing and reduced environmental impact [57,67]. However, this does not change the attitude of investors, for whom new technologies must first and foremost be profitable and competitively priced in relation to already established processes [57,67]. The economic calculation of a bio-fertilizer production plant should also take into account the occurrence of seasonality in the availability of raw materials and demand for the finished product. This is another challenge also in terms of storage and logistics [39,52,66]. Transporting large quantities of biomass and waste can be energy-intensive and expensive. This does not support the creation of centralized plants, but rather decentralization and reduction of production often to the scale of demand for the product for the producer (farm) itself [13,36,1,45,66].

2.4. Environmental and social challenges

An extremely important factor influencing the possibility of producing waste-based fertilizers is the non-toxicity of both final and intermediate products. Wastewater treatment intermediates can be toxic, so they require testing for water discharge [70]. Another example is biorefinery residues, which may contain phytotoxic compounds that negatively affect plant growth and soil health [39]. When decentralising production, i.e. introducing the production of bio-fertilizers for own use on farms, it is also necessary to take into account the issues of safety and appropriate training of people involved in production. Many processes use loose and dusty materials [52,71], another danger may be the formation of hydrogen as a by-product of electrocatalytic processes, which poses a risk of explosion [16]. There is also the issue of restrictive, often complex legal requirements (especially in the EU) regarding bio-fertilizers. This poses a significant challenge for manufacturers in terms of compliance with contamination standards of raw materials, products and the process itself [66]. Public concerns and farmers' scepticism about the use of fertilizers from waste processing can lead to lower sales prices and undermine the profitability of production [66,67].

The potential for waste processing into valuable fertilizers using catalytic processes is enormous. However, moving from laboratory scale to industrial scale requires overcoming many barriers, including improving the technology, ensuring the stability and availability of raw materials, reducing costs, and resolving legal and social issues.

3. Catalytic technologies in fertilizer component recovery from agricultural waste

The most often used plant nutrients recovery method is in the last stage of biomass utilization processes e.g., from ash, wastewater, or anaerobic digestate [77]. An intensively developed approach is also to recover mineral nutrients from the initial stages of biomass biorefinery, especially during the biomass pre-treatment step. However, such an approach is hampered by the relatively low concentrations of nutrients, which negatively influences nutrient recovery [19]. In this chapter potential N/P/K recovery methods from main biomass processing units were presented.

3.1. Nitrogen recovery

3.1.1. Nitrogen recovery from thermochemical biomass processing

The main objective of biomass gasification is to produce valuable syngas, which can be converted into a range of different chemicals, e.g. into fuels via the Fischer-Tropsch process. Nitrogen compounds must be separated from the gas stream to increase its market value. For this reason, two groups of methods are used to remove nitrogen, which is a pollutant from the perspective of the main products of the gasification process.

The first method is based on raw biomass pretreatment methods aiming to reduce or convert it to precursors that are less likely to form NOx, NH_3 and HCN [2]. Physical pretreatment methods reduce the particle size, degree of polymerization, and specific surface area of biomass by altering its fine structure. Chemical pretreatment methods involve decomposing the chemical bonds in lignocellulose using chemicals to reduce the degree of polymerization and crystallinity of biomass raw material, thereby promoting its degradation. The main purpose of pretreatment is to increase the energy density of the raw material, which has a direct impact on the economic viability of the gasification process [2,3]. The pretreatment allows the amount of nitrogen to be reduced in the final gasification product, but practically makes it impossible to recover it for further processing. A different process is the purification of the gas product from the biomass gasification process using the scrubbing method. The gaseous fraction contacts water in a scrubber, which purifies the hydrocarbon stream while forming ammonia [3–6]. Recent studies report wide NH_3 ranges (ppm, dry-gas basis) produced during gasification: softwood pellets 570 [78]; bark 3300 [79], rice husk 7600 [80]; bark + chicken manure (70/30 wt%): 23,800 [79], sewage sludge 46,000 [81], chicken manure 73,200 [79]. The above-mentioned differences in the amount of ammonia obtained influence the unfavorable assessment of this method as a method of recycling nitrogen from waste biomass. The negative assessment results from differences in the concentration of ammonia obtained from different types of biomass. Nevertheless, if it was possible to stabilize the raw biomass material fed to the gasification process (feeding the installation with one type of waste biomass, stabilize the composition, including the composition of impurities, stable moisture content, grain size, etc.), the ammonia concentration would be relatively predictable and it could be used, for example, as a source of nitrogen for fertilizers. The solution proposed in the literature using a scrubber would not cause a significant increase in process costs and would allow the purification of the product stream with the simultaneous possibility of real recovery of nitrogen in the form of ammonia. Ammonia in aqueous solution can be used directly for fertilizer composition. If needed, stripping can be used for a release of ammonia into an e.g. acidic solution [82]; distillation process can be used for ammonia concentration increase [83]. Using efficient but also complex and energy consuming methods mentioned above, 85–90 % of nitrogen can be recovered [28,29].

In the case of the gasification process, nitrogen recovery can be considered mainly from the product which is the gas phase. Depending on the parameters of the pyrolysis process, the recovery of this element, valuable for fertilizers, can be considered for the gaseous product, liquid, and solid pyrolysis char (biochar). Recent studies show, that low temperature pyrolysis ($\leq$500 °C) results in biochar rich in nitrogen: up to the value of 0.12 % (Japanese Larch); 1.04 % (wheat straw ash and sludge) [84]; 2.68 % (sludge) [84]; 7.0 % castor cake [85], 7.8 % shrimp carcass [85]; 9.0 % chitosan [85], 8.2-10.0 % (chicken manure) [86,87]. It was proven, that biochar can be an effective and soil-safe fertilizer carrier [88,89]. In case of the pyrolysis process, as the final temperature as the heating rate play an important role in the process of transferring the nitrogen element to individual product fractions. Low process temperatures and slow heating rates increase the nitrogen content in the biochar. Higher process temperatures and increased heating rates result in increased nitrogen transfer to the liquid product. However, at even higher temperatures, these nitrogen-containing compounds undergo secondary cracking, deamination, and dehydrogenation reactions, resulting in the generation of volatile nitrogen-containing substances such as NH_3 and NOx, which decreases their relative content in the bio-oil [90]. The pyrolysis of biomass within a moderate temperature range (approximately 400–500 °C) promotes the retention of nitrogen in the liquid and solid fractions. In contrast, higher temperatures (above ~600 °C) lead to an intensified release of nitrogen into the gas phase, primarily in the form of ammonia (NH_3), hydrogen cyanide (HCN), and nitrogen oxides (NO_x) [91,92]. According to research findings, lower temperatures (below 500 °C) favour NH_3 emissions as a result of deamination of unstable amine compounds and the depolymerization of proteins. As the temperature increases to around 500–600 °C, the proportion of HCN rises, mainly due to the decomposition of heterocyclic and nitrile structures. At higher temperature ranges (600–900 °C), the NH_3 emission curve exhibits either a plateau or a secondary increase, which can be attributed to secondary hydrogenation of HCN or the thermal breakdown of nitrogen-containing compounds present in the liquid fraction [93]. Optimal nitrogen recovery is therefore achievable at temperatures not exceeding 600 °C, provided that the intensity of secondary deamination and dehydrogenation reactions is limited. In the case of rapid heating (fast, flash pyrolysis), part of the nitrogen is removed from the raw material in the form of NO_x and NH_3. Another variable influencing the presence of nitrogen in various fractions of pyrolysis products is the presence of a catalyst. Catalysts promote cracking, dehydration, deoxygenation reactions into mostly mono-aromatic components [26,27]. The main role of catalysts in this process is to accelerate the decomposition of high-molecular biomass components, which allows to limit the intensity of secondary reactions of light, reactive components at high process temperatures.

Method of nitrogen recovery from liquid and gaseous fractions obtained from waste biomass depends on the original purpose of the obtained products. When the liquid or gaseous fraction is combusted for energy, combustion combined with SCR (Selective Catalytic Reduction) or scrubber (described in the section describing gasification) could be used. SCR is widely used technology for nitrogen oxides (NO_x) removal from exhaust gases. In this process, ammonia is injected into the reaction chamber, where it reacts with NOx in the presence of a catalyst, typically based on metal oxides [15]. In the context of nitrogen recovery, SCR can be adapted to recover ammonia (NH_3) from nitrogen-containing gases released during the pyrolysis or gasification of biomass. To date, this process combination has not yet been demonstrated for biomass-derived bio-oils from biomass pyrolysis. This is due to a number of technological problems related to the combustion of bio-oils of the indicated origin - the complexity of the chemical composition and (as for fuels) the high content of heteroatoms. Therefore, recovery of nitrogen from the combustion of pyrolytic oil obtained in the biomass processing, is currently considered only as a theoretical possibility. In the subject of nitrogen recovery from the liquid fraction, the recovery of nitrogen from wastewater, where total nitrogen content varies in the range of 20-100 mg/L (raw domestic origin wastewater) [94–96]. Electrochemical catalytic wastewater treatment offers a promising route for nitrogen recovery, transforming harmful nitrogen compounds into valuable resources like ammonia [97]. In comparison to ion-exchange [98,99] or reverse osmosis [100,101], electrochemical methods are more eco-friendly, with mild reaction conditions, and the possibility to be coupled with sustainable energy. More importantly, high-value products can be obtained through electrocatalytic nitrate reduction to ammonia – ready to use fertilizer component.

3.1.2. Biological methods for nitrogen recovery

Biological nitrogen recovery in the form of single cell proteins was described in detail by Carey et al. [83]. The catalysts in biological systems (e.g., nitrogen-fixing bacteria or nitrifying bacteria) can enhance the efficiency of nitrogen extraction from biomass. Some microbial strains also help to convert organic nitrogen to ammonia or nitrate. This method is especially relevant for agricultural and food waste biomass, where biological processes can break down proteins and amino acids to release recoverable nitrogen. The biological recovery of nitrogen was also intensively researched from wastewater. Unfortunately, the most popular methods are based on nitrification processes, which in consequence leads to nitrogen removal (in the form of NOx and/or N_2) not recovery to useful forms that could be used, e.g. fertilizer component [15].

3.1.3. Phosphorous recovery

Wastewater treatment for P recovery was described in detail in many review articles, both in the context of research work and the effects of technology scaling [102–105]. Nevertheless, wastewater processing is only indirectly related to biomass processing. Taking into account large-scale processing of biomass, phosphorus recovery is primarily seen in two types of processes: thermal conversion (recovery from ash) and phosphorus recovery from semi-liquid waste from biogas production.

Ash elemental analyses of obtained different biomass fuels was recently evaluated by Tan and Lagerkvist [106]. The authors showed significant variation in P_2O_5 content in ash obtained from biomass, with the average value of about 12-15 % [106]. It is obvious that the phosphorus content in ash depends on the type of biomass being burned. Equally important are combustion parameters, availability and % of oxygen delivered to the process, presence and type of catalyst, combustion temperature, method and time of ash collection and ash storage. Phosphorus recovery from ash is mainly based on leaching technology, which can be divided into: bioleaching, supercritical extraction and chemical extraction. All of the mentioned methods. Möller et al. and Wzorek et al. found that 80 % of the phosphorus in the ash produced by biomass thermal conversion technology is converted into apatite, which is not accessible to plants [107,108]. The solubilization of phosphatic minerals by microorganisms is an area of considerable interest in the agricultural sector due to its potential for bio-fertilization applications [109]. Supercritical extraction technology has been identified as an effective pre-treatment method for enhancing phosphate release from biomass ash, though it is more expensive than other technologies [106]. From all the mentioned, chemical extraction appears to be most promising and cost-effective. It was found, that the efficiency of P extraction with inorganic acids was very similar for the different ash types, indicating that it was not or only slightly affected by the specific P mineralogy [110]. From an economic point of view, the possibility of concentrating waste acids and returning them to the chemical extraction process, influences the positive assessment of chemical extraction as a method of recovering phosphorus from ashes from biomass combustion. An important problem to solve is the standardization of the combustion process of biomass of individual types. This would allow obtaining ash of relatively standardized composition and, subsequently, standardizing the process of phosphorus recovery by chemical methods.

Solid digestate fraction is another interesting source of phosphorous. Due to the significant development of biogas plants around the world, the recovery of elements from fermentation residues is becoming an important topic due to the increasing amount of this waste. Tuszynska et al. reported that the solid fractions of digestate represented from 30 to 70 % of highly unstable phosphorus compounds (i.e. phosphorus with organic matter and in bonds with Al, Fe, Mg and Mn oxides and hydroxides) in relation to total phosphorus. The share of labile phosphorus forms in the liquid fraction of digestates was much higher and accounted for 80–90 % of the total phosphorus [111]. The waste digestate fraction needs to be separated in solid–liquid separation, that produces a solid fraction having high fertilizer value. There are two main ways of processing the waste digestate fraction for phosphorus recovery - its direct use and the use of the solid residue after pyrolysis. Solid digestate fraction can be composted in a short time or used directly as organic fertilizer [112]. If storage is necessary, a biological neutralization process (hygienization) becomes necessary. Solid digestate fraction can be also used as a raw material for pyrolysis. The solid pyrolysis product (biochar) produced from digestate also contains other elements, most notably P (up to the value of 62.6 % [113]). In fact, the P content has been found to be higher in biochar than in the dried digestate. This means that P can be effectively concentrated in the biochar, making it a suitable material for storage and transport. However, during the pyrolysis process, P can be converted to less available forms than in the original feedstock material, which requires optimization of the pyrolysis process depending on the type of fermentation waste (its composition and source).

3.2. Potassium recovery

After nitrogen and phosphorus, potassium ranks third on the list of essential nutrients for plants and crops. Recovering potassium from waste biomass processing is a promising approach to reduce waste and extract valuable resources. Chemical composition of biomass ash for different biomass includes K_2O in the range of 0.4-27.5 %. Agriculture residues as a source of ash are typical of the highest potassium content [114].

There are few studies on the recovery of potassium from biomass ash, and even less are integrated into the actual situation of industrial application. Among several i.e. potassium recovery by chemical extraction [115,116], potassium recovery by electrolysis [117], cyclone separation [118] and bioleaching [119], potassium recovery by extraction process using water appears the most promising. Ma et al. analyzed fly ash from four power plants and found potassium at the levels of: 6.33 %, 5.22 %, 3.16 %, and 10.18 %. The fly ash in straw-fired biomass boiler is typical of a higher potassium content [120]. Authors analyzed that the most cost-effective potassium extraction method was water washing at room temperature with a stirrer time of about 1 h. Considering water recycling, the described method can be described as effective and generating a limited amount of pollution, which makes it interesting from the industrial point of view [120].

4. Case studies implementing catalytic solutions in agriculture products

By 2025, the global population is expected to surpass 8 billion and reach 10 billion by 2050 [121]. The demographic expansion increases the demand for sustainable agricultural intensification. Catalytic processes facilitate the conversion of agricultural residues into fertilizers, reducing dependence on synthetic inputs and mitigating environmental degradation. Escalating food demand strains finite resources, particularly fossil-based fertilizers, while increasing agricultural waste and processing by-products [34].

Large-scale cultivation of corn, rice, wheat, barley, maize, and sugarcane generates the majority of agricultural waste. The global production of crop residues is estimated at 3.5–4.0 billion tons annually, with Europe contributing 400–500 million tons per year [122–124], however, only a portion of this biomass can realistically be used for fertilizer production due to other uses and numerous restrictions. It is estimated that about 44 % of the residue remains in the field to maintain organic matter and soil fertility, about 33 % is used as fodder or bedding for animals, and ~ 16 % is used off-field (e.g., as household or industrial fuel or construction material), leaving only a small "surplus" (estimated at <20-30 % of total biomass, i.e., at most about 0.7-1 billion tons per year) potentially available for processing into fertilizers [125]. Removing too much of the residue, moreover, poses serious environmental risks - even partial harvesting of 30-40 % of the straw from a field can exacerbate soil erosion, deplete soil organic matter and increase greenhouse gas emissions [126]. In addition, there are significant logistical and economic barriers. Leftovers are difficult to harvest (they are large in volume and scattered), and transportation costs are high, especially with the fragmented structure of farms. Many farmers use them for their own consumption and are reluctant to sell, limiting the amount of raw material available for centralized processing [127]. Nevertheless, even this limited accessible fraction constitutes a significant and valuable resource for the production of fertilizers which, if effectively managed and catalytically processed, can play a key role in advancing sustainable agriculture and closing nutrient cycles.

Agricultural waste produced during cultivation and processing is a complex material with variable quantitative composition, but made mainly of cellulose (20-55 %), hemicellulose (10-50 %), lignin (5-40 %), and inorganic salts (usually up to 5 % as ash content) [128,129]. Cellulose (fiber) is a natural polysaccharide in which the particles are built of β-D-glucose units (2-14 thousands) connected by a bridge oxygen atom between carbons 1 and 4. Hemicellulose is a complex mixture of naturally occurring polysaccharides. Its polymer chain is made up of 20-200 units and can be composed of pentoses, hexoses, or polyuronides. Technically, hemicellulose is a constituent that can be dissolved and removed from the biomass matrix (separated from cellulose) using a 17,5 % NaOH solution. Lignin is also categorized as a complex group of polymerized chemical compounds that share similar properties. Chemically, lignin is a condensation polymer constructed of phenylpropane units (monolignols, usually about 70) with various substituents. This cross-linked phenolic polymer binds to the other constituents and cells of biomass. The inorganic salt content of agricultural waste is expressed as the amount of ash after normalized weight analysis. Ash shows alkaline properties since its main constituents are Ca, Mg, and K. Elements such as Na, P, and Mn are present in smaller amounts, while, among others, Fe, Al, Zn, Cu, Ti, Ni, Co, and Mo can be found in trace amounts [124,128–131].

Lignocellulosic biomass from agricultural waste can be converted into valuable products by pyrolysis, a thermal decomposition process in the absence of oxygen. This yields:

- Syngas, a combustible mix of H_2, CO, CO_2, and CH_4, used for energy;
- Bio-oil, a complex blend of over 300 compounds, including organic acids, ketones, and phenolics, with fuel and chemical applications. Its high oxygen content (35–50 %) causes instability and acidity (pH 2–4), leading to polymerization and corrosion;
- Biochar – a carbon-rich solid with high porosity and nutrient retention that serves as a soil amendment. Its stable carbon and mineral content makes it generally alkaline (pH 7–10) [132–134];

Catalytic fast pyrolysis (CFP) is an advanced variant of biomass pyrolysis that enhances product selectivity and efficiency. During CFP, cellulose, hemicellulose, and lignin undergo rapid thermal depolymerization in the presence of a catalyst. The process involves:

- Particle fragmentation (<1 mm) to increase the reaction surface area.
- Rapid heating (850-1250 °C, 0.5-10 s) for efficient conversion.
- Product distribution: 10-20 % syngas, 60-75 % bio-oil, and 15-25 % biochar [132,135].

The role of the catalyst is to shift the reaction balance toward the desired liquid products and to improve the quality of biooil by lowering the oxygen content and acidity. The desired reactions are dehydration (spontaneous removal of oxygen primarily bound to -OH groups in the form of H_2O), hydrodeoxygenation (removal of oxygen by H_2 from syngas), decarboxylation and decarbonylation (removal of oxygen in the form of CO_2 and CO) and condensation reactions (i.e. ketonization, aldol condensation, etherification, esterification) leading to fuel-like chemicals [124]. Catalytic fast pyrolysis can be carried out using zeolite catalysts, mesoporous catalysts, different metal oxides, inorganic salts, and carbon-type catalysts. Among the catalysts suitable for the CFP process, zeolites are the most important [136–140].

Zeolites are a group of crystalline aluminosilicate minerals with a well-developed three-dimensional matrix created by tetrahedral $[SiO_4]^{4-}$ and $[AlO_4]^{5-}$ units bridged by a shared oxygen atom. The negative charge of the zeolite framework is balanced by exchangeable Na^+, K^+ and Ca^{2+} cations. Their large integral surface area and uniform pore size (0.3-1.0 nm microporous structure) allow them to be highly selective catalysts. Studies show that CFP can be effectively catalyzed by synthetic medium-pore zeolites (0.45–0.60 nm), such as ZSM-5 and HZSM-5 [136–139]. The use of ZSM-5 improves bio-oil quality by increasing the carbon content by ~25 %, reducing the oxygen content by 25 %, and adjusting the pH from 2.8 to 5.2, reducing acidity and corrosion risk [141]. It is believed that oxygen is removed mainly by dehydration and decarbonylation reactions and that intermediates formed on the surface of the zeolite into aromatic hydrocarbons such as benzene, toluene, and xylene [139,142–144]. The structure of zeolites can be further optimized for CFP by adjusting the pore size, distribution, and matrix acidity. For instance, a change in the Si/Al ratio or/and a change of cations balancing the zeolite structure for H^+ alter the process and its products. Using ZSM -5 in the protonated version (HZSM-5) allowed a biochar yield nearly up to 60 % [145,146].

Biochar produced from the pyrolysis of agricultural waste is a valuable and ecologically important material. This solid residue contains up to 90 % C, mostly in a stable reduced form, and is considered carbon rich. It exhibits a well-developed porous internal structure formed in a thermal decomposition process from the original lignocellulosic substrate. As a carbon rich, stable, porous material, it can be used in agriculture as a soil additive, which enhances aeration and water retention and can provide an environment for intensified microbial activity. Its alkalinity resulting from the presence of Ca, Mg, and K cations can alter the acidity of the environment. Furthermore, the structure of biochar can be fortified with nutrients essential for soil fertility and high crop yields, transforming this material into a fertilizer [121]. Recent research focuses on the use of biochar as a sustainable precursor for graphite production and as a catalyst [34,147]. Produced graphite is, in turn, intended for obtaining graphene and graphene-based materials such as graphene oxide (GO) and reduced graphene oxide (rGO). Carbon nanoparticles and related materials exhibit unique physicochemical properties and serve as highly effective adsorbents and photocatalysts for the degradation of a wide range of environmental pollutants [34]. Obtaining advanced materials such as graphene and its derivatives from agricultural waste biomass is considered a sustainable and cost-effective solution that fully contributes to the principles of circular economy.

A practical example of successful implementation of biomass conversion technologies can be found in Denmark and Germany, where catalytic hydrothermal carbonization has been effectively integrated into biogas plants [1,49]. These installations convert digestates into nutrient-rich fertilizers, enabling simultaneous utilization of biomass waste streams and significant reduction of nitrous oxide (N_2O) emissions—a potent greenhouse gas typically generated during traditional fertilizer application [9]. According to recent studies, this approach enhances the bioavailability of nitrogen and phosphorus in soils while reducing N_2O emissions by approximately 30 % [1,49]. Such initiatives align closely with the European Commission's Circular Economy Action Plan, promoting sustainable agricultural development within regional economies [12].

5. Environmental and economic benefits of catalytic processes

Fertilizer production improves crop yields by 30–50 % but remains highly energy intensive, with ammonia synthesis accounting for 2 % of global energy consumption [74,148,149]. Catalytic advances can lower energy demand by as much as 30 % and cut associated CO_2 emissions. Synthetic fertilizers, including ammonium nitrate and urea, rely on fossil fuel-derived feedstocks, contributing to greenhouse gas emissions, environmental pollution, and the depletion of finite resources. To address these challenges, catalytic technologies in fertilizer production present a transformative approach that minimizes the environmental impact while enhancing agricultural sustainability [74,148,149].

Mitigating climate change requires reductions in greenhouse gas (GHG) emissions across sectors, including power generation, industry, transportation, and agriculture. Agriculture alone contributes 24 % of global GHG emissions, primarily from CO_2, N_2O, and CH_4 [74]. Catalytic technologies provide a viable solution, particularly in the synthesis from agricultural waste, by reducing emissions and optimizing nutrient efficiency [17,150]. Fertilizer manufacturing represents a substantial source of GHG emissions, primarily due to the energy-intensive Haber-Bosch process, which synthesizes ammonia by reacting atmospheric nitrogen with hydrogen [151]. Furthermore, excessive fertilizer application releases nitrous oxide (N_2O), a greenhouse gas with 298 times the global warming potential of CO_2.

Catalytic advancements significantly reduce GHG emissions in fertilizer manufacturing through improved reaction efficiency and minimized harmful by-products. Innovations reduce energy demands and emissions throughout the production cycle. Catalysts lead to the formation of fewer undesirable by-products, which reduces the need for their removal and minimizes waste. Optimized reactions need less feedstock per unit of product, trimming emissions. Life-cycle assessment (LCA) captures these gains from cradle to gate and permits direct comparison with conventional routes. A prime example is the recent study by Lappalainen et al. [152], which compared the environmental impact of the conventional sulfuric acid roasting process with a newly introduced soda leaching process for lithium hydroxide monohydrate (LHM) production, a key raw material for lithium-ion batteries. The LCA results showed that the soda leaching process has significantly lower environmental impacts across all analyzed categories. Notably, the global warming potential (GWP) in the soda leaching process was approximately 33 % lower compared to the sulfuric acid roasting process. Reductions in other environmental impact categories ranged from approximately 16 % to 72 %, further highlighting the comprehensive environmental benefits of this innovative technology. Such quantifications not only confirm ecological advantages but also help identify "pain points" for further improvements and are critical for making decisions on implementing new technologies.

One key area is the conversion of agricultural waste into high-value fertilizers. Catalytic processes provide a sustainable alternative, converting agricultural waste into high-value fertilizers while reducing the reliance on synthetic inputs. This approach directly represents the basic assumptions of the circular economy (CE) model, which aims to eliminate waste and pollution, circulate products and materials, and regenerate natural systems [153]. CE transforms agricultural waste (e.g., straw, manure) from discarded material into valuable raw materials for fertilizer production. Through catalytic processes, these wastes are converted into organic fertilizers that are returned to the soil, closing nutrient and carbon cycles, reducing GHG emissions, saving resources, and improving soil health [154]. As shown in Fig. 1, this process perfectly illustrates the principles of the circular economy. Agricultural waste, such as plant residues, husks, and animal manure, are rich in essential nutrients like nitrogen, phosphorus, and potassium. Proper treatment of these materials, often highlighted by Chew et al. [13], can transform them into sustainable raw materials for fertilizer production, effectively closing the resource cycle [35,155]. These methods significantly improve nutrient recycling, enhance soil quality, and support

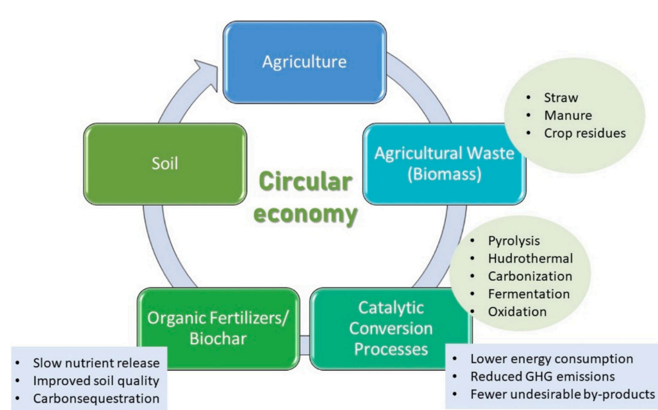

Fig. 1. The role of catalysis in the circular economy model for sustainable fertilizer production from agricultural waste.

long-term carbon sequestration. For instance, biochar-based fertilizers can retain up to 50 % of their carbon content in the soil for centuries [37,156]. The use of catalysis in waste-to-fertilizer processes allows for better use of nitrogen, reducing losses and minimizing negative impacts on the environment. [157,158]. Another example is the use of catalytic processes to treat agricultural waste such as manure to produce fertilizers with high nitrogen, phosphorus, and potassium contents. In a study [59] hydrothermal processes were effective in reducing N_2O emissions during fertilizer production while converting waste into valuable fertilizer. The process used a combination of catalysts and hydrothermal carbonization, allowing the fertilizer to retain its high nutrient content while minimizing the environmental impact. Hydrothermal carbonization further transforms biomass into nutrient-enriched charcoal, contributing to carbon-neutral or negative systems aligned with global sustainability goals. Additionally, catalytic pyrolysis offers a promising route for producing biofuels and fertilizers from agricultural waste by breaking down organic matter [73]. Catalytic technologies can support this CE model by transforming waste into valuable products that can be fed back into the production cycle [159]. Yin et al. demonstrated the conversion of biomass to fertilizers using catalysts, allowing the recycling of agricultural waste while reducing the reliance on traditional raw materials such as phosphorus and potassium [159]. Chew et al. emphasize that the conversion of biomass waste, such as agricultural waste, into organic fertilizers is a promising strategy that fits the concept of circular economy [13]. Organic fertilizers, unlike mineral fertilizers, do not require a large amount of energy to produce, which results in lower greenhouse gas emissions. Furthermore, organic fertilizers produced from biomass waste are characterized by a slow release of nutrients, which reduces the risk of leaching into groundwater and minimizes the negative impact on the environment. Converting biomass waste to organic fertilizers is a strategy that offers both environmental and economic benefits. Catalysis can also be used to convert biomass to biofuels, such as bioethanol and biodiesel [160].

Fertilizer production is heavily dependent on nonrenewable natural resources, particularly fossil fuels and minerals such as phosphorus and potassium. Phosphorus is a key ingredient in fertilizers, but it is a finite resource, and the world supply is finite. Therefore, it is essential to move toward more sustainable fertilizer production practices to avoid depleting these resources and avoiding the environmental degradation associated with their extraction [161]. Furthermore, the fertilizer industry is under increasing pressure to reduce waste and promote a circular economy. As demand for fertilizers grows, so does the volume of agricultural and industrial waste that could be used to produce fertilizers. However, a significant part of this waste ends up in landfills, contributing to pollution and greenhouse gas emissions [155]. In the production of fertilizers from agricultural waste, catalysis is a strategic step toward the sustainable development of agriculture and environmental protection. Production of nitrogen fertilizers such as ammonium nitrate and urea is largely based on fossil fuels, both as an energy source and as a raw material. This dependence on non-renewable resources increases the costs of the production process, which are often passed on to consumers. In addition, traditional fertilizer production processes are energy intensive, especially in the case of ammonia synthesis using the Haber-Bosch process. The high pressure and temperature required for the reaction make the process energy-intensive, leading to increased operating costs. Continuous investment is needed to maintain and upgrade the aging infrastructure, which places an additional burden on fertilizer producers [151]. The Haber-Bosch process, although crucial for agriculture, is energy intensive and generates greenhouse gas emissions [69,162]. Therefore, more sustainable technologies are being sought, such as the use of renewable energy sources, CCS technology, biomass, or electrochemical synthesis [55]. There are several underexplored catalytic systems and approaches that can contribute to further reduction of energy consumption and emissions in fertilizer production. For instance, ruthenium catalysts for ammonia synthesis significantly increase the catalytic efficiency of N_2 to NH_3 conversion by enhancing the number of active sites. This process can also operate under milder conditions (<400 °C and < 200 bar) compared to Haber-Bosch, leading to reduced energy costs [163]. Electrochemical ammonia synthesis powered by renewable energy offers a viable alternative to the Haber-Bosch process [16]. Studies show [74] that the use of such catalysts significantly increases the catalytic efficiency of N_2 conversion into NH_3 by increasing the number of active sites. However, it is in the early stages of development. Nevertheless, electrochemical synthesis of NH_3 has the potential for lower capital costs on a small scale and the key advantage of independence from fossil fuels. However, it faces several key performance limitations, such as low energy efficiency or low catalyst selectivity, and still low production rates [16]. Currently, its capital and operating costs are typically higher than for Haber-Bosch. The use of photocatalytic and electrocatalytic nitrogen fixation methods (so-called solar fertilizers) also seems promising. The process still requires solving the problems of low conversion and stability, but its application could reduce the carbon footprint and energy consumption (compared to Haber-Bosch) [45]. Another example is the catalytic oxidation of manure to humic acids. A CuO catalyst is under investigation for this purpose. In the process, we primarily reduce the environmental pollution of manure but we can also generate heat that can be used in another way [59,65].

Sustainable fertilizers that meet the growing demand for environmentally friendly agriculture further strengthen market competitiveness [131]. The use of advanced catalytic technologies in fertilizer production reduces the cost of raw materials by replacing synthetic inputs with waste biomass. This leads to significant economic advantages, as agricultural waste is often a low-cost or even negative-cost input, unlike the finite and price-volatile fossil fuels and mineral resources (e.g., phosphorus and potassium) required for conventional fertilizers [164]. Optimized reaction kinetics improve energy efficiency, while reduced waste generation decreases disposal costs and enhances resource use [165]. Furthermore, the production of organic fertilizers from biomass often requires substantially less energy compared to the energy-intensive Haber-Bosch process for ammonia synthesis, leading to lower operational expenditures [131]. Beyond production, organic fertilizers offer cost-effectiveness at the application stage due to their slow-release nutrient profiles, which minimize nutrient losses through leaching and volatilization. This can lead to reduced fertilizer application rates and frequency for farmers, translating into direct savings on input costs and labor. Long-term benefits include improved soil health, increased water retention capacity, and enhanced crop resilience, potentially lowering future needs for soil amendments and increasing yields without proportional increases in input. Moreover, converting agricultural waste into a valuable product eliminates disposal costs, creating a new revenue stream or cost-saving for agricultural producers [165]. The economic rationale for adopting catalytic technologies in fertilizer production is further strengthened by the growing demand for sustainable and environmentally friendly products. Consumers and agricultural producers are increasingly looking for fertilizers that are environmentally friendly, cost-effective, and sustainably produced. This demand creates a huge market opportunity for companies investing in advanced catalytic technologies. Fertilizers produced using catalytic technologies that use renewable raw materials and generate less environmental pollution fit perfectly into the growing market preferences. Lateef's work on sustainability highlights how market trends and consumer demand are pushing industries, including fertilizer production, to adopt sustainable technologies. Companies using catalytic processes are more likely to gain market advantage by taking advantage of the growing demand for environmentally friendly agricultural products [41].

Integrating catalytic technologies into fertilizer production offers significant environmental and economic benefits. Reducing greenhouse gas emissions, conserving natural resources through recycling, and improving production cost-effectiveness position catalytic innovations to transform the fertilizer industry into a more sustainable and profitable sector. Technologies mitigate the environmental impact of traditional fertilizer production while meeting the growing global demand for sustainable agricultural practices.

6. Challenges and opportunities in fertilizer innovation

Advancing catalytic technologies in fertilizer production offers benefits but faces technological, economic, and regulatory challenges. Table 1 summarizes key barriers and opportunities in the development of catalytic fertilizers.

6.1. Technological and economic barriers

Variability in feedstock composition influences catalyst efficiency, as fluctuations in agricultural waste characteristics impact reaction kinetics [35]. Catalyst longevity is compromised by fouling, poisoning, and structural degradation, which limits its useful life [26,27]. The high costs associated with metal oxides and zeolites further challenge economic feasibility, particularly with respect to catalyst synthesis and regeneration [43]. To reduce catalyst fouling and extend its lifespan, periodic regeneration is recommended, for example calcination of the spent catalyst in an oxidizing stream (air or steam) at high temperatures, which enables the removal of deposited coke and largely restores the catalyst's porosity and activity [167–169]. Additionally, modifications to the catalyst material such as introducing a mesoporous structure (e.g. through partial desilication of zeolite) improve reagent diffusion and reduce the tendency for coke deposits to form, thereby extending the effective operating period of the catalyst [170]. These approaches can be framed as part of broader catalyst and process level strategies aimed at preventing deactivation and ensuring long-term process stability [171].

The large-scale implementation of catalytic processes demands substantial capital investment in specialized infrastructure, limiting rapid adoption [74]. Synthetic fertilizers retain market dominance due to their cost advantage and well-established supply chains [49]. Additionally, the limited availability of key raw materials, including rare earth metals, presents scalability and cost barriers [166].

6.2. Regulatory and policy support

Regulatory frameworks impose stringent environmental and safety standards, which require compliance with heavy metal limits, controlled nutrient release, and biodegradability criteria [66]. Extensive testing requirements and complex certification procedures delay market entry of bio-based fertilizers. Furthermore, the absence of uniform global regulations complicates cross-border commercialization, restricting international adoption [66].

Government subsidies and tax incentives improve the financial viability of sustainable fertilizers, promoting market competitiveness [150]. Collaborative public-private investments in R&D accelerate the advancement of catalytic technologies [37,156]. Policy frameworks that emphasize the principles of circular economy encourage waste valorization, facilitating the large-scale integration of catalytic nutrient recovery solutions [159].

6.3. Future research directions

Research efforts must prioritize the development of durable catalysts capable of resisting fouling and deactivation [26,27]. The utilization of abundant and low-cost materials, such as biochar-supported catalysts, offers potential to reduce production expenses [69,162]. Data-driven methods for catalyst optimization can improve nutrient-recovery efficiency and process sustainability [16]. In addition, hybrid catalytic-biological systems, which incorporate microbial processes, could revolutionize nutrient cycle and fertilizer efficacy [60]. Researchers have identified both nanocatalytic and enzyme-assisted routes that operate under significantly milder conditions than conventional catalytic fast pyrolysis (CFP). For example, enzymatic bioconversion processes (such as cellulase-catalyzed hydrolysis of biomass) run at low temperatures (~40–50 °C and near-neutral pH) [172], far gentler than the ~500 °C required in CFP. These enzyme-assisted pathways can achieve effective breakdown of biomass with much lower energy input [173,174]. Similarly, novel nanostructured catalysts enable high conversion efficiencies at reduced severity. One study reported ~96 % biodiesel yield using a snail shell–derived CaO **nanocatalyst**, attributed to its high surface area facilitating the reaction under milder conditions [175]. In general, the superior activity and selectivity of nanocatalysts allow processes (e.g. transesterification or hydrogenation) to proceed at lower temperatures or pressures than traditional methods. Consequently, such alternatives, including low-temperature catalytic **hydrothermal** treatments and **biocatalytic** depolymerizations, are indeed showing promise for producing fuels and chemicals under milder reaction conditions than CFP [176]. Each offers a potential pathway to reduce energy intensity while still achieving efficient biomass conversion.

Nevertheless, high costs, raw material variability, and catalyst degradation remain key challenges that require advancements in materials and cost-effective synthesis. Regulatory complexities and

Table 1
Challenges and opportunities in catalytic fertilizers.

Category	Barrier/Opportunity	Description	References
Technological Barriers	Feedstock variability	Inconsistent biomass composition affects catalyst efficiency.	[35]
	Catalyst degradation	Fouling, poisoning, and structural instability reduce performance.	[26,27]
	High material costs	Metal oxides and zeolites require significant investment; exploring biochar-supported or natural aluminosilicate catalysts is recommended.	[43]
Economic Barriers	High capital investment	Scaling requires costly infrastructure and operational adjustments.	[74].
	Market competition	Synthetic fertilizers dominate due to cost-effectiveness.	[49]
	Supply chain constraints	Limited access to rare earth metals restricts scalability.	[166]
Regulatory Barriers	Stringent environmental standards	Compliance with heavy metal limits, nutrient release criteria, and biodegradability regulations.	[66]
	Complex certification processes	Lengthy approval and testing requirements delay commercialization.	[66]
	Inconsistent global policies	Regulatory differences hinder international adoption.	[66]
Policy Opportunities	Financial incentives	Subsidies and tax relief can improve economic viability.	[150]
	R&D investment	Public-private collaboration drives catalytic innovation.	[37,156]
	Circular economy promotion	Waste valorization policies support large-scale implementation.	[159]
Future Research	Advanced catalyst design	Development of durable and cost-effective catalysts.	[26,27]
	Alternative catalyst materials	Exploration of low-cost or biochar-based catalysts.	[69,162]
	AI-driven process optimization	Machine learning improves reaction efficiency and nutrient recovery.	[16]
	Hybrid catalytic-biological systems	Microbial integration improves nutrient cycling.	[60]

inconsistent policies slow commercialization, but financial incentives and supportive regulations could accelerate adoption [150]. AI-driven optimization and microbial-assisted catalysis are emerging as transformative innovations. Integrating catalysis with biological systems could significantly improve fertilizer efficiency [16].

7. Conclusions

Catalytic processes transform fertilizer production through improved nutrient recovery, reduced environmental impact, and integration of the circular economy. Advancements can cut CO_2 emissions by about 30 % and lower N_2O emissions, whose GWP is nearly 298 × that of CO_2, supporting climate-mitigation goals. Efficient nutrient extraction from biomass waste eases dependence on finite phosphate and nitrogen reserves, strengthening long-term sustainability in fertilizer manufacture. Cost-effective catalytic solutions improve economic feasibility and improve market competitiveness. Although catalytic technologies offer substantial benefits, their industrial-scale deployment faces key challenges. Ensuring catalyst longevity, minimizing fouling, and achieving cost-effective synthesis remain major technical hurdles. Policy-driven strategies, including subsidies, tax incentives, and regulatory harmonization, play a crucial role in accelerating market adoption. Standardized international environmental and safety regulations are essential for the facilitation of global trade and widespread adoption of catalytic fertilizers. Data-driven and microbial-assisted catalysis improve nutrient bioavailability and fertilizer efficiency, streamlining processes and enhancing agronomic performance. Catalytic innovations improve soil health, nutrient efficiency, and emission reduction, supporting climate-resilient agriculture. Successful scale-up will hinge on harmonized regulations and robust, long-lived catalysts. Integrating catalytic processes strengthens the food-energy-water nexus by reducing emissions, improving resource efficiency, and enabling circular waste reuse. Decarbonization, hydrogen integration, and computational modelling will spur innovation, while pilot-scale validation, cost-benefit analysis, and supportive policies are essential for adoption; with robust regulations and investment, catalytic fertilizers can transform sustainable agriculture.

CRediT authorship contribution statement

Dawid Skrzypczak: Writing – original draft, Conceptualization. **Katarzyna Pstrowska:** Writing – original draft. **Anna Niciejewska:** Writing – original draft. **Anna Mazur-Nowacka:** Writing – original draft. **Łukasz Wilk:** Writing – original draft. **Katarzyna Chojnacka:** Writing – review & editing, Writing – original draft, Supervision, Funding acquisition, Conceptualization.

Ethical approval and consent to participate

Not applicable.

Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

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Data availability

The data and materials can be available on request.

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