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REVIEW

Nitrogen-enriched liquid organic fertilizers (LOFs) production for sustainable agriculture: A review

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Abstract

Purpose: Although the popularity of liquid organic fertilizers (LOFs) has considerably increased recently, there have been concerns over their usage due to low nitrogen content. This study aims to discuss the current developments in nitrogen-enriched LOFs that address the above limitation, subsequently promoting sustainable agricultural practices.

Method: A thorough review of existing literature on nitrogen-enriched LOFs based on their chemical attributes and methodologies to increase the nitrogen content.

Results: The research highlights several promising methods for nitrogen enrichment, such as using high-nitrogen raw materials like cottonseed meal, bone meal, and blood meal, which also provide phosphorus and potassium benefits. Also, techniques like thermal hydrolysis, plasma activation, and inoculation of microorganisms can release and fix nitrogen in LOFs. Membrane technologies promise sustainably by recycling organic waste. Combining these materials and processes results in well-balanced nutrient profiles and improve the agricultural value of LOFs. However, formulating nitrogen-enriched LOFs requires considering critical factors like organic carbon content, pH values, raw material availability, cost implications, and overall sustainability. Optimizing these factors potentially lead to eco-friendly solutions for sustainable agriculture.

Conclusion: Cost-effective nitrogen enrichment in LOFs can be achieved through diverse methods and raw materials. Future investigations should focus on discovering raw materials with high nitrogen content, devising innovative enrichment techniques, and rigorously evaluating the efficacy of fertilizers. Investments in research, development, distribution, storage, packaging, and value-addition processes are essential to bolster LOF production and enhance affordability and accessibility, thus fostering sustainable agricultural practices.

Keywords: Nitrogen-enrichment, Liquid organic fertilizers (LOFs), Plasma activation, Nitrogen-fixing microorganisms, Membrane techniques, Sustainable agriculture

Introduction

The rapid growth in global population and mounting climate pressures has necessitated agricultural intensification as a crucial measure to ensure food security. Among the various methods employed, the application of fertilizers has notably augmented crop productivity and bolstered soil fertility (Meers 2016). Nitrogen (N), phosphorus (P), and potassium (K) constitute the fundamental nutrients in fertilizers, indispensable for enriching soils and nurturing crops (Soler-Cabezas et al. 2018). In the period spanning 1990 to 2020, there was a remarkable 46% surge in inorganic fertilizer utilization in agriculture. N-based fertilizers comprised 56% of the total, followed by P-based fertilizers at 24% and K-based fertilizers at 20% (FAOSTAT 2022). However, while farmers heavily rely on inorganic fertilizers to attain high yields and superior crop quality, it's imperative to consider the environmental and economic ramifications of such strategies (Herawati et al. 2020).

In contemporary agriculture, synthetic fertilizers are extensively utilized to bolster crop yields. Yet, they also inflict detrimental consequences on the environment and public health. Excessive use of synthetic fertilizers leads to runoff and leaching, contaminating water bodies. Research indicates that the N and P chemicals in these fertilizers can pollute rivers, lakes, and groundwater, sparking eutrophication and toxic algal blooms (Guan et al. 2023; Margalef-Marti et al. 2021). Furthermore, the production and application of N-based fertilizers generate nitrous oxide, a potent greenhouse gas, contributing to increased greenhouse gas emissions (Tian et al. 2023;

Astals et al. 2021). The long-term use of synthetic fertilizers also depletes organic matter and beneficial soil microbes, causing erosion and fertility loss (Bisht and Chauhan 2020). From an economic perspective, the escalating cost of chemical fertilizers burdens small-scale farmers in developing nations (Abebe et al. 2022). Additionally, the energy-intensive production of N-based fertilizers makes them susceptible to rising energy costs, jeopardizing both energy security and food production, especially in low-income countries (Taghizadeh-Hesary et al. 2021; Mousavi et al. 2023).

In light of these challenges, it is crucial to explore viable alternatives to chemical fertilizers that are both economically viable and environmentally sustainable (Assefa and Tadesse 2019). Several such alternatives exist, including organic fertilizers, nano fertilizers, slow-release fertilizers, and bio-fertilizers, all of which aim to enhance and sustain production while safeguarding the environment. For instance, organic fertilizers, derived from natural sources like plant and animal matter, offer numerous advantages over urea fertilizers, promoting sustainable and eco-friendly agriculture. Organic fertilizers improve soil structure, water retention, and microbial activity, thereby enhancing nutrient availability and reducing soil erosion risk (Hazra 2016). They also release nutrients gradually, mitigating the risk of leaching and runoff that can pollute water bodies (Karami et al. 2016). Moreover, organic fertilizers foster soil biodiversity and contribute to long-term soil fertility, diminishing the dependence on synthetic inputs. Their adoption aligns with agro ecological principles, supporting sustainable food production while minimizing ecological harm.

Organic fertilizers come in two forms: solid organic fertilizers (SOF) and liquid organic fertilizers (LOFs) (Herawati et al. 2020). SOF provides nutrients to the soil gradually, necessitating more time for soil enrichment (Muktamar et al. 2017). Conversely, LOFs offer numerous advantages in commercial agriculture. Notably, LOFs provide all three essential plant nutrients (NPK) along with micronutrients, ensuring comprehensive plant nourishment (Phibunwatthanawong and Riddech 2019). Furthermore, LOFs excel in nutrient distribution and plant-specific application. They ensure uniform nutrient availability throughout the growing area, allowing growers to tailor nutrient application to different plant requirements (Ginandjar et al. 2019). Additionally, LOFs support beneficial microorganisms, enhancing soil fertility, nutrient availability, and overall plant health. By integrating LOFs with modern irrigation and fertilizing practices, nutrient utilization efficiency is improved, minimizing environmental impacts and maximizing nutrient application effectiveness. In sum, the advantages of LOFs in comprehensive nutrient supply, efficient absorption, even distribution, support for beneficial microorganisms, and improved nutrient utilization render them valuable tools for sustainable agriculture and enhanced crop productivity.

Despite these benefits, LOFs often have lower N content compared to synthetic fertilizers. The N content of LOFs varies based on source material, production process, concentration, and target plant, all of which play a pivotal role in determining their effectiveness in enhancing nutrient content and agricultural productivity (Pujiwati et al. 2021). Developing cost-effective, nutrient-rich LOFs is essential for achieving sustainable agricultural intensification, making it imperative to explore strategies for N enrichment in LOFs.

The current review aims at 1) studying the characteristic features essential for the development of effective LOF; 2) exploring the available methods for N enrichment in LOF production, and 3) proposing the most effective LOF production method(s) with high N content that can be easily implemented.

Materials and methods

The research conducted in this study involved a comprehensive literature survey using various keywords such as LOFs, N enrichment, plasma activation, N-fixing microorganisms, thermal hydrolysis, membrane techniques and sustainable agriculture. The gathered data were then categorized based on the N enrichment methods employed in producing liquid fertilizers. The literature search was conducted from 2012 to 2023, accounting for recent developments and innovations in N-enriched LOF productions. The selection criteria outlined in Table 1 were used to narrow the search results further. To delineate the scope of the study more precisely, we categorized the selected papers based on the specific N enrichment methods employed in the production of liquid fertilizer. These categories include raw materials with high N content, thermal hydrolysis, plasma activation, microbial activity, and N enrichment through membrane techniques. The majority of the selected papers were peer-reviewed journal articles published in internationally recognized agriculture-related journals. Following the initial screening, papers that met the selection criteria were subjected to a second round of filtration. Each paper was scrutinized meticulously during this phase, focusing on experimental conditions and chemical analytical data. This rigorous literature search also targets to identify research gaps, assess the advantages and drawbacks of different N enrichment approaches, and propose potential directions for future research and industrial applications.

Results and discussion

Production of liquid organic fertilizers (LOFs)

LOFs can be produced from organic materials such as plant wastes, animal waste, seaweeds and other types of organic wastes after undergoing different production and fermentation processes either aerobically (Tsaniya et al. 2021) or by anaerobically (Rafiuddin et al. 2018; Yerizam et al. 2022; Fahrurrozi et al. 2020). Increasing N content in LOFs is critical for supplying optimal plant nutrition and identifying and implementing the best approaches to enhance N levels to improve the effectiveness of these fertilizers. Based on the literature survey, numerous methods have been employed to enhance N content in LOFs. The selection of raw materials with high N content, thermal hydrolysis (TH) in N enrichment Gao et al. (2021), N fixation by plasma activation Graves et al. (2019), use of microorganisms for N enrichment Sarbani and Yahaya (2022), and the use of membrane techniques Aquino et al. (2023) are the most common five (05) methods that have been investigated for the N enrichment, according to many researchers.

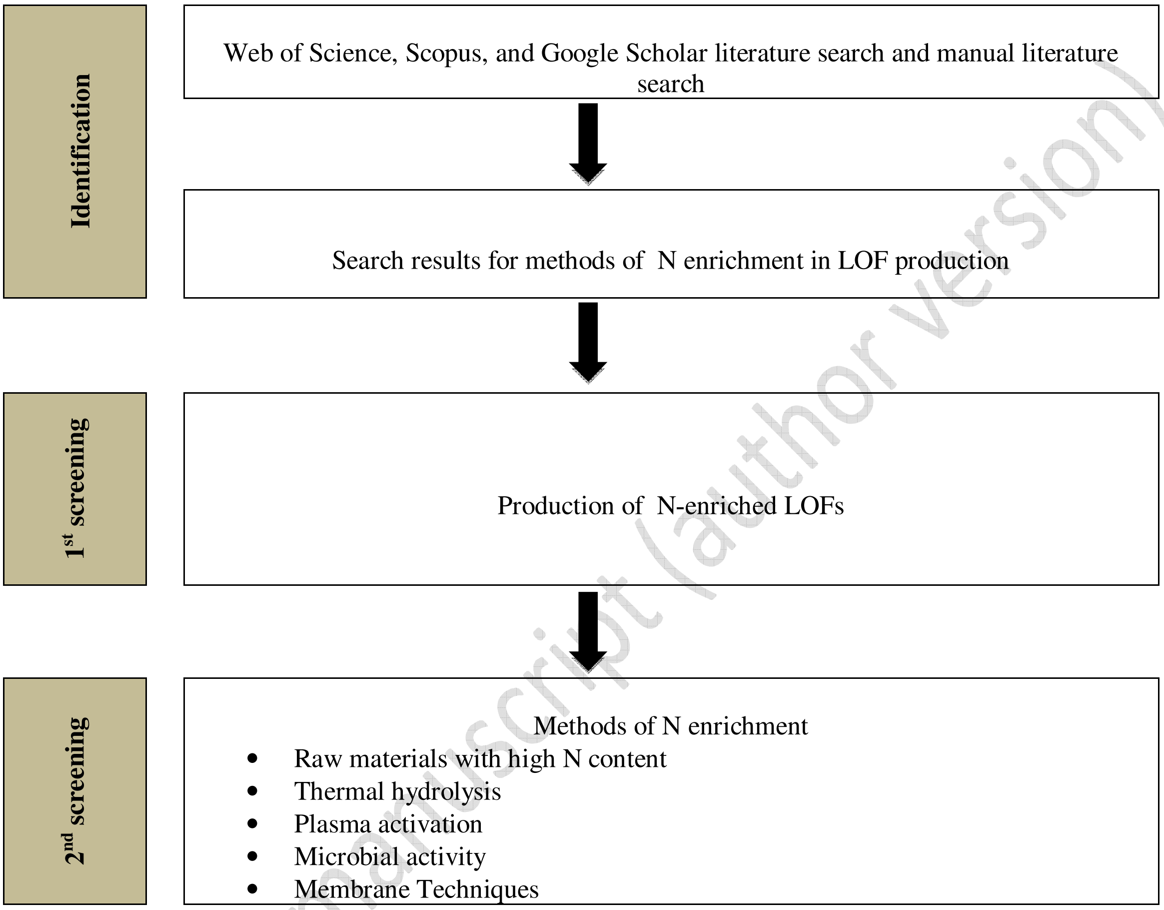
Use of raw materials with high nitrogen content

Production of LOFs involves using various raw materials, including plant-based and animal waste and seaweeds. When reviewing the data (see Table 2) on the highest N, P, and K contents from the given sources, it is evident that certain raw materials stand out regarding nutrient concentration. As illustrated in Fig. 1, it is evident that out of all the reviewed raw materials, 40% of the raw materials were based on animal waste and 37% were based on plant materials. For N content, cottonseed meal (see Fig. 2a) has the highest value of 7.38% (Green 2022). This makes it a potentially valuable raw material for producing N-rich LOF.

Regarding P content, bone and blood meal exhibit the highest concentration at 0.12% (Guajardo et al. 2018). Although this value is relatively low compared to other raw materials, it should be noted that as in Fig 2b, bone and blood meal are primarily used as a source of other nutrients, such as calcium and iron, rather than as a P source.

Only 23% of used raw materials were based on seaweeds where the N content (see Fig 2c) found to be notably lesser than that of animal and plant-based raw materials. But it is noteworthy that P content is 9%in *Sargassum* *crassifolium* for the considerations of NPK formulation. In terms of K content, molasses, sugarcane leaves, and alfalfa meal demonstrate relatively high concentrations (5.25, 2.45, and 2.46%). These raw materials could be advantageous for formulating LOFs focusing on K enrichment.

Table 1. The selection criteria for conducting the literature survey from 2012 to 2023.



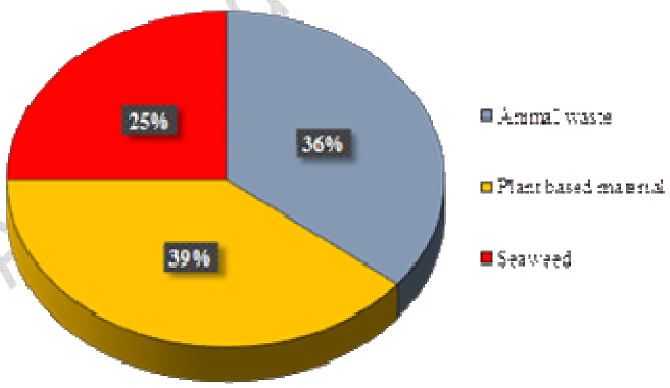


Fig. 1 Major sources of raw materials used for LOF production.

Table 3 reveals that among the available data for raw material combinations, the N content consistently falls below 2%. However, organic waste from banana peels, moringa leaves, onion peels, bean sprouts, and banana hump demonstrates potential as a LOF due to their N content exceeding the SLS 1702-2021 quality standards for LOFs (4.07, 3.93, 3.76, 3.75, 3.97%). To create a balanced and effective LOF formulation, a careful examination of potential combinations of these nutrient-rich raw materials is essential. One promising approach involves blending cottonseed meal (rich in N), bone and blood meal (a source of P), and either sugarcane leaves or alfalfa meal (abundant in K), which could yield a well-rounded nutrient profile. Nevertheless, it's crucial to emphasize the significant influence of aerobic and anaerobic fermentation methods on the final nutrient content of LOFs, with anaerobic fermentation resulting in higher nutrient content (Fahrurrozi et al. 2020). However, it's worth noting that specific details, such as fermentation duration, organic carbon content, and pH values of the raw materials, are absent for certain data entries. These parameters are vital for evaluating the overall quality and stability of the LOF. Additionally, when formulating nutrient-enriched LOFs, one must also consider factors like raw material availability, cost, and sustainability.

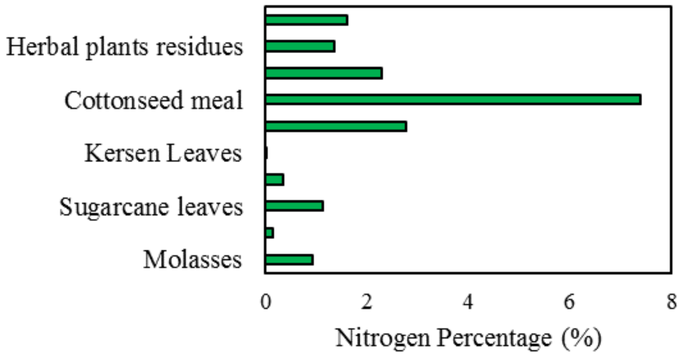


Fig. 2a Reported nitrogen % of plant-based raw materials.

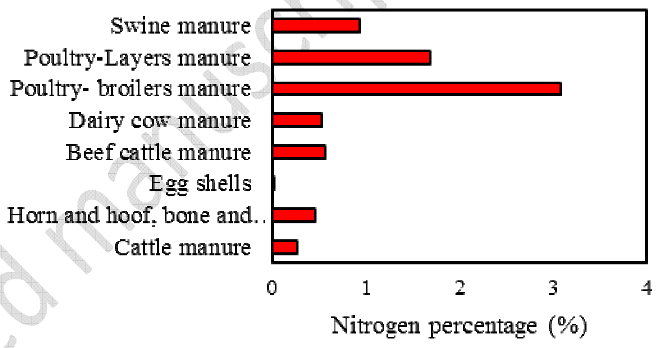


Fig. 2b Reported nitrogen % of animal-based waste materials.

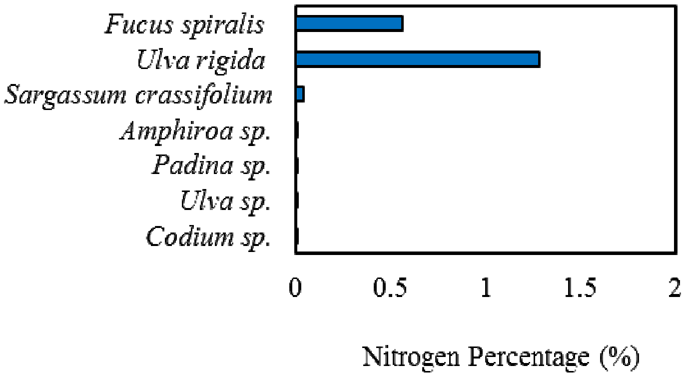


Fig. 2c Reported nitrogen % of seaweeds.

Table 2. Commonly used raw materials to produce LOFs.

Source	**Raw material**	**N%**	**P%**	**K%**	**Organic-C %**	**pH**	**Reference**
Plant-based material	Molasses	0.92	0.04	5.25	75.5	6.69	Phibunwatthanawong and Riddech (2019)
	Distillery slop	0.15	0.08	1.1	2	7.14	
	Sugarcane leaves	1.12	0.08	2.45	51	-	
	Banana pseudostem extract	0.36	0.05	0.97	-	-	Kalaivani and Gnanavelrajah (2021)
	Kersen Leaves	<0.01	0.17	0.04	-	-	Yeirzam et al. (2022)
	Cottonseed meal	7.38	1.16	1.65	-	-	Green (2022)
	Rice bran	2.30	1.73	1.89	-	-	
	Herbal plants residues	1.35	0.36	0.42	9.4	4.3	Khater (2015)
	Sugar cane plants residues	1.62	1.12	1.36	20	7.1	
	Alfalfa meal	2.77	0.25	2.46	-	-	Green (2022)
Animal waste	Panchagavya	0.75	0.3	0.76	-	-	Kalaivani and Gnanavelrajah (2021)
	Cattle manure	0.27	0.24	0.49	-	-	
	Chicken manure	2.44	0.67	1.24	16.1	-	Lubis et al. (2021)
	Horn and hoof, bone and blood meal	0.46	0.12	0.05	-	-	Guajardo et al. (2018)
	Egg shells	<0.01	0.05	0.02	-	-	Yerizam et al. (2022)

Countinued Table 2. Commonly used raw materials to produce LOFs.

	Beef cattle manure	0.57	0.14	0.41	-	-	Green (2022)
	Dairy cow manure	0.52	0.12	0.36	-	-	
	Poultry- broilers manure	3.08	1.28	1.82	-	-	
	Poultry-Layers manure	1.68	1.06	1.20	-	-	
	Swine manure	0.93	0.31	0.48	-	-	
Seaweed	*Codium* sp.	<0.01	<0.01	<0.01	-	-	Nasmia et al. (2020)
	Ulva sp.	<0.01	<0.01	<0.01	-	-	
	Padina sp.	<0.01	<0.01	<0.01	-	-	
	Amphiroa sp.	<0.01	<0.01	<0.01	-	-	
	sargassum crassifolium	0.04	9	0.15	-	9	Sutharsan et al. (2014)
	Ulva rigida extract	1.28	-	0.05	-	-	Latique et al. (2013)
	Fucus spiralis extract	0.56	-	0.01	-	-	

Table 3. Potential characteristics of LOFs produced after fermentation.

No	Liquid fertilizer	Days after fermentation	Nitrogen content %	Phosphorus %	Potassium %	Organic carbon %	pH	Source	Plant used to test	Fermentation method	Reference
01	Eggshells 0.5 kg: molasses 50 ml: water up to 4 L	10	0.02	<0.01	0.08	-	-	Plant based	-	Anaerobic	Siahaan et al. (2023)
02	Banana peels 0.5 kg: molasses 50 ml: water up to 4 L	10	4.07	<0.01	0.14	0.56	4.07	Plant based	-	Anaerobic	
03	Moringa Leaves 0.5 kg: molasses 50 ml: water up to 4 L	10	3.93	<0.01	0.10	0.53	3.93	Plant based	-	Anaerobic	
04	Onion leels 0.5 kg: molasses 50 ml: water up to 4 L	10	3.76	0.01	0.10	0.53	3.76	Plant based	-	Anaerobic	
05	Bean sprouts 0.5 kg: Molasses 50 ml: water up to 4 L	10	3.750	0.01	0.11	0.54	3.75	Plant based	-	Anaerobic	
06	Banana hump 0.5 kg: molasses 50 ml: water up to 4 L	10	3.97	<0.01	0.10	0.51	3.97	Plant based	-	Anaerobic	
07	Distillery slop: sugarcane leaves: filtrate water 1:0.1:0.25 v:w:v	30	0.16	<0.01	0.82	2.93	-	Agro-industry factories	Green Cos Lettuce	Aerobic	Phibunwatthanawong and Riddech. (2019)
08	Distillery slop: sugarcane leaves: filtrate water 1:0.25:0.25 v:w:v	30	0.14	<0.01	0.96	0.26	-			Aerobic	
09	Maize residues (vegetal-based) and faeces sheep manure (animal-based) p	-	-	-	-	-	-	Agro-industrial waste	Citrus	Hydrolysis	Martínez -Alcantara et al. (2016)
10	Moringa	-	-	-	-	-	-	Plant-based	Upland red rice	-	Nasira et al. (2021)

Countinued Table 3. Potential characteristics of LOFs produced after fermentation.

11	*Gracilaria* sp.	14	0.56	0.05	0.33	0.67	6.49	Seaweeds-macroalgae	-	Aerobic	Tsaniya et al. (2021)
12	*Sargassum* sp.	14	0.45	<0.01	0.68	0.06	7.03				
13	Siam weed	-	0.36	6.80	0.96	-	6.76	Weed plants	Black soybean.	Aerobic	Pujiwati et al. (2021)
14	Yellow creeping daisy	-	0.22	6.61	0.75	-	7.44				
15	Goat weed	-	0.44	6.94	0.61	-	6.14				
16	5 Kg Tithonia weed (*Tithonia diversifolia*) 2.5 kg of topsoil, 5 kg of cow dung, 10 L of EM-4 starter solution, 10 L of coconut water	28	1.04	0.58	0.60		6.12	Weed plant	Sweet corn	Aerobic	Puteri et al. (2021)
17	10 kg animal's feces (cattle), 20 L cattle's urine, 5 kg of topsoil, 10 kg of Tithonia diversifolia (Hamsley) A. Gray), 20 L solution of 24-hour incubated 20 ml EM 4 + 0.25 kg white sugar	35	1.09	2.16	0.58	1.02	6.66	Animal waste	Lettuce	Anaerobic	Fahrurrozi et al. (2020)
18	10 kg animal's feces (chicken), 20 L cattle's urine, 5 kg of topsoil, 10 kg of Tithonia diversifolia (Hamsley) A. Gray), 20 L solution of 24-hour incubated 20 ml EM 4 + 0.25 kg white sugar	35	1.26	2.48	0.61	0.75	6.88	Animal waste	Lettuce	Anaerobic	

Countinued Table 3. Potential characteristics of LOFs produced after fermentation.

19	10 kg animal's feces (goat), 20 L cattle's urine, 5 kg of topsoil, 10 kg of Tithonia diversifolia (Hamsley) A. Gray), 20 L solution of 24-hour incubated 20 ml EM 4 + 0.25 kg white sugar	35	1.16	1.92	0.57	0.96	6.66	Animal waste	Lettuce	Anaerobic	
20	10 kg animal's feces (buffalo), 20 L cattle's urine, 5 kg of topsoil, 10 kg of Tithonia diversifolia (Hamsley) A. Gray), 20 L solution of 24-hour incubated 20 ml EM 4 + 0.25 kg white sugar	35	1.17	1.84	0.56	0.70	6.97	Animal waste	Lettuce	Anaerobic	
21	Gamal Leaves (*Gliricidia sepium*)	25	0.11	0.03	8.02	-	5.05	Plant waste	Lettuce (Lactucasativa L.)	Anaerobic	Qoniah et al. (2020)

Table 4. Characteristics of thermally hydrolyzed LOFs.

Raw materials	Temperature (°C)	N%	P%	K%	pH	Reference
Food waste	180	0.17	0.02	0.03	-	Gao et al. (2021)
Broiler chicken manure	180	0.45	0.03	0.41	7	Perera et al. (2015)
Broiler chicken manure	200	0.38	0.02	0.41	5.5	
Layer hen manure	180	0.29	0.02	0.43	7.5	
Layer hen manure	200	0.28	0.01	0.47	6.7	
Infected pig carcasses	100	2.26	-	6.12	11.9	Kang et al. (2019)
Chicken feathers	160	0.71	0.01	0.05	-	Nurdiawati et al. (2019)
Chicken feathers	180	1.57	0.01	0.04	-	
Poultry litter	160	0.2	0.01	0.01	-	

Thermal hydrolysis (TH) for nitrogen enrichment process

TH is a treatment method involving heat, pressure, and water applied to organic waste materials, like sewage sludge or food waste. It facilitates the breakdown of complex organic compounds into simpler molecules via hydrolysis reactions, releasing nutrients, including N, in a plant-accessible form. TH has proven effective in boosting the nutrient content of organic waste, particularly in terms of N enrichment. Research indicates that it significantly enhances N availability by breaking down proteins and other N-containing compounds in the waste, making the recovered N a valuable resource for organic fertilizer production (Gao et al. 2021).

Despite its potential, TH faces challenges. High energy requirements and associated costs are primary concerns (Xie et al. 2022). Contaminants like heavy metals and pathogens in the organic waste may necessitate additional treatment steps to ensure fertilizer safety and quality.

Numerous studies have explored TH for N enrichment. For example, Kang et al. (2019) investigated alkaline hydrolysis using infected pig carcasses. They achieved an N% of 2.26% and K of 6.12% at 100°C, though P% values weren't reported. The resulting LOF had a pH of 6.12, indicating slight acidity. These findings underscore TH's efficacy in N enrichment for LOF production. Different raw materials and temperatures influence fertilizer nutrient composition, and pH values suggest the process can be adjusted for optimal plant nutrient uptake. Table 4 summarizes TH waste material nutritional content and pH.

Further research should explore parameters like reaction time and pressure to optimize TH for N enrichment in LOF production. Understanding these factors will enhance sustainable agricultural practices and efficient use of organic waste.

Nitrogen fixation by plasma activation

Plasma, the fourth fundamental state of matter after solid, liquid, and gas, is an electrically conducting medium containing unbound ions, radicals, electromagnetic radiation, and strong electric fields (Wang et al. 2020). While plasma processes naturally occur on Earth, they can also be generated artificially by passing an electric current through gas. Plasma technology has diverse applications in industries like food, agriculture, and medicine. It's widely explored for NOx production and direct conversion of N2 and H2 into NH3 using plasma reactors (Li et al. 2018).

Recent research reveals that plasmas containing N2, O2, and H2O can produce nitrate, nitrite, and hydrogen peroxide in nearby water surfaces. Air plasma-treated organic fertilizer liquids decrease atmospheric NH3 and CH4 release while potentially increasing nitrous oxide-N2O emissions from fertilized soil. Nonetheless, plasma-assisted organic fertilizers (PAOF) reduce reactive N loss from agro ecosystems and enhance the commercial value of organic waste-based fertilizers by altering N quantity and form, while also reducing odors (Graves et al. 2019). Table 5 summarizes recent findings on organic fertilizer production via plasma activation, considering plasma setup types and experimental conditions. The commercial feasibility of PAOF depends on plasma process energy efficiency, equipment capital costs, and power expenses. These factors, especially crucial for developing countries, must be considered when evaluating PAOF technology viability.

Table 5. Key findings from recent studies on the production of organic fertilizers using plasma activation.

Plasma setup type	Plant used for the experiment	Other treatments used for the experiment	Major finding	Reference
Atmospheric pressure plasma jet (APPJ)	Lentil	Tap water, demineralized water, and liquid fertilizer	By plasma-activating tap water, obtained high germination rates, higher stem elongation rates and final stem lengths.	Zhang et al. (2017)
Transient spark discharge	Wheat	Plasma-activated tap water, plasma-activated distilled water	The plasma-activated tap water (PAW) improves germination, early development of the seedlings, the content of photosynthetic pigments in the leaves and soluble protein content in the roots, and suppresses the activity of antioxidant enzymes.	Kucerova et al. (2019)
Pinhole plasma jet technique	Green oak lettuce	No nitrate in the nutrient solution and use of nitrate sourced from a commercial chemical fertilizer	Plasma nitrate could be an alternative source of nitrate N which provides a safer way for the environment and human health in terms of nitrate accumulation.	Ruamrungsri et al. (2023)

Use of microorganisms in nitrogen enrichment

Plant probiotics, or bio-fertilizers, offer an eco-friendly alternative to chemical synthetic fertilizers, mitigating their adverse effects. These bio-fertilizers comprise beneficial microorganisms like bacteria, fungi, and algae, which support crop growth while suppressing plant pathogens. These microorganisms enhance nutrient breakdown and uptake rates and are integrated into both liquid and solid organic fertilizers to boost efficiency. This approach is cost-effective and user-friendly, making it highly sought after in sustainable agriculture.

Bio-fertilizers interact with crop plants, facilitating the absorption of essential nutrients such as N, P and K For instance, N-fixing bacteria convert atmospheric N into ammonia (Sarbani and Yahaya 2022), and similar processes apply to other major nutrients. Furthermore, they increase crop yield and profitability while mitigating the downsides of chemical fertilizers. They detoxify pollutants, produce bioactive compounds like hormones and enzymes, and induce systemic resistance, enabling plants to combat multiple pathogens (Nowruzi et al. 2021; Santoyo 2021; Xue et al. 2021).

The genus Bacillus, found in the plant rhizosphere, promotes tomato plant growth (Kalam et al. 2020). Naturally occurring N fixers, including *Azotobacter* sp., *Rhizobium* sp., Cyanobacteria, and others, reside in the soil and convert atmospheric N into ammonium ions by releasing nitrogenase enzymes (Kumar et al. 2017). Inoculating these N-fixing strains into fertilizers can supply plants with sufficient N. *Azotobacter tropicalis* strains have shown significant positive effects on maize growth, stimulating a fourfold increase in crop yield (Su et al. 2023).

Moreover, there is substantial potential to discover more efficient N-fixing strains for incorporation into LOFs to further enhance productivity. Table 6 summarizes common microorganisms involved in producing N-enriched LOFs.

Table 6. Microorganisms involved in the production of nitrogen-enriched LOFs.

Microorganism	Mechanism	Nitrogen Enhancement Outcome	Reference
Rhizobium spp.	Biological N fixation	Increased N content	Bamdad et al. (2022)
Azotobacter spp.	Solubilization of mineral-bound N	Enhanced N availability	Dahham et al. (2021)
Frankia spp.	Actinorhizal N convert atmospheric N into ammonia, which can be utilized by plants fixation	Improved plant growth	Santi et al. (2013)
Cyanobacteria	N fixation and biofertilization	Enhanced fertilizer efficacy	Chittora et al. (2020)
Archaea	Ammonia production via archaeal nitrification	Increased N uptake	Zou et al. (2022)

Nitrogen enrichment by membrane techniques

The use of membrane techniques for ammonia recovery in the production of LOFs is noteworthy. These membranes efficiently capture ammonia ions from various waste sources, such as livestock manure, industrial effluents, or sewage, curbing ammonia emissions and turning waste streams into valuable resources (Aquino et al. 2023; Vecino et al. 2019; Rodríguez-Alegre et al. 2023; Mayor et al. 2023).

In recent years, membrane techniques have gained attention for enhancing N content in LOFs while preserving organic integrity (Vecino et al. 2019). They offer an environmentally responsible solution for addressing plant N needs. Two membrane-based methods, membrane distillation (MD) and membrane contactor (MC), are well-recognized for ammonia removal and recovery due to the use of hydrophobic membranes that allow volatile ammonia gas to pass through (Zhu et al. 2023). Additionally, forward osmosis (FO) and reverse osmosis (RO) show promise in N enrichment. FO relies on an osmotic potential gradient to concentrate N compounds, while RO uses pressure to achieve the same goal (Rodríguez-Alegre et al. 2023; Courtney and Randall 2023).

Recent research highlights the effectiveness of these membrane techniques in increasing N concentration in LOFs, as shown in Table 7. These methods consistently elevate N content, demonstrating their potential to enhance agricultural sustainability. Considering the available data, liquid-liquid membrane techniques offer a sustainable way to produce N-rich LOFs by efficiently extracting and concentrating N compounds, aligning with organic farming principles. However, specific challenges exist with these technologies. For instance, hollow fiber membrane contactor (HFMC) technology may encounter membrane wetting issues that disrupt the process (Atsbha et al. 2023). On a positive note, FO boasts advantages like minimal fouling and low energy requirements, prolonging its operational lifespan, particularly with certain feed solutions (Yi et al. 2022).

Table 7. Impact of membrane techniques on nitrogen concentration.

Contractor	Membrane technique	Type of raw material	Recovered N%	Recovered P%	Recovered K%	Reference
Direct Contact Membrane Distillation (DCMD)	Membrane Distillation (MD)	Digestate is produced by a digester that treats cattle manure and agricultural residues	-	-	-	Aquino et al. (2023)
Hollow fibers liquid-liquid membrane contactors (HF-LLMC)	-	Urban wastewater	7.8	21.6	-	Vecino et al. (2019)
HFMC	FO	Pig slurry	28.3	43.5	46.6	Rodríguez-Alegre et al. (2023)
HFMC	-	Treated urban wastewater	10-15	-	-	Mayor et al. (2023)

Conclusion

This review concentrates on various methods and approaches to enhance the N content in LOFs. Among numerous methods, the selection of raw materials with high N content, thermal hydrolysis for N enrichment, N fixation through plasma activation, the utilization of microorganisms for N enrichment, and membrane techniques have emerged as prominent strategies for LOF production. The analysis of raw materials has revealed that certain sources, such as animal waste and plant materials, exhibit higher nutrient profiles than seaweeds. Materials like cottonseed meal, bone and blood meal, sugarcane leaves, and alfalfa meal have demonstrated high N, P, and K contents, making them promising candidates for N-rich LOF production. Thermal hydrolysis has proven to be an effective process for N enrichment, breaking down organic waste into simpler molecules and releasing nutrients, including N, in a readily available form for plant uptake. However, challenges related to energy requirements, costs, and the presence of contaminants needs to be addressed for practical implementation. N fixation through plasma activation reduces N loss from agro ecosystems and modifies N quantity and chemical form in organic waste-based fertilizers. While commercial viability depends on factors such as energy efficiency and capital expenditures, the potential benefits of reducing odor and reactive N loss are substantial. The use of microorganisms, including N-fixing bacteria and plant probiotics, offers a biofertilizer approach to increase N availability in LOFs. These microorganisms can promote nutrient breakdown and uptake, improve crop yield, and mitigate the adverse effects of synthetic fertilizers. Future research in this area should focus on identifying more efficient N-fixing strains and exploring their incorporation into LOFs.

Additionally, membrane techniques such as HFMC hold promise for sustainable LOF production by upcycling waste into valuable products, providing valuable research direction. However, to further advance LOF production, it is essential to identify new raw materials with high N content, develop efficient N enrichment methods, and assess the effectiveness of the produced fertilizers for sustainable agriculture. In conclusion, as the demand for sustainable and N-rich organic fertilizers continues to rise globally, the current review provides intriguing information about the recent developments in N-enriched LOFs, including crop yield improvements and sustainable farming practices worldwide.

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