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Can Direct Conversion of Used Nitrogen to New Feed and Protein Help Feed the World?

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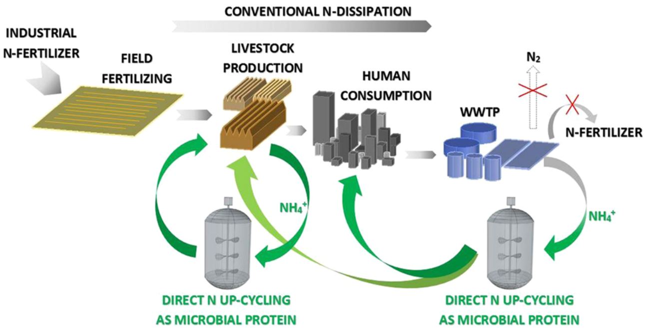

The increase in the world population, vulnerability of conventional crop production to climate change, and population shifts to megacities justify a re-examination of current methods of converting reactive nitrogen to dinitrogen gas in sewage and waste treatment plants. Indeed, by upgrading treatment plants to factories in which the incoming materials are first deconstructed to units such as ammonia, carbon dioxide and clean minerals, one can implement a highly intensive and efficient microbial resynthesis process in which the used nitrogen is harvested as microbial protein (at efficiencies close to 100%). This can be used for animal feed and food purposes. The technology for recovery of reactive nitrogen as microbial protein is available but a change of mindset needs to be achieved to make such recovery acceptable.

INTRODUCTION

Sustainable boundaries of human activities on earth have been widely identified and are of strong concern. Top of the list are ecological diversity, climate change, the terrestrial water balance, and the impact of nitrogen on the overall ecosystem.[1] There are clear links between different boundaries. Indeed, climate change is directly linked with CO_2 emissions, but the latter has a strong connection with the anthropogenic nitrogen impact (i.e., fertilizer) used to produce feed and food. About 1−2% of the total world energy consumption is used to produce reactive nitrogen by means of the Haber Bosch process. Current anthropogenic sources of nitrogen are 100 Mt of nitrogen by chemical fixation, 35 Mt by biological crop fixation and 10 Mt by atmospheric deposition in animal rearing. Yet of this total only 13 Mt nitrogen are consumed as vegetable protein and 10 Mt nitrogen as animal protein, totaling only a mere 16% net efficiency. These massive losses in the nitrogen cycle are largely due to losses during primary (plant) agriculture (runoff, leaching, volatilization, and denitrification). Losses are high because plant agriculture is the entry point for nitrogen to the food chain (and hence the largest amount is at this point). In addition, nitrogen entering waste streams is currently mainly converted to dinitrogen gas and lost to the atmosphere rather than reused to make food. Indeed, wastes generated by animals and humans not only generate greenhouse gases (N_2O and CH_4) but also destroy resources which could, by proper recycling, help to abate climate change. In this work, problems relating to the energy demanding production of reactive nitrogen by industry or by recovery processes from wastes, and the overall ineffective use of nitrogen in the conventional agrosystem are examined. Subsequently, a new approach is proposed in which the used nitrogen is converted to single cell microbial protein to be used as feed and food. Finally, the overall impact of such direct conversion for the planet, in the context of population urbanization toward megacities, is evaluated.

BETTER NITROGEN MANAGEMENT IS PIVOTAL FOR A SUSTAINABLE FEED/FOOD SUPPLY

Nitrogen (N) in its reactive forms (ammonium, nitrite, and nitrate) is essential for plant growth and thus for synthesis of proteins to be supplied to animals and humans. While N constitutes almost 80% of the terrestrial atmosphere, its availability in a reactive form is limited. The supply of biologically available nitrogen relying on biofixation (leguminous crops), atmospheric deposition, or on crop residues, fecal matter and animal manure recycling covers only about half of the present agricultural demand, largely due to enhancement in agricultural plant growth rates through supply of chemically derived reduced nitrogen.[2] Indeed, since the Haber-Bosch process was invented in the early 1900, industrial production of N-based fertilizers and better seeds supported the largest historical increase in food production capacity.[3] As direct consequence, the global population has reached levels which otherwise could not be achieved. Further growth is expected to bring world population between 8 and 10 billion by 2050,[4] resulting in substantial pressure on food supply, especially in terms of high value protein supply. This supply of industrial fertilizer changed the nitrogen cycle, with 30% of terrestrial

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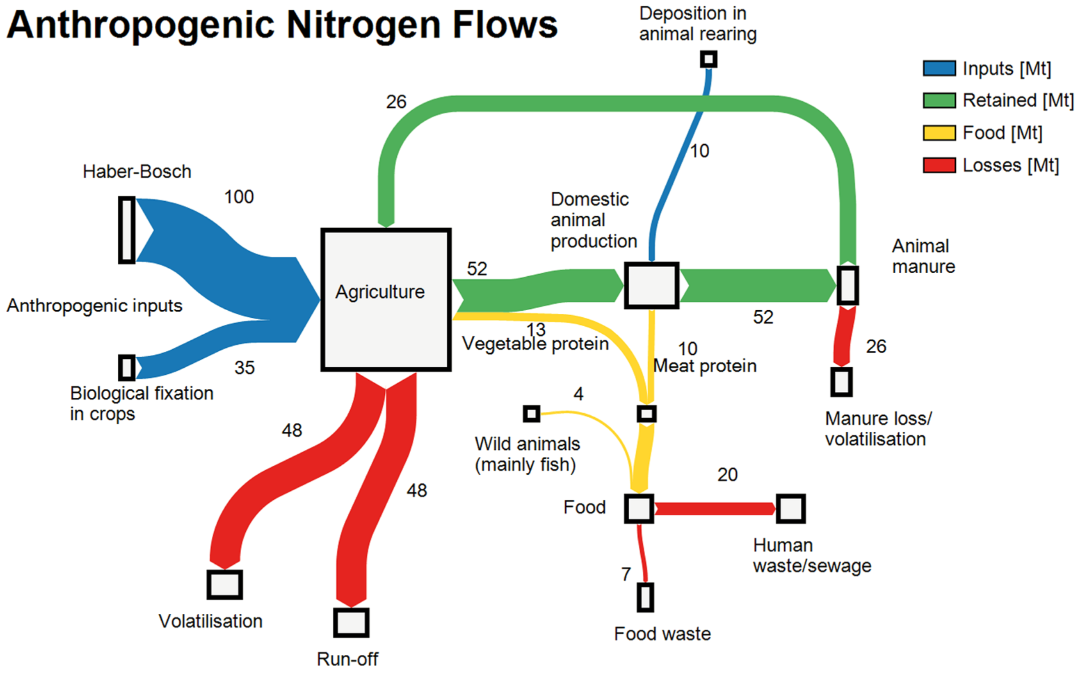

Figure 1. Anthropogenic nitrogen cycle proportional to current Haber-Bosch fixation (100 Mt), with a focus on industrialized agriculture. Calculated based on agricultural N-utilization efficiency of 40%,[7] feed conversion efficiency of 15%,[9] manure utilization of 50%,[8] and with proportional nitrogen input fluxes taken from[5] and.[17] Of 135 million tons N entering the agricultural process (Haber-Bosch, Biological fixation in crops), 17% is retained in vegetable and meat protein, and 15% in the urban wastewater process. The remainder is dissipated to the natural environment. See also Bodirsky[18,19] which was done independently in global simulation software, but which matches these calculations.

nitrogen being generated from human activities (mainly due to fertilizer production and utilization),[5] and this is projected to rise.[6]

At present, of the nitrogen used as fertilizer, only a few percent is effectively consumed as food protein, particularly if the majority is consumed as meat protein. Fertilization by industrial N-fertilizer suffers from a number of inherent losses. Overall, losses for runoff, leaching, ammonia volatilization, and denitrification make up from 50 to 70% of the initial amount of N supplied as fertilizer.[7] The other key inefficiency is generation of meat protein from plant protein, with unconverted nitrogen being discharged as manure, of which only 50% is reused as fertilizer.[8] The feed-meat nitrogen conversion ratio depends heavily on species, overall feed conversion ratios (FCR—kg dry feed per kg whole animal weight gain), ranges from 1.5 to 2 for chickens, to 3 for pigs, to 7−20 for sheep and cattle,[9] with intensive livestock generally having advantageous ratios. As dry grain feeds and whole animal nitrogen are both on the order of 2−3% N (mass basis), FCR is approximately reciprocal to nitrogen conversion efficiency (kgN_{fed}/kgN_{animal}). The current land area devoted to livestock feed and production constitutes about 75−80% of the total agricultural land use.[10] This makes the industrial N-fertilizer production and its massive utilization for protein supply a serious concern in terms of its large environmental footprint. Actually, nitrogen manufacturing exceeds the estimated sustainable boundaries by a factor of 5.[5,9,11] It has been calculated that the industrial production of N-based fertilizers by the Haber-Bosch process constitutes about 1−2% of the world power generation,[12] with 4−8 tons of CO_2-eqv per ton N fertilizer produced.[13] Ammonia and nitrate loss to the environment causes eutrophication, and nitrification contributes to agricultural and environmental N_2O emissions, a gas with a greenhouse warming potential 300 times higher (on a mass basis) than CO_2, and with the highest impact on ozone depletion among other ozone-depleting gases.[14,15] Because of the major role played by nitrification, N_2O emissions from agriculture account for about 25% of the global N_2O emissions.[16]

If feed/food supply continues to rely on the present soil-plant based production system, the increasing demand for edible protein in the near future will exacerbate even more these aspects.[14] Already at present, about 30% of all ice-free land, 70% of freshwater, and 20% of energy are used in the feed and food production system.[10] Global fertilizer consumption is expected to increase by 50% by 2050 to sustain the increase needed in food production capacity.[6] Therefore, a more sustainable and efficient route for nitrogen conversion into edible protein needs to be found, especially when considering the inherent losses in the nitrogen cycle, with a large fraction dissipated in both plant and animal production (Figure 1). A range of alternative options have been proposed to improve nitrogen usage, including a change in diet to reduce animal protein consumption, improved efficiencies in fertilizer application and animal rearing, and better resource management.[19] As an example, switching world diets to only vegetarian would have a dramatic impact, but a more realistic scenario of limiting animal protein intake to no more than 29% of total protein intake, has nitrogen usage efficiency gain of about 20% only.[19] The key issue is that none of these options fully address the major losses involved with open-field plant agriculture. Here we propose an alternative pathway, which is up-cycling of used nitrogen directly to microbial protein, which would enable productivity gains independent of agricultural production.

Table 1. Different Scenarios for N Routes[a]

scenario	route	process no.		energy requirement MJ/kg N	potential use[e]	ref
N-production: N_2 to NH_3	fixation	1	ammonia production (best available technology)	37	NA	26
		2	average N-fertilizer production Europe	45	NA	26
		3	average ammonia production Europe	43	NA	26
N-removal: NH_3 to N_2	biological	4	nitrification/predenitrification in WWTP (CAS)	45	NA	26
		5	mainstream deammonification	12	NA	27
N-recycle	physico-chemical	6	thermal volume reduction of stabilized urine[b]	34	CP	26
		7	volume reduction of stabilized urine with reverse osmosis[c]	29	CP	26
		8	struvite precipitation for P recovery	69	CP, FF	28
		9	adsorption (ion exchange)	116	CP, IA, FF	29
		10	electrodialysis	65	CP, IA, FF	30
		11	stripping with air and $(NH_4)_2SO_4$ production	90	CP, IA, FF	26
	Combinations	12	Anammox + Haber-Bosch	54	NA	31
		13	bio electrochemical system (BES)[d]	−11	NA	32

[a]Primary energy requirement are compared for reactive nitrogen production by conventional industrial processes, reactive nitrogen removal and recovery from used water as well as reactive nitrogen recycle by the combination of different routes. A conversion efficiency of 0.31 was used to convert the electricity consumption to primary energy. Source, ref 26. [b]Calculated for urine: 10-fold concentration with vapor compression. [c]Calculated for urine: 5 fold concentration. [d]Calculated for a microbial fuel cell (MEC) treating urine and recovering nitrogen via air stripping; as yet only at lab-scale. [e]Potential uses of the physicochemical recycled N: process 6 to 11. CP = crop production, IA = industrial application (such as $DeNO_x$, synthesis of N-polymers), FF = feed and food, NA = not applicable.

■ ROLE OF CLIMATE CHANGE IN THE NEED FOR NEW FEED AND FOOD

Climate change is another factor affecting the goal of feeding the world. First of all, increases in soil temperature might accelerate microbial conversion of organic matter and nitrogen, thus enhancing the losses of both in the soil ecosystem.[20] Moreover, if the climate decreases our ability to produce food, particularly in sub-Saharan Africa, south Asia, and Latin America our prospects for feeding the world become dismal. The Intergovernmental Panel on Climate Change estimates that climate could reduce global crops production yield by 10% by 2050, with regional variations reaching up to −50%.[21] Production of protein using direct conversion of mineral nitrogen to microbial protein is less climate sensitive and can help alleviate these stresses. In recent years, our global average caloric intake rose to a respectable 11.6 MJ/person·day based on new protein sources.[22] Country-by-country and commodity-by-commodity projections indicate that this quantity could rise to 12.8 MJ/person·day by 2050. A growth in agricultural production of at least 60% would be needed, at the same time that population is projected to increase by 37% during the period 2005−2050. A significant fraction of that 60% requirement could be reduced by reuse of nitrogen in wastewater by microbial growth.

■ USING ENERGY TO DISSIPATE NITROGEN: SEWAGE TREATMENT OF URBAN WASTES

Taking urban wastewater as the key example, protein consumed as food is excreted mainly as urea and NH_4^+ by human metabolism, and discharged to the sewer. The amount of N excreted as a fraction of that fixed by the Haber Bosch process varies from 18−30%, with lower levels in industrialized nations due to losses in animal conversion (21% in our example) (see Figure 1).[23] Current sewage treatment technology is based on the Conventional Activated Sludge (CAS) process, which dissipates nitrogen through the nitrification/denitrification or deammonification process.[24] Reduced, reactive nitrogen is hence biologically converted to its nonreactive dinitrogen gas form, and then released back into the atmosphere, with N_2O gas emissions representing an intermediate of increasing concern in terms of greenhouse gas (GHG) emission from WWTP.[25] In terms of energy consumption, the two processes of N-fixation for fertilizers production and N-dissipation for wastewater treatment are comparable, both requiring around 40 MJ/kg N fixed or dissipated.[23] Therefore, the present sewage treatment system destroys reactive nitrogen using the same amount of energy as used to fix it into fertilizers. While there has been a strong focus on retrieving the direct energy value of the organics present in used waters (used mainly to produce biogas), recovering mineral nitrogen potentially represents an equivalent gain, with broad applicability beyond urban contexts to agro-industrial streams for direct nitrogen recovery to avoid its dissipation in the environment.

■ COST-EFFECTIVE NITROGEN RECOVERY: CAN THIS BE ACHIEVED?

It is generally not considered justified to produce fertilizers from nitrogen recovered from fecal matter, urine, sewage, etc. at higher energy expenditure than is needed by the Haber-Bosch process.[26] However, this viewpoint does not consider nonscope 1 carbon emissions (i.e., those relating to transport, downstream processing etc.), or emissions relating to fertilizer formulation and distribution, and wastewater treatment of produced nitrogen, which are highly region specific. This can make the recovery of nitrogen from various streams, particularly where there is no existing wastewater treatment infrastructure or wholesale replacement is required, a more appealing approach. Physico-chemical and biological processes, as well as the combination of both have been studied and implemented for nitrogen removal and recovery from used water. A comparison between the energy requirements of biological, physicochemical and combined N-removal/recovery techniques is shown in Table 1. As shown most of the “best” established

Table 2. Energy Needed to Produce 1 kg Edible Protein Nitrogen with Conventional Route (Meat Protein) And through Microbial Growth (Single Cell Protein)

protein production system		energy source	carbon conversion efficiency	MJ/kg N-protein[a]	advantages (+) and disadvantages (−)
conventional route: edible meat protein		fossil fuel	na	4000[59b]	+ consolidated technology—high inefficiencies, environmental burdens and land requirement
microbial protein	organotrophic	organic matter[c]	Organic-C to cell-C: 0.3−0.4	230[60,61]	+ applicable in a circular biobased economy; sustainable; minimal land requirement
	lithotrophic	hydrogen gas	CO_2−C to cell-C: 1.0	452[62]	
	methylotrophic	methane gas	CH_4−C to cell-C: 0.1−0.2	361[60,61]	
	phototrophic (anaerobic phototrophic bacteria)	organic matter, light	organic-C to cell-C: 1.0	450[d43,56]	− energy requirement for processing the biomass
	photosynthetic (algae)	light	CO_2−C to cell-C: 1.0	5000[e54]	+ natural light only—High footprint

[a]For the single cell protein production, a biomass composition of $C_1H_{1.8}O_{0.5}N_{0.2}$ was assumed as reference for the N-content [b]Beef cattle was used as reference for meat protein production [c]Acetate was considered as organic carbon substrate. A value of 2MJ/kg O_2 was considered for aeration. [d]Phototrophic bacteria: 80% of energy delivered chemically, 20% as infrared light. [e]Photosynthesis light as chemical energy.

recovery technologies such as struvite precipitation, adsorption, electrodialysis and air stripping are still not competitive with the Haber-Bosch manufacturing, though they avoid the costs of ammonia manufacturing. Indeed, all these techniques are usually applied at relative small scale and although they recover the nitrogen, they are more expensive than the Haber-Bosch process, which is practiced at such massive industrial level that it profits from the dimensions of scale.

Of particular interest are the combined physicochemical and biological approaches for the removal of used N and production of a new usable form. In this context, process no. 12 demonstrates how a biological N-removal technique (Anammox) succeeded by the Haber-Bosch provides an efficient way of handling nitrogen, although this represents only a theoretical concept with the atmosphere as overall N-pool. The process no. 13 utilizes the inherent chemical energy in urine to drive electro-pervaporative ammonia recovery. However, it relies on source separation to urine, has only been reported in lab scale.[32−34] Improvements of the stripping efficiency and the implementation of further technical advances already proposed for other electrochemical systems treating N-rich streams will make these innovative systems more practical.[35]

Overall, the current mature recovery technologies can achieve energy parity with Haber-Bosch manufacturing, only on concentrated wastewaters such as from certain food industries. This does not consider economic issues, and the cost of these technologies (particularly bioelectrochemical, or pervaporative systems given the high capex costs) drives the cost per unit nitrogen above the current market price of \$700/ton.[36] As an alternative to nitrogen recovery and reuse, the long path of dinitrogen to plant or animal edible protein-N should be critically examined; there is a need for a shorter more effective route.

■ CONVENTIONAL VS DIRECT REUSE: UP-CYCLING NITROGEN BY A SHORT ROUTE

At this moment, the anthropogenic and natural nitrogen cycles interact and pool to create vegetable and animal proteins,[37] with by far the largest magnitude of loss occurring through production of plant protein, mainly because the largest amount of nitrogen enters plant agriculture and hence absolute losses are high. Waste derived nitrogen both from human and animal can be reused directly as a field fertilizer, either as a concentrate (recovered using technologies identified in the previous section), or directly reused following primary treatment and a form of hygienization.[38] This is of course, widely applied to animal manures, and 50% of all animal manure is recycled for agricultural purposes.[8] This latter case saves 40 MJ/kg sewage-N, but this has limited applicability, due to seasonal variations, cost of transport particularly in case of sewage N (limited also by presence of heavy metals and micropollutants), and limits in agricultural land near urban centers. Moreover, once applied in the field, the sewage ammoniacal N will be subject to large field losses for instance by runoff of soluble NH^{4+} and NO^{3-} and by volatilization of NH_3, N_2O and N_2.

An alternative, which inherently avoids losses in field production from plants, is direct production of animal-edible proteins from used nitrogen. This means that the nitrogen cycle is short-circuited in the most direct way, avoiding all the inherent losses of crops or even potentially livestock production.

Recovered Nitrogen: Nothing New. Recovered nitrogen is indeed already part of our daily life. Production of edible mushrooms is actually based on the direct use of organic wastes such as agricultural byproducts (particularly the N-rich chicken manure) as well as industrial and municipal wastes.[39] In this way, used nitrogen is directly incorporated into valuable and edible fungal matter. Another practice of direct up-cycling of fecal nitrogen to edible protein is currently ongoing in aquaculture. The nitrogen excreted by fish, instead of being treated and neutralized by means of the traditional biological nitrification/denitrification, is incorporated by the so-called biofloc technology in new microbial biomass rich in protein.[40,41] This has enabled a dramatic shift in sustainability and feed-conversion levels in aquaculture[42] for generating low-cost fish protein that can also be realized for other species.

Biotechnologies for Direct Upcycling of Used N. Bacteria or microalgae can be used directly in the assimilative partitioning of reactive nitrogen supplied or recovered from wastewater.[43,44] Particularly fast growing photosynthetic algae and bacteria, and phototrophic and organotrophic bacteria can be used to completely exhaust the reactive nitrogen by taking it up in cell biomass and form animal digestible protein.[45,46] In this case, the outcome is a high uptake of the nitrogen in N-rich biomass[47] which can be used, for example, as fertilizer[43,44] but also as feed or food.

Microbes have been extensively and historically studied as potential producers of feed and food, and their actual use is visible in our daily life.[45,48] Yeast, for example, represents a direct microbial source of food or food additive.

Chemotrophs are interesting as they allow recovery of carbon dioxide present in the water or in biogas and energy, as well as nitrogen from wastewater. Methylotrophs, which are bacteria able to grow on natural gas, have been studied extensively as possible source of single cell protein,[49] that is, protein accumulated by single cell microorganisms.[45] They are already used, for example, as feed for aquaculture.[50] Organotrophic single cell protein production is possible as feed and food protein producer.[49,51] In this case an inexpensive and available organic carbon present in the form of residual organics derived from the original vegetable matter (e.g., food industry process water) is used to grow microbial biomass able to accumulate proteins. Other kinds of bacteria suitable as potential protein producers are lithotrophic bacteria, using molecular hydrogen to fix carbon dioxide into protein-rich biomass.[52] All the above-mentioned microbial species might be useful to up-cycle used reactive nitrogen directly to edible protein. The question arises to what extent this route of biotechnological direct conversion of used N can represent a valid alternative to the established anthropogenic N cycle. It is generally accepted that about 200−500 MJ of electron donor (organic carbon, hydrogen, or methane) are required for the production of 1 kg of microbial N (see Table 2). In case the latter is harvested and consumed directly, it appears that direct nitrogen conversion is highly advantageous and clearly offers perspectives for up-cycling fecal nitrogen, even via the route of stripping and upgrading the stripped N in the form of single cell protein (Table 2). In all fairness, the issues related to the quality of the edible protein (plant-animal-single cell protein) are not integrated in this discussion, but certainly are of value.

Photosynthetic organisms reduce inorganic carbon (carbondioxide) by deriving electrons from water to produce oxygen to generate organics. They are generally inefficient in terms of light efficiency (<9%) but they can utilize natural light.[53] They hence require large amounts of space to drive substantial nitrogen uptake. Algae are an effective source of protein[54] but with lower digestibility than bacteria.[60] Electrical consumption in operating large-scale photobioreactors can also be substantial, due to requirements for algae harvesting and CO_2 delivery, and can be on the same order as the energy harvested through photosynthesis.[55] Phototrophic organisms such as purple phototrophic bacteria are an interesting alternative, as they utilize infrared light to drive organotrophic uptake of soluble organics (similarly to how organotrophs utilize chemical energy to drive growth), without producing oxygen, including on domestic wastewater.[43] Only small amounts of light energy are needed to drive organic uptake because growth is anoxygenic (i.e., phototrophic not photosynthetic). Phototrophic bacteria are effective as animal feed.[56]

The key restriction for microbial food/feed production from wastewater is potential contamination of the product for instance with pathogens. Only in specific cases such as food processing wastewater is there a case for direct-contact assimilation from wastewater.[51,57,58] Microorganisms might, on the other hand, serve as a vehicle for the direct assimilation of nitrogen recovered as mentioned in Table 1. In this case the produced biomass will be of hygienic quality, and the absence of direct contact with wastewater allows their use as animal feedstuff or even as human food. This might be achieved, for instance, by coupling an N-recovery technique with the intensive production of such protein rich microbial biomass. In this sense anaerobic digestion would play a key role, converting most of the organic N embedded in the wastewater into ammonium. The latter could be then recovered from concentrated streams (e.g., digestate) by means of physicochemical processes such as stripping, membrane technology, adsorption etc. After further polishing, the liquid and/or gaseous recovered ammonium stream could be finally integrated in microbial cells to be harvested as feed or food.

These approaches engage with the emerging biorefineries concept, in which mixed, low value organic material is fed to a multiroute and converted to value added products.[63,64] For instance, nitrogen can be processed to generate organonitrogen chemicals, including amino acids, through catalytic conversion. These can be used directly as feeds, or even to generate very high nitrogen fertilizers such as cittruline, which are more effective and less readily lost to volatilization compared with chemical nitrogen.[65]

■ FUTURE MEGACITIES AND MEGA N-FFLUXES

Recovery of nitrogen from urban centers requires a major reimagining of wastewater treatment, as the current paradigm of conventional activated sludge only allows for recovery of 20% of the N which accumulates in waste sludge.[66] In view of enhancing the recovery of used nitrogen and improving its economic feasibility, new concepts for wastewater treatment should be applied within the urban water cycle.[67−70] Preconcentrating organic carbon and nutrients at the head of the main treatment line for instance by means of High Rate Activated Sludge (HRAS) will allow, for example, to recover maximum energy (in form of biogas) and resources (nutrients and minerals) after digesting the concentrated stream of the "minor water line", as well as water reuse on the "major water line".[71] This so-called Major and Minor (M&M) water line approach shifts the focus from dissipation to resource reclamation. The amount of reactive nitrogen discharged in the sewer is only a small fraction (10−30%) compared to what is used in agriculture for crops and livestock production.[23] This emphasizes once again the importance to explore the microbial cell protein recovery route (Table 2). It is also important to identify which of the technology methods as mentioned in Table 2 for direct recovery of nitrogen can be applied to animal manures, and hence make meat protein production more efficient while offering unchanged consumer products. The technology for this is already appearing in the market, and directly utilizes the natural advantages of concentrated and degradable animal manure.[72]

Besides the substantial global population growth expected in the near future, another relevant phenomena will contribute to affect the nitrogen cycle. The concentration of people in metropolitan areas has been already recognized as one of the trends that will reshape our lives.[73] The (over)growth of the so-called megacities will pose several issues in terms of sustainability.[74,75] Feeding millions of people living in focused urban locations will be one of the main challenges. The expansion of the cities will subtract arable land from agriculture, which is already suffering from a lack of land availability, and suggests the implementation of urban farming where possible. At the same time, massive amounts of nitrogen in the form of food protein will be supplied to these urban areas, and will leave via the sewage system. Treating such large quantities of reactive nitrogen will be needed to avoid its regional impact.[76] The fact that microbial nitrogen recovery can be designed so that it occurs in intensive reactor systems with a small footprint is in this context of significant importance. Indeed, if one assumes the production of single cell protein based on hydrogen (produced from renewable electricity by electrolysis of water or reforming of biogas),[77,78] carbon dioxide (e.g., from biogas) and recovered ammonia, the production of the latter in high density reactor systems can surpass the normal plant protein by several orders of magnitude in terms of physical footprint. As example, in case of water electrolysis powered by photovoltaic energy (average solar radiance of 1800 $kWh/m^2\cdot year$, photovoltaic conversion efficiency of 15%, electrolysis efficiency of 82%) an unit of land would deliver an equivalent of 5.6 kg $H_2/m^2\cdot year$ (39.4 kWh/kg H_2), corresponding to actual 2.8 kg $H_2/m^2\cdot year$ (1 m^2 of photovoltaic panels requires 2 m^2 of available land).[79,80] Wind energy, at an average power per unit area of $2W/m^2$ would deliver about 1300 kg $H_2/m^2\cdot year$.[81] Using the latter as energetic substrate to support the growth of single cell protein (hydrogen-oxidizing bacteria with a yield of 2.4 kg dry biomass/kg H_2),[52] could yield up to 67 and 3120 tons/hectare·year of microbial protein respectively for solar and wind based systems. Compared to current soy productivity of about 3 tons/hectare·year,[82] microbial protein production by means of renewable hydrogen is potentially 1−3 orders of magnitude more efficient in terms of land use.

Up-Cycling Used Nitrogen to Feed the Future. Up-cycling used reactive nitrogen directly to feed or food can be seen as a possible way to reduce the dependency of food supply from conventional agriculture. The use of phototrophic, organotrophic or lithotrophic bacteria must be considered as crucial processes to feed the increasing future global population. Exploiting sun light or inexpensive organic carbon substrates, respectively, for phototrophic and organotrophic bacteria, to assimilate and up-cycle recovered nitrogen might open new promising perspectives. Lithotrophic hydrogenotrophic bacteria could be utilized with off-peak green energy and ammonium recovery to produce directly high value protein at low energy costs and net environmental benefits (CO_2 capture). The inherent fear related to the use of microorganisms for food must be overcome by education as well as application of safe and effective technology. Managing the anthropogenic nitrogen cycle in a more efficient way will be therefore of crucial importance for meeting the future global food challenge in a new and sustainable way.

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Notes

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