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Nitrogen mitigation

INMS guidance document on measures for sustainable nitrogen management

To be used alongside the INMS Nitrogen Measures Database – *www.inms.international/measures*

Published by the UK Centre for Ecology & Hydrology (UKCEH), Edinburgh, UK.

Recommended citation

Brownlie, W.J., Aziz, T., Sutton, M.A., Shenk, A., Winkler, M.K.H., Robinson, G., Adhya, T.K., Amon, B., Awan, M.I., Bittman, S., Bleeker, A., Borghardt, G., Butterbach-Bahl, K., Brandani, S., Constantinescu, M., Dahl, K.R, Dalgaard, T., Delon, C., Döhler, H., Galy-Lacaux, C., Garnier, J., Groenestein, K., Hailemariam, M., Hayashi, K., Hillier, J., Jensen, L.S., Kawamoto, T., Kozlova, N., Lukin, S., Lund, T., Marques-dos-Santos, C., Maqsood, M.A., Mathenge, C., Medinets, S., Minamisawa, K., Misselbrook, T., Nishina, K., Oenema, O., Pacheco, F., Parajuli, D., Rahman, M.M., Rees, R.M., Sanz-Cobeña, A., Shiraz, H., Takahashi, A., Tanaka, H., Uchida, Y., Wakeel, A., Winiwarter, W., Yan, X., (2024) Nitrogen Mitigation. INMS Guidance Document on Measures for Sustainable Nitrogen Management. INMS Guidance Document Series (Series Editors: M.A. Sutton, M. Schlegel, J. Baron and H.J.M. Van Grinsven). International Nitrogen Management System, UK Centre for Ecology & Hydrology, Edinburgh, UK. ISBN: 978-1-906698-90-4. DOI: 10.5281/zenodo.13831114.

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Acknowledgements

Meetings, preparation and publication of the Guidance Document were kindly supported by contributions from the Global Environment Facility (GEF) through the United Nations Environment Programme (UNEP) project "Towards the International Nitrogen Management System" (Towards-INMS) and the UK Centre for Ecology & Hydrology. The contribution of many experts and workshops in 2017/2022 and to the chapters is gratefully acknowledged. We thank all the experts attending workshops, contributing comments and peer reviews.

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This report has been prepared and peer reviewed as a scientifically independent process. The views and conclusions expressed are those of the authors and do not necessarily reflect policies off the contributing organizations. This work is an expert contribution to the UNEP Working Group on Nitrogen, the Global Partnership on Nutrient Management (GPNM) and the UNECE Task Force on Reactive Nitrogen.

Report Production

Will Brownlie

Figures and photographs

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Contents

Foreword

This INMS Guidance Document builds on a well-established tradition of the United Nations and its expert groups. As countries come together to agree ambitious targets, the question rapidly arises: what actions should we take to meet the ambition?

Whether or not the targets themselves are mandatory, such guidance is typically voluntary, offering options and opportunities for governments, business and civil society to take action. To foster wide uptake, the guidance needs to be accessible, easily understandable and appealing. It means making complex information available in a form that non-specialists can understand, while giving them a basis to compare options, especially if investment is needed to implement them.

The present guidance document builds on this approach. In 2014, the Air Convention of the United Nations Economic Commission for Europe (UNECE) published its 'Ammonia Guidance Document' (ECE/EB.AIR/120, see Bittman et al., 2014, cited in the present document). This was a legal requirement for one specific form of nitrogen air pollution, according to provisions of the convention's Gothenburg Protocol. Since then, the same convention has gone the next step and published a first ever 'Guidance Document on Integrated Sustainable Nitrogen Management' (ECE/EB.AIR/149, see Sutton et al., 2022). That document covers all major nitrogen forms, linking air and water pollution, greenhouse gases and overall nitrogen loss. One of the core messages is that action on sustainable nitrogen management offers multiple co-benefits across environment, health and economy. Loss of reactive nitrogen represents a wasted resource, worth around US$150-300 billion annually (at 2022-2024 prices), with even larger costs to society through impacts on human health, ecosystems and climate. It means that managing nitrogen sustainably can be good for the pocket and the planet at the same time.

The next steps came in partnership with the United Nations Environment Programme (UNEP), which had already established the Global Partnership on Nutrient Management (GPNM) in 2009. With the support of the International Nitrogen Management System (INMS), funded by GEF/UNEP through the 'Towards INMS' project, and by UK Research and Innovation through its Global Challenges Research Fund (GCRF) 'South Asian Nitrogen Hub', resources were in place to build the global research effort on nitrogen and strengthen partnerships with governments. Under the successive leadership of India and Sri Lanka, with co-sponsorship by Bangladesh, Brazil, Maldives, Pakistan and Uganda, this led to adoption of the first United Nations Environment Assembly (UNEA) resolutions on sustainable nitrogen management in 2019 and 2022 (UNEP/EA.4/Res.14, UNEP/

EA.5/Res.2), further accelerated by the Colombo Declaration in launching the 'UN Global Campaign on Sustainable Nitrogen Management'.

In the UNEA 4/14 resolution, UN member states requested that the Executive Director of UNEP to:

> *Support, in close collaboration with relevant United Nations bodies, including the Food and Agriculture Organization of the United Nations and, as appropriate, multilateral environmental agreements, exploration of the options for better management of the global nitrogen cycle and how they could help to achieve the Sustainable Development Goals, including the sharing of assessment methodologies, best practice, guidance documents and emerging technologies for recovery and recycling of nitrogen and similar nutrients [emphasis added].*

The present INMS guidance document contributes to meeting this request. It takes the next step beyond the UNECE guidance documents mentioned by covering multiple economic sectors, while extending geographically to the global scale. Most importantly, the present guidance document is directly linked to the INMS Measures Database. In this way, the guidance document itself provides an entry point, supported by information on 'key principles' and development of coherent 'packages of measures'. The INMS Measures Database extends this with further evidence and access to key literature, enabling readers to follow up and make connections.

We thank all the authors for their contribution and the many individuals who have provided expert advice along the way. Most importantly, we hope that the product will be useful to the UNEP Working Group on Nitrogen, which has been established to follow up Resolutions 4/14 and 5/2 in mobilizing governments around the world to take action in grasping the nitrogen challenge.

Mark A. Sutton, Martha Schlegel, Jill Baron and Hans J.M. Van Grinsven

INMS Guidance Documents Series Editors.

Executive summary

Main messages

- A wide array of technical and non-technical measures exists to address nitrogen (N) losses throughout the anthropogenic N cycle.
- Socioeconomic barriers, fragmented policies and limited stakeholder access to guidance hinder the widespread implementation of N management measures.
- Guidance and governance on sustainable N management are currently fragmented among different N forms and sectors, indicating a need for consolidation.
- This document details over 150 measures to reduce N losses and improve N use efficiency across seven management stages. Used in conjunction with the INMS Nitrogen Measures Database (Brownlie et al., 2024), it provides guidance for integrated sustainable N management across the anthropogenic N cycle.
- Nine key principles of integration are outlined to facilitate sustainable N management, including consideration of all N forms, sources, and emissions across spatial and temporal scales. Where possible, conditions should be encouraged that favour circularity of N flows, enabling external N inputs to be minimised and outputs maximized.
- Agriculture, being the largest consumer and emitter of reactive N, is identified as a critical sector for sustainable N managements, however opportunities to enhance N sustainability extend across all sectors involved in the anthropogenic N cycle, including organic waste/residue management, land and aquatic resource management, aquaculture and fuel combustion.
- Leveraging economic incentives for recovering N resources and utilizing advancements in data collection and technology dissemination can mobilise change in N management practices.
- Integrated sustainable N management offers multifaceted benefits across environmental, economic and health domains, aligning with UN Sustainable Development Goals and UNEA resolutions on Sustainable Nitrogen Management.

A wide range of technical and non-technical measures are available to address nitrogen (N) losses across all stages of the anthropogenic N cycle. However, currently, guidance and governance on sustainable N management tends to be fragmented between different forms of N and different sectors. To exploit the synergies that exist across the N cycle, there is a pressing need to develop consolidated guidance on sustainable N practices.

This guidance document is intended to be used alongside 'The INMS Nitrogen Measures Database'[1] (Brownlie et al., 2024), to provide consolidated guidance on the 'measures' or actions available to support sustainable N management across the anthropogenic N cycle.

We provide an overview of over 150 measures (see Table ES 1.1) to reduce N losses and improve N use efficiency (NUE) throughout the anthropogenic N cycle. Measures are grouped into seven management stages representing the flows of N between and across the anthropogenic N cycle. These stages are: i) cropping systems, ii) livestock systems, iii) landscape and waterbody management, iv) wastewater and solid organic waste management v) consumers vi) aquaculture and vii) fuel combustion systems (Figure ES 1.1). The impact and evidence differ across measures, each presenting a range of technological demands, which may, in certain instances, restrict widespread implementation. However, the diversity of measures provides a toolkit from which effective priority actions can be selected for specific systems and/or stakeholders. Case studies are used to demonstrate how a 'package of measures' can be selected from this toolkit to improve N management of any given system.

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1 https://www.inms.international/measures

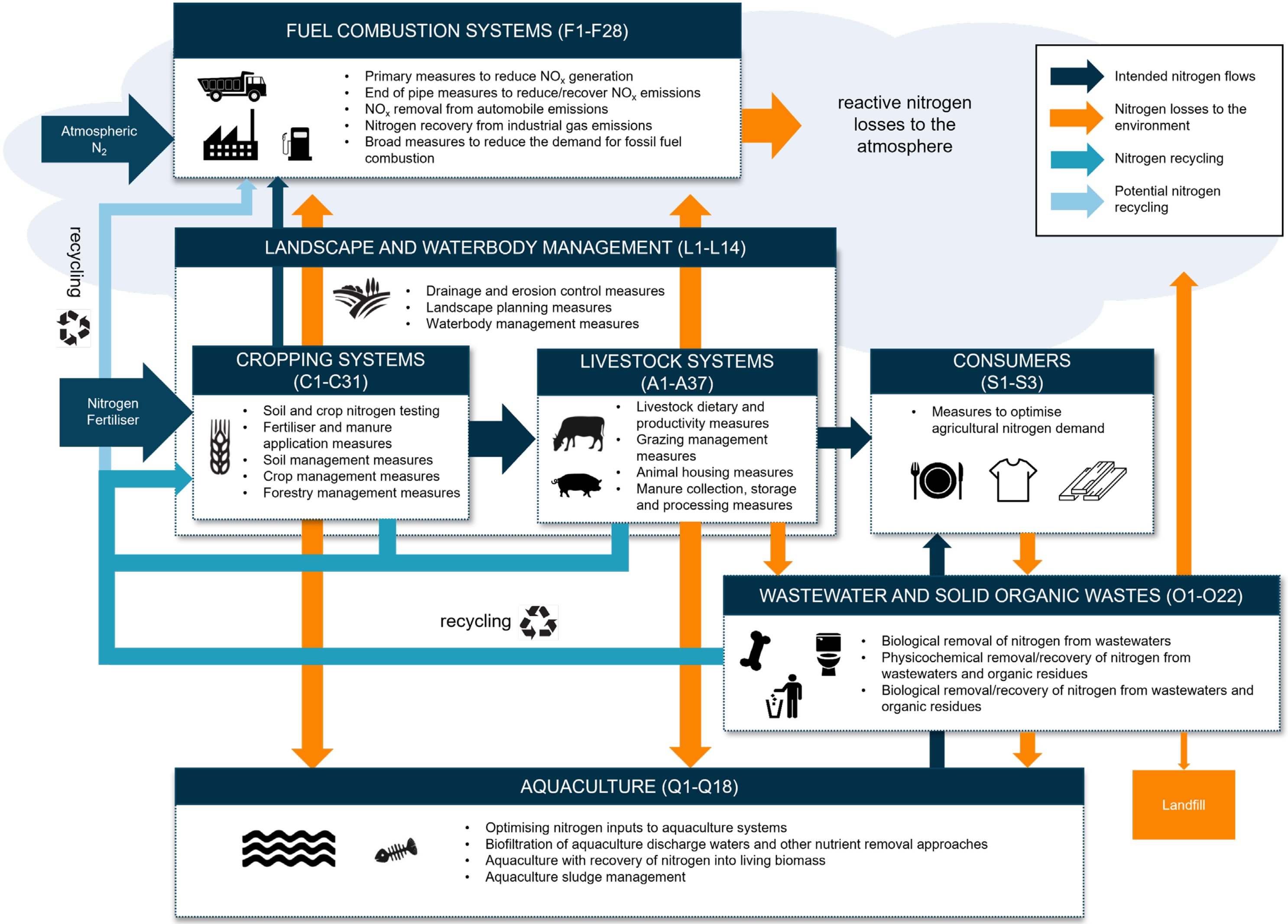

Figure ES 1.1 The N cycle, showing flows of N between seven management stages across the anthropogenic N cycle: i) cropping systems, ii) livestock systems, iii) landscape and waterbody management, iv) wastewater and solid organic waste management v) consumers vi) aquaculture and vii) fuel combustion systems. Within each group, measures are broken into sub-categories as shown. Measures reference codes used in this guidance document are shown in parenthesis following the management state title. Where possible, external N inputs should be minimised, outputs maximized and conditions that favour circularity of N flows optimized. Importantly, any reduction in N losses must be matched by a decrease in N inputs and/or increased outputs.

To support this holistic approach, nine key principles for integrated sustainable N management (see Chapter 2 for details) are outlined including:

i) consideration of all N forms, sources and emissions across spatial and temporal scales

ii) matching any reduction in N losses with a decrease in N inputs and/or increased outputs and,

iii) striving towards a transition to circular N systems.

Importantly, it is emphasised that any reduction in N losses must be matched by a decrease in N inputs and/or increased outputs, otherwise, there is an increased risk of 'pollution swapping', where abatement of one form of nitrogen loss is exchanged for another form. We also use the terminology 'nitrogen waste' by which we mean the sum of all nitrogen species lost, including wasteful reconversion to dinitrogen (N_2). Such losses represent a huge waste of the energy and money needed to make reactive N (N_r). Measures that reduce nitrogen waste thus promote efficient and cost-effective use of nitrogen in the context of moving to a nitrogen circular economy.

Agriculture, as the largest consumer and emitter of N_r, is identified as a critical sector for N sustainability actions, although opportunities to improve N sustainability are available across all sectors involved in the anthropogenic N cycle. The management of organic wastes/residues (e.g., wastewater and food wastes etc.) presents opportunities for N recovery and recycling that are not yet fully utilised. Improvements in N sustainability can also be achieved through changes in land and aquatic resource management, aquaculture and reduction in fuel combustion. Consumers, with the support of broader regulatory systems, can contribute by lowering their demand for animal products with high 'nitrogen footprints' and by reducing food waste.

A lack of stakeholder access to guidance on what to do and how to do it can be a barrier to implementation of measures. This can be exacerbated by socioeconomic barriers, as well as missing and fragmented policies. Advances in data collection, satellite monitoring and artificial intelligence, combined with the rapid rise in GPS-enabled smartphones, should be fully utilized to disseminate accurate, site-specific nutrient management guidance to stakeholders. Efforts should be made to develop strategies aimed at jointly decreasing N, phosphorus (P), methane (CH_4) and other nutrient losses. Approaches that lead to the economic value of recovering N_r resources can help mobilise change. This can be further accelerated by recognising the even-larger costs of nitrogen pollution for health, ecosystems and climate. Done well, reducing nitrogen waste offers immediate economic benefits to businesses and wider economic benefits to society as a whole. Further research and political support are needed to mainstream and invest in innovations in the recovery of 'white nitrogen' (e.g., N recovered from organic residues) that have the potential to significantly reduce reliance on new fixation of N_2 for fertilizer production.

Implementing integrated sustainable N management thus offers benefits across environmental, economic and health domains, while minimising policy trade-offs. By demonstrating the benefits of taking an integrated approach to ‘the nitrogen challenge’ this guidance document supports progress towards fulfilling multiple United Nations Sustainable Development Goals (SDGs) and the United Nations Environment Assembly (UNEA) resolutions 4/14 and 4/2 on Sustainable Nitrogen Management.

This guidance is prepared by the Global Environment Facility (GEF)/United Nations Environment Programme (UNEP) funded project ‘Towards an International Nitrogen Management System project' (Towards INMS), as a contribution to the work of the International Nitrogen Initiative (INI). In this way it provides input to the work of the UNEP Working Group on Nitrogen and the accompanying work of the Global Partnership on Nutrient Management (GPNM), the United Nations Economic Commission for Europe (UNECE) Task Force on Reactive Nitrogen (TFRN) and other processes globally.

Table ES 1.1 Measures for better N management across the anthropogenic N cycle. The 'impact' on N emissions (i.e., 1 = large reduction, 2 = medium reduction, 3 = small reduction, 4 = potential increase and x = unclear or unknown effect), 'reliability' and 'technological requirement' (i.e., expertise and/or specialized equipment) are indicated for each measure. See Box 1.1 for further details on these indicators. For further guidance on implementation, efficiency and the cost, risks and benefits of implementing measures, see the INMS Nitrogen Measures Database – www.inms.international/measures.

Measure sub-cateogory	Measure reference and name		Net effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Technical Rqmt
Key actions for better nitrogen management in crop farming										
Soil and crop nitrogen testing	C1	Leaf colour chart/nitrogen sufficiency chart	2	2	2	2	2	2	Promising	Basic
	C2	Hand-held leaf chlorophyll content sensors	2	2	2	2	2	2	Promising	High
	C3	Remote sensor-based crop nutrient testing	2	2	2	2	2	2	Promising	High
	C4	Soil nutrient testing	1	1	1	1	1	1	Robust	High
	C5	Plant tissue nutrient analysis	1	1	1	1	1	1	Robust	High
Fertilizer and manure application measures	C6	Diluting slurry before field application	2	1	4	4	4	4	Promising	Intermediate
	C7	Low-emission slurry application	1	1	x	x	x	x	Robust	Intermediate
	C8	Rapid manure incorporation with soil	1	1	x	x	x	x	Robust	Intermediate
	C9	Limit/avoid fertilizer use in high-risk areas	2	3	2	2	2	2	Robust	Basic
	C10	Timed placement of nutrients	2	2	2	2	2	2	Robust	Intermediate
	C11	Supply nutrients at the appropriate rate	1	1	1	1	1	1	Robust	Intermediate
	C12	Precision placement of fertilizer	1	1	x	x	2	x	Robust	Intermediate
	C13	Replace urea with an alternative nitrogen fertilizer	1	1	x	x	3	3	Robust	Intermediate
	C14	Nitrification inhibitors	2	4	1	1	1	1	Robust	Intermediate
	C15	Urease inhibitors	1	1	2	2	3	2	Robust	Intermediate
	C16	Controlled release fertilizer technologies	2	2	2	2	2	2	Robust	Intermediate
Soil management measures	C17	Soil inoculation with rhizobacteria	3	2	2	x	x	x	Promising	Intermediate
	C18	Lower soil acidity with lime/gypsum amendments	2	4	2	x	2	x	Promising	Intermediate
	C19	Biochar application	2	2	x	x	x	x	Promising	Intermediate
	C20	Surface Mulching	3	x	x	x	3	x	Promising	Intermediate
	C21	Reduced tillage or no-tillage	2	x	1	x	x	x	Robust	Intermediate

Measure sub-cateogory	Measure reference and name		Net effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Technical Rqmt
Crop management measures	C22	Conservation cover crops	2	3	x	x	2	x	Robust	Basic
	C23	Perennial crops and set-aside	1	3	2	2	1	2	Robust	Basic
	C24	Crop rotation with nitrogen fixing crops	2	2	2	2	2	3	Robust	Basic
	C25	Select crop varieties with enhanced nitrogen use efficiency	2	2	2	2	2	2	Promising	High
	C26	Ploughing in crop residues	1	1	3	3	2	3	Robust	Basic
	C27	Zaï or Tassa farming techniques	x	3	x	x	1	4	Unproven	Basic
	C28	Fertigation	2	2	x	x	2	x	Promising	Basic
	C29	Irrigation water/nutrient capture and reuse	1	x	x	x	1	x	Robust	Basic
Forestry mgmt measures	C30	Increase agroforestry/trees/hedges in the landscape	2	2	2	2	2	2	Promising	Basic
	C31	Zero burning of forestry and crop biomass	1	1	1	1	x	x	Robust	Basic
Key actions for better nitrogen management in livestock farming										
Livestock dietary and productivity measures	A1	Optimise the protein intake of cattle	1	1	1	x	1	1	Robust	Intermediate
	A2	Optimise the protein intake of pigs	1	1	1	x	1	1	Robust	Basic
	A3	Optimise the protein intake of poultry	1	1	1	x	1	1	Robust	Basic
	A4	Increase longevity of dairy cattle	2	2	3	x	3	2	Promising	Basic
	A5	Increase productivity of dairy and beef cattle	2	2	3	x	3	2	Promising	Basic
Grazing mgmgt measures	A6	Extend cattle grazing time (daily and seasonally)	2	1	4	4	4	4	Promising	Basic
	A7	Rotational grazing	2	3	2	2	1	2	Robust	Basic
	A8	Avoid grazing high-risk nitrogen loss areas	2	3	2	2	1	2	Robust	Basic
Animal housing measures	A9	Use of acid air scrubbers in cattle housing	2	1	x	x	x	x	Robust	High
	A10	Use of acid air scrubbers in pig housing	1	1	2	2	3	3	Robust	High
	A11	Use of acid air scrubbers in poultry housing	1	1	2	2	3	3	Robust	High
	A12	Use of biological air scrubbers in pig housing	2	1	4	4	3	4	Robust	High
	A13	Use of biological air scrubbers in poultry housing	2	1	4	4	3	4	Robust	High
	A14	Reduce indoor temp. and airflow in cattle housing	2	1	3	x	x	x	Robust	Intermediate

Measure sub-cateogory	Measure reference and name	Net effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Technical Rqmt
Animal housing measures(cont)	A15 Reduce indoor temp. and airflow in pig housing	2	2	x	x	x	x	Robust	Intermediate
	A16 Increase in bedding material in cattle housing	3	3	3	x	x	x	Robust	Basic
	A17 Increase in bedding material in pig housing	3	3	3	x	x	x	Robust	Basic
	A18 Remove cattle slurry from under slats to outside store	2	2	x	x	x	x	Robust	Basic
	A19 Remove pig slurry from under slats to outside store	2	2	x	x	x	x	Robust	Basic
	A20 Regular cleaning of floors in animal housing	2	2	x	x	x	x	Robust	Basic
	A21 Livestock housing floor design to reduce nitrogen emissions	1	1	x	x	x	x	Robust	Intermediate
Manure collection, storage and processing measures	A22 Segregation of urine and faeces in cattle houses	2	1	x	x	x	x	Promising	Intermediate
	A23 Mechanical solid/liquid slurry separation	2	2	2	x	x	2	Promising	High
	A24 Rapid drying of poultry manure	1	1	2	2	2	2	Robust	Intermediate
	A25 Manure storage under dry conditions	2	2	2	2	2	2	Robust	Intermediate
	A26 Manure storage: solid base, permeable (dispersed/floating) covering	2	2	x	x	1	x	Robust	Intermediate
	A27 Manure storage: solid base, impermeable cover	1	1	3	x	1	3	Robust	Intermediate
	A28 Manure storage: solid base with walls	2	4	4	4	1	4	Promising	Basic
	A29 Manure storage: solid base, natural crust	2	2	4	x	1	3	Promising	Basic
	A30 Zeolite and/or biochar additives to slurry	2	2	2	x	x	x	Promising	Basic
	A31 Alum treatment of poultry litter	1	1	2	x	3	2	Robust	Basic
	A32 Acidification of slurry during storage	1	1	2	x	3	2	Robust	Intermediate
	A33 Acidification of slurry during application	1	1	3	3	x	3	Robust	Intermediate
	A34 Anaerobic digestion of manure	1	1	2	x	1	2	Robust	High
	A35 Manure composting	x	4	4	4	x	4	Promising	Basic
	A36 Plasma treatment of slurry	2	1	3	x	x	x	Robust	High
	A37 Drying and pelletizing of manure solids	4	4	x	x	x	x	Promising	High

Measure sub-cateogory	Measure reference and name		Net effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Technical Rqmt
Key actions for better nitrogen management related to land-use, landscapes and waterbodies										
Drainage and erosion control	L1	Off-stream watering facilities/ alternative watering facilities	2	3	2	2	1	2	Robust	Basic
	L2	Streambank fencing	1	3	2	2	1	2	Robust	Basic
	L3	Trenches of organic matter to capture nitrate in runoff	4	3	4	4	1	4	Unproven	Basic
	L4	Dry detention and bio-retentions basins	2	3	2	2	4	2	Unproven	Basic
	L5	Field border buffer strips (e.g. vegetated open channels)	1	x	1	1	1	x	Promising	Basic
Landscape planning measures	L6	Contour farming/strip farming	1	x	x	x	1	x	Robust	Intermediate
	L7	Digital planning of land-use based on a suitability assessment	1	2	2	2	1	2	Promising	High
	L8	Integrating arable and livestock farming	1	1	1	1	1	1	Promising	Basic
	L9	Environmentally smart placement of livestock facilities and outdoor animals	2	2	3	3	2	x	Robust	Basic
	L10	Shelterbelts around nitrogen points sources	x	2	4	4	x	3	Promising	Basic
Waterbody management measures	L11	Planting wetland plants in riparian zones and wetlands	1	1	x	2	1	x	Robust	Basic
	L12	Constructed wetlands for biological nitrogen removal	4	3	4	3	1	4	Unproven	Basic
	L13	Biological nitrogen removal from coastal waters	2	3	3	3	2	2	Promising	Intermediate
	L14	Structural coastal erosion control	2	3	3	3	2	2	Promising	High
Key actions for better nitrogen management of wastewater and solid organic waste										
Biological removal of nitrogen from wastewaters	O1	Conventional nitrification/ denitrification	2	x	x	x	1	4	Robust	High
	O2	Anaerobic ammonium oxidation (anammox)	2	x	x	x	1	4	Robust	High
	O3	Completely autotrophic nitrogen removal over nitrite (CANON)	2	x	x	x	1	4	Robust	High
	O4	Simultaneous nitrification and denitrification	2	x	x	x	1	4	Robust	High
	O5	Shortcut/partial nitrification and denitrification	2	x	x	x	1	4	Robust	High
	O6	Oxygen-limited autotrophic nitrification-denitrification (OLAND) processes	2	x	x	x	1	4	Robust	High
	O7	Aerobic dammonification	2	x	x	x	1	4	Robust	High

Measure sub-cateogory	Measure reference and name		Net effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Technical Rqmt
Physicochemical removal/recovery of nitrogen from wastewaters and organic residues	O8	Struvite precipitation from wastewater	1	2	x	x	1	4	Robust	High
	O9	Ammonia stripping and acid absorption from wastewater	1	1	x	x	1	4	Robust	High
	O10	Bio-drying sludge with acid scrubbing of exhaust air	3	2	4	4	x	3	Robust	High
	O11	Physical adsorption of nitrogen from wastewaters	2	x	x	x	2	x	Robust	High
	O12	Membrane systems for treatment of nitrogen in wastewaters	1	x	x	x	1	x	Robust	High
	O13	Thermal stripping with nitrogen recapture from wastewaters	1	1	x	x	1	x	Robust	High
	O14	Electrocoagulation systems for treatment of nitrogen in wastewaters	1	1	x	x	1	x	Robust	High
	O15	Electrodialysis systems for treatment of nitrogen in wastewaters	2	2	x	x	2	x	Robust	High
Biological removal/recovery of nitrogen from wastewaters and organic residues	O16	Microbial fuel cell for wastewater treatment	2	x	x	x	2	x	Robust	High
	O17	Microbial electrolysis cell for wastewater treatment	2	x	x	x	2	x	Robust	High
	O18	Bio-electrodialysis for wastewater treatment	1	x	x	x	1	x	Robust	High
	O19	Membrane bioreactors for wastewater treatment	1	x	x	x	1	x	Robust	High
	O20	Phototrophic bacteria and microalgae systems for wastewater treatment	1	1	x	x	1	x	Robust	Intermediate
	O21	Anaerobic digestion of solid organic residues	2	2	x	x	2	x	Robust	High
	O22	Covered composting of solid organic residues	2	2	x	x	2	x	Promising	Basic
Key actions for better nitrogen management of aquaculture										
Optimising nitrogen inputs to aquaculture systems	Q1	Regular water quality monitoring	1	2	2	2	1	1	Robust	High
	Q2	Nutrient budgeting in aquaculture systems	1	2	2	2	1	1	Robust	High
	Q3	Optimise protein intake of farmed aquatic species	1	2	2	2	1	1	Robust	Intermediate
	Q4	Minimise excess aquaculture feed and feed loss	1	2	2	2	1	1	Robust	Intermediate
Biofiltration of aquaculture discharge waters and other nutrient removal approaches	Q5	Conventional recirculating aquaculture systems (nitrification only)	2	1	x	x	4	4	Robust	High
	Q6	Rotating biological contractors (nitrification only)	2	1	x	x	4	4	Robust	High
	Q7	Recirculating aquaculture systems with integrated denitrifying filters	2	1	4	4	2	4	Robust	High

Measure sub-cateogory	Measure reference and name		Net effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Technical Rqmt
Aquaculture with recovery of nitrogen into living biomass	Q8	Periphyton treatment technique	1	1	2	2	1	1	Robust	Intermediate
	Q9	Macroalgal systems	1	1	2	2	1	1	Robust	Intermediate
	Q10	Microalgal bioreactors	1	1	2	2	1	1	Robust	High
	Q11	Aquaponics	1	1	2	2	1	1	Robust	High
	Q12	Proteinaceous bio-flocs technology	1	1	2	2	1	1	Robust	High
	Q13	Integrated multi-trophic aquaculture	1	1	2	2	1	1	Robust	Intermediate
Aquaculture sludge management	Q14	Constructed wetlands to treat aquaculture sludge	1	1	x	2	1	x	Robust	Intermediate
	Q15	Application of aquaculture sludge to land as a fertilizer	1	2	2	2	1	1	Robust	Intermediate
	Q16	Composting aquaculture sludge (with proper storage)	1	2	2	2	1	1	Robust	Basic
	Q17	Cultivation of deposit feeders to process aquaculture sludge	1	1	2	2	1	1	Robust	Intermediate
	Q18	Anaerobic digestion of aquaculture sludge	1	1	2	2	1	1	Robust	High
Key actions for better nitrogen management by optimising societal demand										
Measures to optimise agricultural nitrogen demand	S1	Reducing domestic food waste	1	1	1	1	1	1	Robust	Basic
	S2	Reduce food processing waste	1	1	1	1	1	1	Robust	Basic
	S3	Reduce consumption of foods with high nitrogen footprints	1	1	1	1	1	1	Robust	Intermediate
Key actions for better nitrogen management related to fuel combustion										
Primary measures to reduce NOx generation	F1	Switching to low NOx producing fuels	3	x	x	2	x	x	Promising	High
	F2	Fuel cleaning to remove nitrogen compounds from fuels	3	x	x	2	x	x	Promising	High
	F3	Low excess air combustion	1	x	x	x	x	x	Robust	High
	F4	Air staging (in combustion systems)	1	x	x	2	x	x	Robust	High
	F5	Fuel staging (in combustion systems)	1	x	x	1	x	x	Robust	High
	F6	Fuel re-burning (in combustion systems)	3	x	x	2	x	x	Promising	High
	F7	Flue gas recirculation (in combustion systems)	3	x	x	2	x	x	Promising	High
	F8	Reduced air preheat (in combustion systems)	2	x	x	2	x	x	Robust	High
	F9	Low NOx burners	2	x	x	2	x	x	Robust	High

Measure sub-cateogory	Measure reference and name	Net effect	NH$_3$	N$_2$O	NO$_x$	Nr to water	N$_2$	Reliability	Technical Rqmt
Primary measures to reduce NOx generation(cont)	F10 Water/steam injection (in combustion systems)	2	x	x	2	x	x	Robust	High
	F11 Oxycombustion (to reduce NOx generation)	2	x	x	2	x	x	Robust	High
	F12 Catalytic combustion (to reduce NOx generation)	1	x	x	x	x	x	Robust	High
	F13 Improving efficiency stoves and fireplaces	1	x	x	x	x	x	Robust	Intermediate
End of pipe measures to reduce/recover NOx emissions	F14 Selective Catalytic Reduction	1	3	3	1	x	x	Robust	High
	F15 Selective Non-Catalytic Reduction	2	3	3	2	x	x	Robust	High
	F16 Sorption/neutralisation of NOx	1	x	x	x	x	x	Robust	High
	F17 Selective catalytic reduction of automobile exhausts	1	x	x	1	x	x	Robust	High
	F18 Exhaust gas recirculation	2	x	x	2	x	4	Promising	High
	F19 Lean burn combustion	2	x	x	2	x	4	Unproven	High
	F20 Plasma-assisted catalytic system	1	x	x	1	x	x	Promising	High
	F21 Selective adsorber catalysts	1	x	x	1	x	x	Robust	High
Nitrogen recovery from industrial gas emissions	F22 NOx partial oxidation followed by physical or chemical adsorption	2	x	x	2	x	x	Robust	High
	F23 Chemisorption aided physisorption of NO in microporous adsorbents	2	x	x	2	x	x	Robust	High
	F24 NOx partial oxidation followed by adsorption in water or aqueous alkali solutions	2	x	x	2	x	x	Robust	High
Broad measures to reduce the demand for fuel combustion	F25 Energy efficiency improvements	1	x	1	1	x	1	Robust	Intermediate
	F26 Electrification of transportation	1	x	1	1	x	1	Robust	Intermediate
	F27 Sustainable urban planning	1	x	1	1	x	1	Robust	Intermediate
	F28 Transition to renewable energy microporous adsorbents	1	x	1	1	x	1	Robust	Intermediate

1

Introduction

1.1 The nitrogen challenge

As an essential nutrient, nitrogen (N) has a pivotal role in securing global food sources and facilitating bioenergy production. However, the escalating emissions of reactive nitrogen (Nr) pose a significant threat to soil, air and water quality, contributing to biodiversity loss and intensifying climate change impacts. Sustainable N management aligns with various United Nations Sustainable Development Goals (SDGs), including zero hunger, climate action, life below water and life on land. As described by Sutton et al., (2021), the intricate connection between N and these critical global challenges forms the essence of the 'nitrogen challenge'.

The biogeochemical N cycle has been radically changed by a multitude of industrial and agricultural processes (Ackerman et al., 2019; Bouwman et al., 2017; Sutton et al., 2013a). In addition, Steffen et al., (2015) have proposed a planetary boundary for anthropogenic N fixation at 62 Mt N yr^{-1}, beyond which there are substantial risks of abrupt and irreversible change to the 'Earth System'. It is therefore alarming that current levels of global N fixation are estimated at around 150-200 Mt N yr^{-1} (Fowler et al., 2013a; Sutton and Bleeker, 2013). The ambition to half nitrogen waste by 2030, as adopted by the Colombo Declaration at the launch of the United Nations (UN) Global Campaign on Sustainable Nitrogen Management in 2019 (UNEP, 2019a), and latterly endorsed in other regional and international initiatives, is ambitious but necessary, if adverse effect of N are to be addressed (Sutton et al., 2021). At 2020 prices, such a reduction could save $100 billion worth of N resources a year, contributing to post COVID-19 economic recovery (Sutton et al., 2021). Since 2020, fertilizer prices increased three-fold, linked to the war in Ukraine, implying a tripling of the economic value of nitrogen waste reduction, whilst the United Nations Convention on Biological Diversity UNCBD (2022) has adopted its Global Biodiversity Framework Target 7, which looks to at least halve pollution from excess nutrients. Sustainable N management is thus critical to support food, fibre and energy production, whilst mitigating N impacts to soil, water and air, climate and biodiversity (Reis et al., 2016a; Sutton et al., 2013b).

Meeting the 'nitrogen challenge' and realizing aspirations for a sustainable nitrogen future, as outlined within international declarations (UNEP, 2019a) and Resolutions 4/14 and 5/2 on Sustainable Nitrogen Management adopted by the United Nations Environment Assembly (UNEA) (UNEP, 2022, 2019b), will require an integrated approach to sustainable N management. Developing strategies that enhance N sustainability within a specific system that also considers broader interactions within the N cycle, offers a pathway to circumvent pollution swapping and optimize co-benefits (Houlton et al., 2019; Kanter and Brownlie, 2019).

However, current N policies are highly fragmented from national to global scales (Morseletto, 2019; Sutton et al., 2021), resulting in an uneven distribution of efforts to manage N sustainably across the N cycle. To support a more cohesive approach to N management, stakeholders need consolidated guidance on sustainable N practices. The UNECE Convention on Long-Range Transboundary Air Pollution, addresses this need through the publication of the guidance documents 'Options for Ammonia Mitigation' (Bittman et al., 2014), and 'Integrated Sustainable Nitrogen Management' (Sutton et al., 2022). Both UNECE guidance documents focus largely on agriculture within the UNECE region.

The present INMS guidance document goes the next step to consider nitrogen mitigation measures relevant globally. We also extend beyond the agricultural domain, providing a comprehensive overview of opportunities for improved N management across all crucial sectors involved in the N cycle. This emphasises the importance of integrated N management to achieve a sustainable N future.

The guidance document is intended to be used alongside the INMS Nitrogen Measures Database (see www.inms.international/measures – Brownlie et al., 2024). This guidance document and the INMS Nitrogen Measures Database were developed as part of the GEF/UNEP 'Towards INMS' project, which has provided support to the wider 'INMS process' developed in partnership between United Nations Environment Programme (UNEP), the International Nitrogen Initiative (INI), the Global Environment Facility (GEF) and the UK Centre for Ecology and Hydrology (UKCEH). The INMS process is designed to provide global and regional scientific support for international N policy development, practice and awareness-raising.

1.2 How to use this guidance document

This INMS guidance document identifies opportunities to improve N management throughout the anthropogenic N cycle (Figure 1.1) and emphasises the importance of considering the full set of environmental, social and economic consequences of N use. It reflects the fact that sustainable N management is a prerequisite for achieving most of the

SDGs. The present guidance document is aimed at policymakers, regulators and advisors, who will benefit from the overview of principles and measures presented when formulating integrated sustainable N management strategies and policies.

This guidance document is intended to be used alongside the INMS Nitrogen Measures Database (see www.inms.international/measures – Brownlie et al., 2024). The INMS Nitrogen Measures Database is a freely accessible online repository, providing more comprehensive information on each measure than is summarised in this document. The database considers the intricacies of implementation and efficiency, as well as the costs, risks and benefits associated with the adoption of N measures. The database is intended as a living body of evidence allowing independent peer-review and future inclusion of new emerging technologies and approaches.

In this INMS guidance document we discuss the 'principles' that underpin integrated sustainable N management (see Chapter 2). An overview of >150 measures to mitigate N losses and enhance NUE throughout the anthropogenic N cycle is then provided. Measures are organized into seven N management stages across the anthropogenic N cycle (Figure 1.1):

i) cropping systems (measures C1-C31) – see Chapter 3,

ii) livestock systems (measures A1-A37) – see Chapter 4,

iii) land-use, landscapes and waterbody management (measures L1-L14) – see Chapter 5,

iv) wastewater and organic solid wastes (measures O1-O22) – see Chapter 6,

v) aquaculture (measures Q1-Q18) – see Chapter 7,

vi) consumers (measures S1-S3) – see Chapter 8,

vii) fuel combustion systems (measures F1-F28) – see Chapter 9.

For each management stage, measures are grouped into sub-categories (Figure 1.1). For example, measures associated with land-use, landscape and waterbody management are sub-categorised into 'drainage and erosion control measures' and 'landscape planning measures' and 'waterbody management measures'. An overview description is provided for each measure, alongside an estimated 'impact' (i.e., magnitude of effect on N emissions), 'reliability' (i.e., breadth of evidence underpinning measure efficacy) and 'technological requirement' (i.e., the level of expertise and/or specialized equipment required to implement the measure). Box 1.1 provides details on these indicators. High technical requirements of some measures may constrain their applicability across diverse regions.

For quick comparative reference, the measures for each management stage are also tabulated at the end of each chapter with their indicators for impact, reliability and technological requirements.

Box 1.1 Indicators with definitions used to describe each measure in sector summary measures tables.

Impact indicates the magnitude of effect on nitrogen emissions. **Reliability** indicates the breadth of evidence underpinning the *impact* of the measure and is based on UNECE categories defined in Bittman et al., (2014). **Technological requirement** (i.e. Tech. Rqmt.) indicates the level of expertise and/or specialised equipment required to implement the measure.

Impact

1	**Large reduction** Large reduction in nitrogen emissions
2	**Medium reduction** Medium reduction in nitrogen emissions
3	**Small reduction** Small reduction in nitrogen emissions
4	**Increase** Potential increase in nitrogen emissions
×	**Unclear or unknown effect** Unclear impact on nitrogen emissions

Reliability

Robust: Thoroughly researched and considered practical or potentially so, with quantitative data on abatement efficiency, at least at the experimental scale (equivalent to UNECE Category 1 techniques and strategies).

Promising: Current research is insufficient, or quantifying abatement efficiency is persistently challenging. However, it may be incorporated into a nitrogen abatement strategy, depending on local circumstances (equivalent to UNECE Category 2 techniques and strategies).

Unproven: Not yet demonstrated as effective or likely impractical (equivalent to UNECE Category 3 techniques and strategies).

Technical Requirement

High: Demands advanced expertise and/or specialised equipment.

Intermediate: Requires fundamental knowledge/expertise and may involve some specialised equipment.

Basic: Requires basic knowledge without specialised equipment.

In Chapter 10, synergies and trade-offs of applying multiple measures are considered. The chapter goes onto consider how a 'package of measures' can be selected to achieve integrated N management for a given system. The guidance document concludes with a brief discussion on the future challenges and opportunities in taking an integrated approach to N management.

It is intended that the guidance document and the accompanying INMS Nitrogen Measures Database will help mobilise efforts to control N pollution from anthropogenic activities, fostering change by highlighting the multiple benefits of reducing N emissions for air quality, climate change, water quality, human health, ecosystems and economy. By developing an integrated approach to N management, a more coherent and effective response is encouraged that maximizes synergies, minimises trade-offs and accelerates progress towards the SDGs.

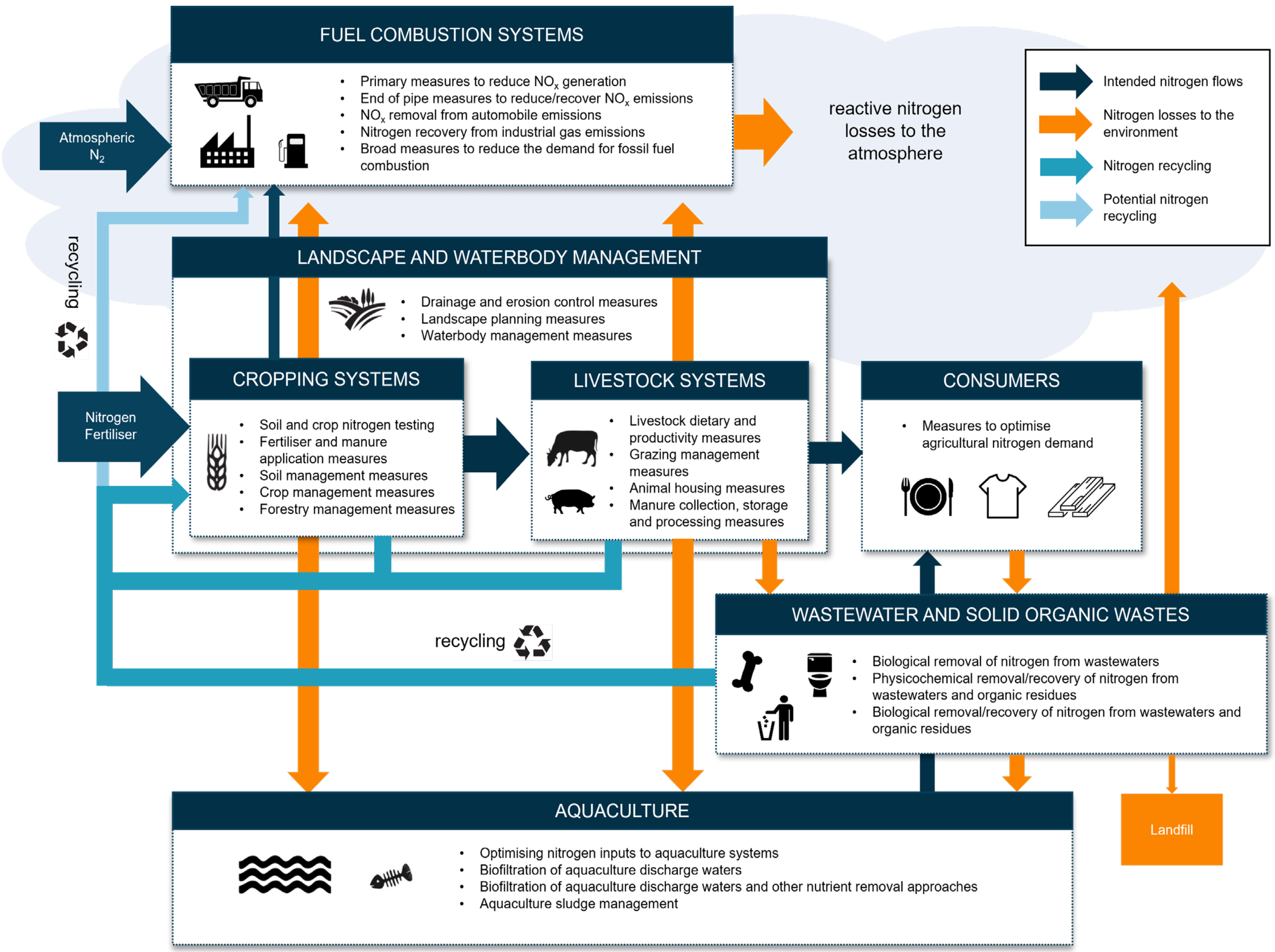

Figure 1.1 The N cycle, showing flows of N between seven (management) stages across the anthropogenic N cycle: i) cropping systems, ii) livestock systems, iii) landscape and waterbody management, iv) wastewater and solid organic waste management v) consumers vi) aquaculture and vii) fuel combustion systems. Within each group, measures are broken into sub-categories as shown. Where possible, N inputs should be minimised, outputs maximized and conditions that favour circularity of N flows optimized. Importantly, any reduction in N losses must be matched by a decrease in N inputs and/or increased outputs.

2

Principles of integrated sustainable nitrogen management

Nitrogen flows across the stages of N management (Figure 1.1) necessitates holistic and integrated strategies, emphasising the need to avoid treating them in isolation. In the context of integrated sustainable N management, 'integration' can be defined as the process of linking separate elements in an organized way so that they can function cooperatively (Sutton et al., 2022). In the following, we present 9 cross-cutting principles of integrated sustainable N management, selected from the longer list of 24 principles described by (Sutton et al., 2022).

Key principle 1. Integrated management should consider all N forms, sources and emissions across spatial and temporal scales. As conceptualised by the N cascade model (Galloway et al., 2004, 2003), a single N molecule can transition through multiple forms/compounds within the environment, across temporal and spatial scales. These include the low energy state of N, atmospheric di-N (N_2) and a wide range of high energy 'reactive N' (N_r) compounds, which include ammonia (NH_3) and ammonium (NH_4^+), nitrous oxide (N_2O), N oxides (NOx), nitrite (NO_2^-), nitrate (NO_3^-), nitric acid (HNO_3) and organic N compounds (Org-N). Substantial energy is needed to create N_r, whether that be lightning, fertilizer manufacture or biological fixation. Reactive N is a valuable resource that tends to naturally convert to N_2, supplying energy to soil bacteria and producing other N_r gases. However, N_r also causes a wide range of deleterious impacts, including smog, acid rain and biodiversity loss.

Wasteful N losses are influenced by a complex set of factors, including the availability and form of N sources, climate, soil and geomorphological/hydrological conditions and management (Sutton et al., 2013a). Hence, diverse sets of measures must be applied throughout the anthropogenic N cycle to mitigate wasteful N losses and their impacts. The dominant Nr loss pathways are:

i) NH3 volatilisation,

ii) leaching of (mainly) NO_3^- to ground and surface waters,

iii) overland flow and erosion of all Nr forms to surface waters,

iv) nitrification-denitrification processes combined with the gaseous emissions of N_2O, NOx, N_2 and,

v) NOx, N_2O and NO, (nitric oxide) emissions from the combustion of fuels.

Whilst N_2 per se does not lead to adverse environmental effects, its emission from manures, agricultural soils and wastewaters etc., represents a waste of valuable Nr (Sutton et al., 2021).

Key principle 2. Control of N input can influence N loss pathways. Lowering N inputs reduces the flow of Nr throughout the whole N cycle, offering integrated opportunities to reduce all forms of N losses simultaneously and may, in some cases, improve economic performance (Oenema et al., 2009; Quemada et al., 2020). The introduction of excessive 'new' Nr into the anthropogenic N cycle should be avoided, without compromising the yields of agricultural products. Such measures include those that prevent excess fertilizer use and feeding excess protein to animals and reduce fuel combustion.

Key principle 3. Any reduction in N losses must be matched by a decrease in N inputs and/or increased outputs. Any measure that reduces one form of pollution leaves more N available in the anthropogenic N system, which should be used productively, or it will increase N losses somewhere else in the system (i.e., 'pollution swapping'). For example, avoiding manure application when crops are not growing (i.e., winter) can reduce the risk of manure NO_3^- losses, however, suitable measures to avoid the potential increase in NH3 losses from stored manures should be applied (e.g., manure covers). This principle, of 'what goes in must come out' is encapsulated by the N input-output balance (Figure 2.1). This is important for all sectors, particularly the crop and livestock sector. Reduced N inputs or increased harvested outputs are thus an essential part of integrated N management while supplying the opportunity for increased economic performance (Oenema et al., 2009; Quemada et al., 2020).

Key principle 4. A transition to circular N systems is needed (Figure 2.2). Where possible Nr in manures and waste/residue streams should be recovered and recycled, as a replacement for newly fixed N fertilizer (Robles et al., 2020; Valve et al., 2020). The most widespread example of N recycling is the application of manure to croplands. However, a transition to a circular N cycle will likely require a transformational change in our production systems, including the geographic coupling of livestock and crop systems to support N recycling. The 200 billion tonnes of N lost to the environment annually (Fowler et al., 2013b; Sutton et al., 2013a)

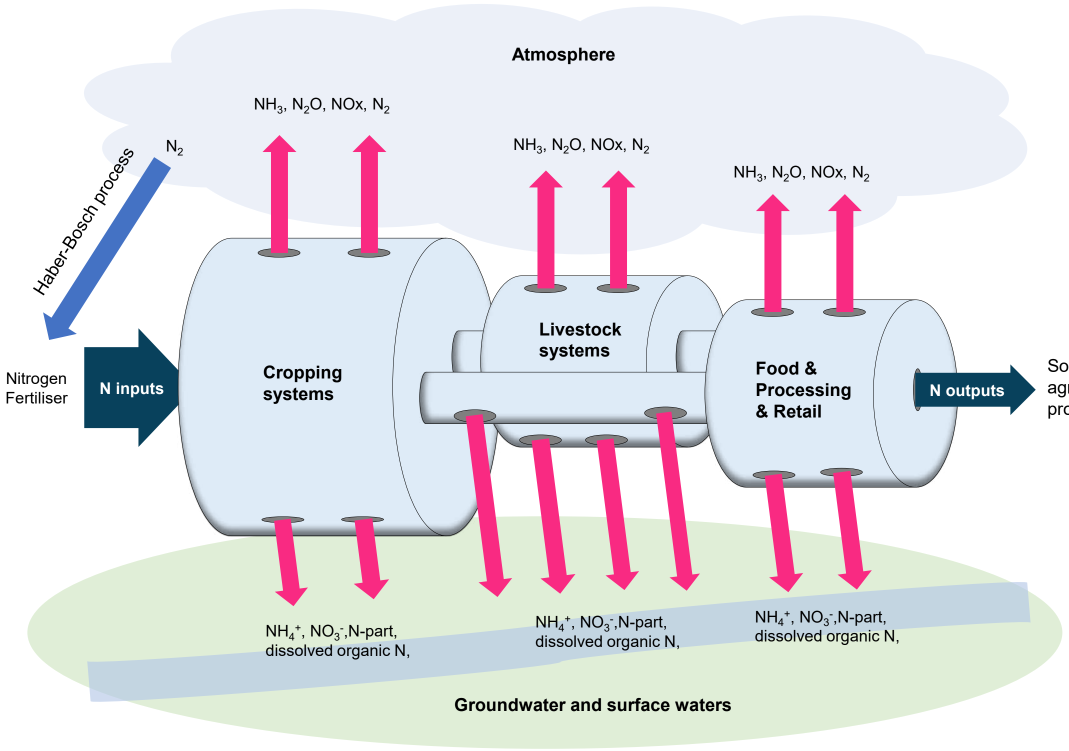

Figure 2.1 Concept of the N flows in mixed crop-livestock production systems. N losses (pink arrows) for NH_3, N_2O, NOx, N_2, NH_4^+, NO_3^-, particulate N (N-part) and dissolved organic N are shown (pink arrows), as are N inputs (fertilizers) and outputs (agri-products) (blue arrows) and N_2 fixation via the Haber-Bosch process (purple arrow). Recycling flows are not shown but include recycling of manures and organic wastes. Total inputs must balance total outputs, following corrections for possible changes in storage within the system. The concept is applicable at the field, farm, regional and global scales for all farm types. Based on the 'hole in the pipe' model (Firestone and Davidson, 1989) and modified from Oenema et al., (2009).

represents a significant resource with which to mobilize innovation in the N circular economy. A range of techniques is available to recover N from wastewater, food waste and gaseous emissions from animal housing and fuel combustion. The recovery and subsequent recycling of N represents a contribution to both circular and green economies (Robles et al., 2020; Valve et al., 2020).

Key principle 5. Strategies aimed at jointly decreasing losses of N, phosphorus (P) and other nutrients are a win-win. Several elements/compounds interact with N in the environment and can share drivers and impacts (Kanter and Brownlie, 2019). Agricultural sources of N and P pollution share many of the same drivers, namely the inefficient management of synthetic fertilizers and manure. Consequently, several measures address both nutrients simultaneously. Eutrophication of waters, a key shared impact of N and P pollution, is a complex function of the amount and relative availability of N versus P, as well as carbon (C) and silica, and so a narrow focus on either N or P in aquatic systesm may not adequately or permanently resolve the problem (Garnier et al., 2010). The N and C cycles are equally closely linked: N can affect carbon dioxide (CO2) and CH_4 emissions through its effect on C sequestration in the biosphere and by alteration of atmospheric chemistry (Butterbach-Bahl et al., 2011). Similarly, NOx, sulfur dioxide and particulate matter are all often present in combustion emissions, requiring their interactions to be considered.

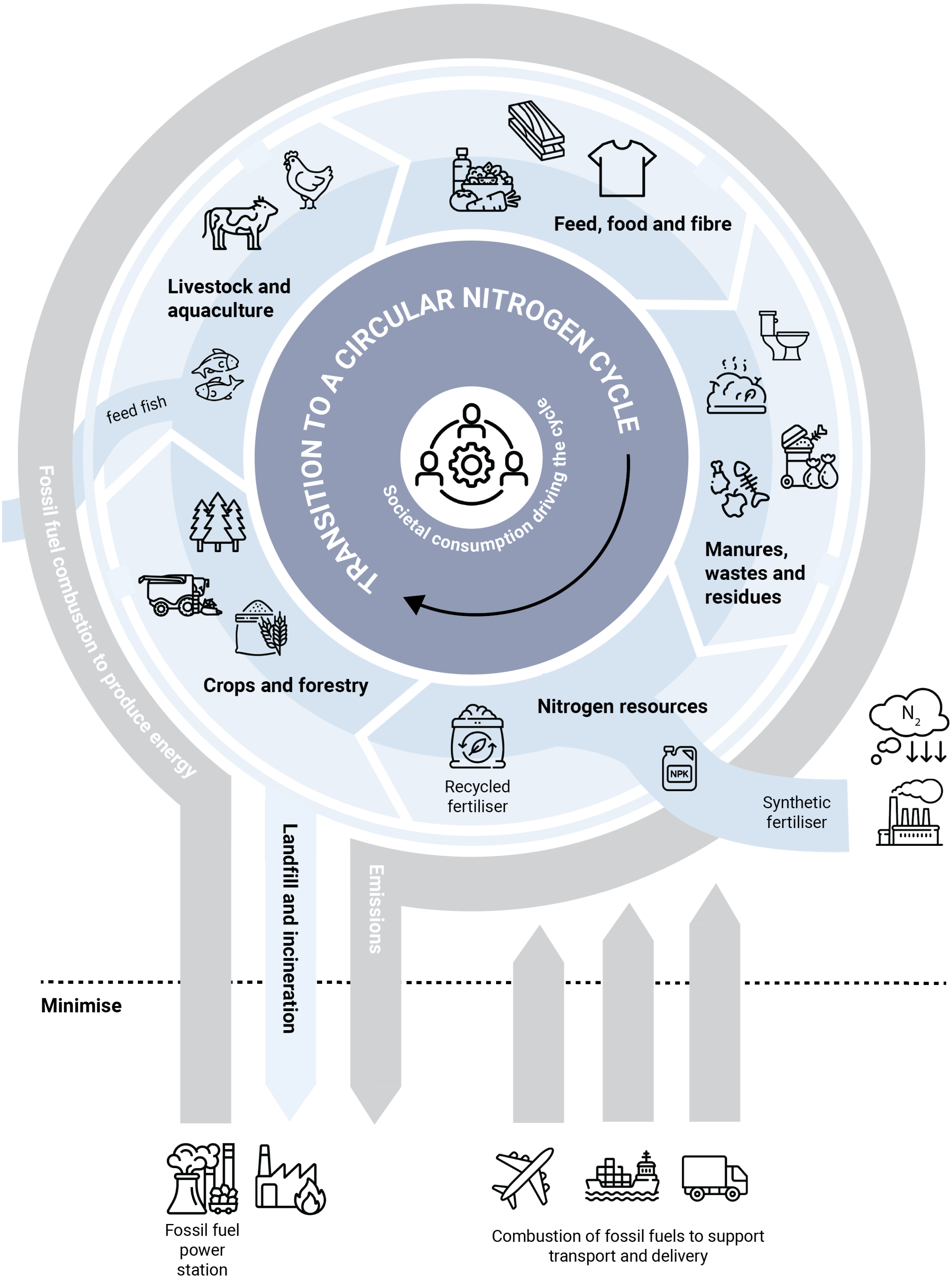

Figure 2.2 Nutrient flow can be seen as a cycle from N resources through the stages of use (blue arrows). To support a transition to a circular N cycle that is less reliant on synthetic fertilizer inputs, measures to reduce N losses and improve N use efficiency should be applied at all stages of the cycle. The combustion of fuels and the landfill and incineration of organic products should also be minimised. The system is powered by 'drivers' related to human consumption.

Key principle 6. Nitrogen management strategies should be developed with consideration to local environmental conditions. Spatial variations in: i) the vulnerability of agricultural land to N losses, ii) the sensitivity of natural habitats to N loadings and iii) landscape capacity to store/buffer N flows require site-specific N management measures. For example, land gradient, soil type and heterogeneity and weather patterns can affect soil N delivery, N loss pathways and hence crop growth. Natural habitats in the agricultural landscape with intensive livestock farms are likely to be hotspots for NH_3 emissions, and therefore sensitive to added N inputs. Such spatially diverse conditions can only be addressed by locally tuning agricultural management techniques (such as 'precision farming' techniques, where management actions are adjusted for each field location) and the use of site-specific emission abatement measures (Sutton et al., 2022).

Key principle 7. To facilitate uptake, measures should be cost-effective, and relevant stakeholders have sufficient resources to implement them. The effectiveness of measures must be examined under practical conditions and must consider context and basic environmental limitations. Socioeconomic factors can be barriers to N management. Currently, farmers carry much of the economic burden of implementing N mitigation measures but have little to no 'market power' to transfer costs to other actors (Freidberg, 2020; Sexton and Xia, 2018). Farmers may be reluctant or unable to afford to implement costly measures to reduce N losses. As the same time farmers are often heavily subsidised by governmental financial support and contribute to pollution with costs that are treated as 'external' to its prevailing business model. Funding/financing via appropriate instruments may therefore need to be tuned to nudge environmental actions as part of a policy to support a transition to sustainable N management. Cost-effectiveness analysis should also take into consideration holistic co-benefits of practices (e.g., greenhouse gas emissions, nutrients recovered, bio-energy production etc.).

Key principle 8. All stakeholders share the responsibility to decrease N losses. There are many stakeholders involved in the anthropogenic N cycle, including: i) suppliers and manufacturers of fertilizers, feed, germplasm, seed and machinery ii) advisors and extension services, iii) economists and financial organizations, iv) farmers, v) product handling and processing industries (crop products, dairy, meat, manure), vi) retail organizations, vii) consumers, viii) organic waste/residue managers, ix) non-agricultural food system actors such as industrial manufacturers and oil/gas companies, x) governments and non-governmental organizations (NGOs) and international organizations, xi) scientists and xii) citizens. Ensuring N management is scientifically and analytically sound, cost-effective and fair to users requires communication and knowledge exchange between stakeholders. Integration of stakeholders' views may ultimately improve the acceptance of management strategies, and thereby facilitate a more agile implementation of the management strategies into practice.

Key principle 9. Possible trade-offs will require priorities to be set. Sustainable nitrogen management offer many win-wins, such as reducing pollution, increasing resource efficiency, increasing resilience to economic risks. This is especially the case for measures focused on NUE and reducing nitrogen waste. However, certain mitigation actions can lead to unequal benefits between different threats. Some measures may mainly help air quality or climate mitigation. This can lead to trade-offs, so that priorities need to be agreed by stakeholders in setting policies related to sustainable nitrogen management.

3

Key actions for better nitrogen management in crop farming

3.1. Overview of nitrogen management in crop farming

Effective N management in crop systems involves several key elements to enhance crop productivity, optimize nutrient utilisation and mitigate environmental impacts. Measures focus on optimizing crop production factors, including matching N inputs to crop needs and reducing the risk of N losses, to maximize yield whilst saving farmers excess N fertilizer costs (Lassaletta et al., 2014). Measures for cropping systems (see Table 3.1) are grouped into:

i) soil and crop N testing measures,

ii) fertilizer and manure application measures,

iii) soil management measures,

iv) crop management measures, and

v) forestry management measures.

While the following sections provide brief summaries, more detailed descriptions including access to relevant literature are provided in the INMS Nitrogen Measures Database. 3.2 Soil and crop nitrogen testing measures

Soil nutrient testing (Dahnke and Johnson, 2018) and plant tissue nutrient analysis (Muñoz-Huerta et al., 2013) can be used to support appropriate manure and fertilizer application rates and help quantify potential N losses to the environment. All essential nutrient elements have to be considered, including phosphorus, potassium (K), sulfur, calcium, magnesium and micro-nutrients, because the effect of applying N is highest when all other essential nutrients are not limiting crop growth (de Wit, 1992). However, reducing uncertainty in N mineralisation for crop uptake and leaching remains a future challenge (Bijay-Singh and Craswell, 2021). Hand-held leaf chlorophyll content sensors and remote sensor-based crop nutrient testing can be used to indicate quickly and non-destructively the N fertilizer needs of crops (Muñoz-Huerta et al., 2013). A low-tech version of this measure is the leaf colour chart (LCC) widely promoted used in rice farming (Singh, 2022).

An overview of soil and crop nitrogen testing measures is provided below. While the following sections provide brief summaries, more detailed descriptions including access to relevant literature are provided in the INMS Nitrogen Measures Database.

Measure	**Impact**						**Reliability**	**Tech. rqmt**
	Net Effect	NH_3	N_2O	NO_x	N_r to water	N_2		
C1 Leaf colour chart/ nitrogen sufficiency chart	2	2	2	2	2	2	Promising	Basic

A leaf colour chart (LCC), also known as a N sufficiency chart or chlorophyll meter, is a simple tool used to visually assess the N status of plants based on leaf colour. The primary purpose of the LCC is to determine the optimal timing of N application in crops (most used for rice crops), synchronising it with the crop's demand. The LCC provides a reference scale of leaf colour variations corresponding to various levels of N deficiency/sufficiency. This enables farmers to effectively map and analyse soil fertility, addressing nutrient deficiencies while preventing over-fertilisation. The efficiency of an LCC depends on whether fertilizer use exceeds crop demands and the subsequent actions taken by farmers to optimize fertilizer application and crop uptake.

	Net Effect	NH_3	N_2O	NO_x	N_r to water	N_2		
C2 Hand-held leaf chlorophyll content sensors	2	2	2	2	2	2	Promising	High

Handheld leaf chlorophyll sensors offer a convenient and non-destructive method for promptly evaluating plant N levels. These sensors measure how leaves reflect or absorb light related to the green pigment, indicating the concentration of chlorophyll in chloroplasts and the plant's overall health. This provides insight into the plant's N status, enabling informed decisions regarding the application of N-based fertilizers. This measure does not reduce N emissions directly but can provide highly accurate data that can be used to better inform the nutrient needs of crops, and subsequently appropriate fertilizer requirements.

Measure	Impact						Reliability	Tech. rqmt
	Net Effect	NH_3	N_2O	NO_x	N_r to water	N_2		
C3 Remote sensor-based crop nutrient testing	2	2	2	2	2	2	Promising	High

Remote sensors provide a convenient and non-destructive method for assessing plant N levels. By observing the visible and near-infrared spectrum, these sensors offer valuable insights into leaf chlorophyll content, facilitating early detection of nutrient insufficiencies in plants. Canopy chlorophyll content shows a robust correlation with canopy N levels. Optical sensors are mounted on agricultural equipment like sprayers or applicators, as well as on unmanned aerial vehicles (UAVs) and satellites equipped with RGB/CIR cameras, multispectral cameras and infrared cameras. This measure does not reduce N emissions directly but can provide highly accurate data that can be used to better inform the nutrient needs of crops and subsequently appropriate fertilizer requirements.

	Net Effect	NH_3	N_2O	NO_x	N_r to water	N_2		
C4 Soil nutrient testing	1	1	1	1	1	1	Robust	High

Soil nutrient testing plays a pivotal role in advancing sustainable N management in agriculture. Directly measuring available 'soil mineral nitrogen' in NO_3^- or ammonium forms provides a more accurate indication of N application needs than the use of historical data, precipitation and soil type. Methods include chemical analysis, test strips, kits, spectroscopy, electrochemical sensors, remote sensing and soil profiling, offering a range of accuracy, convenience and scalability options. Depending on the approach taken this measure can provide a robust approach to support a reduction in N emissions with mid-high technological requirements.

	Net Effect	NH_3	N_2O	NO_x	N_r to water	N_2		
C5 Plant tissue nutrient analysis	1	1	1	1	1	1	Robust	High

Plant tissue analysis involves directly measuring N content within plant tissues, providing real-time information on crop nutritional needs. This approach allows for timely adjustments in N fertilizer applications, considering factors such as growth stage, environmental conditions and crop type, ultimately enhancing N use efficiency. Techniques include chemical digestion (Kjeldahl), combustion (Dumas), automation, near-infrared spectroscopy (NIRS), colorimetry, ion-selective electrodes and infrared spectroscopy (NIR/MIR). The selection of techniques depends on accuracy, sample size, equipment and research goals, often involving the use of multiple methods for comprehensive analysis. Plant tissue analysis serves as a preventive measure against both N deficiencies and excessive N application.

3.3 Fertilizer and manure application measures

Low-emission slurry methods like injection, band spreading and rapid incorporation reduce NH_3 emissions (Pan et al., 2016). Compared with the surface broadcast application, slurry injection (Figure 3.1) can cut NH_3 emissions by 70–90%, while trailing hose spreading can reduce NH_3 emissions by 30–35% (Bittman et al., 2014). For broadcast slurry application, the dilution of slurries allows more rapid infiltration into the soil, hence reducing NH_3 losses (Sutton et al., 2022). Manure/fertilizer application should be limited in areas that have a higher risk of N losses. Timing nutrient application to crop needs through multiple/split applications can reduce the risk of large leaching events and enable later additions to be tuned according to yield expectations (Cameron et al., 2013). Appropriate timing should take account of climatic differences, as well as weather forecasts, e.g., manure spreading during cool weather and avoiding fertilizer application during the hot and moist spring/summer period can reduce N_2O losses without compromising yields (Rowlings et al., 2013; Schwenke and Haigh, 2019). Precision placement of synthetic fertilizers directly into the soil close to the rooting zone of the crop can enhance nutrient uptake (Bittman et al., 2014), indeed deep soil placement of synthetic fertilizers can reduce NH_3 volatilisation by up to 55%-95% (Pan et al., 2016).

Choosing the right fertilizer form for soil type is also crucial; ammonium nitrate (NH_4NO_3) emits less NH_3 than urea (Sutton et al., 2022). Enhanced efficiency fertilizers synchronize N supply with crop uptake, but their performance varies, requiring local assessments. Relying on enhanced efficiency fertilizers to improve N synchrony and NUE may not be possible without improving typical fertilizer N management practices. Nevertheless, new economical fertilizer formulations are being designed using enzyme inhibitors with modifiable chemical structures and biodegradable coatings that respond to plant rhizosphere signalling molecules (Lam et al., 2022).

An overview of fertilizer and manure application measures is provided below.

Measure	Impact						Reliability	Tech. rqmt
	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
C6 Diluting slurry before field application	2	1	4	4	4	4	Promising	Intermediate

Diluting slurry before field application is a strategic measure to mitigate N losses, particularly NH_3, associated with surface broadcast slurry application. Slurries with lower dry matter exhibit reduced NH_3 losses due to their quicker infiltration into the soil. The extent of NH_3 emission reduction varies depending on the characteristics of the undiluted slurry and prevalent soil and weather conditions during application. Studies indicate that a 1:1 dilution of slurry with water can result in approximately a 30% reduction in NH_3 emissions. This approach aims to enhance the efficiency of N use in agriculture by minimising losses during slurry application.

Measure	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
C7 Low-emission slurry application	1	1	x	x	x	x	Robust	Intermediate

Low-emission slurry application methods reduce NH_3 emissions by minimising the surface area of exposed slurry. Measures include slurry injection, band spreading and rapid manure incorporation. Placing slurry in narrow surface slots via shallow or deep injection significantly decreases the exposed slurry surface area and can achieve 70-90% NH_3 emission reduction compared to surface broadcast application. Spreading slurry with trailing hose technology can achieve a 30–35% reduction in NH_3 emissions. If crops are actively growing and soil disruption is impractical and a tall canopy is in place, placing the slurry beneath the crop canopy can utilise the canopy as a physical structure, reducing the NH_3 loss rate by as much as 60%. Whilst these techniques carry the potential for increased emissions of N_2O, NO_x and N_2, this risk can be mitigated by adjusting N application rates to compensate for the N saving by reducing NH_3 emissions.

Measure	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
C8 Rapid manure incorporation with soil	1	1	x	x	x	x	Robust	Intermediate

The rapid incorporation of applied manure into the soil, ideally within a few hours after application, serves as a strategic measure to diminish N losses. This practice significantly reduces the exposed surface area of the manure, thereby mitigating NH_3 volatilisation. It additionally contributes to the reduction of N and phosphorus losses in run-off. However, this measure is only applicable to tilled land and situations where manure is applied before crop establishment.

Measure	Impact						Reliability	Tech. rqmt
	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
C9 Limit/avoid fertilizer use in high-risk areas	2	3	2	2	2	2	Robust	Basic

Certain areas on the farm can be classified as higher risk in terms of N losses to water, by direct run-off or leaching, or to air through denitrification. Pollution can be reduced by avoiding or limiting fertilizer application to these locations (e.g., in the vicinity of ditches and streams and on steeply sloping areas). Risks of transfer may be further reduced by imposing zones in which fertilizers and manures should not be applied, or in which application rates and timings are strictly regulated (e.g., Nitrate Vulnerable Zones within the EU).

	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
C10 Timed placement of nutrients	2	2	2	2	2	2	Robust	Intermediate

The risks of N losses can be reduced by applying N to soils according to the timing of crops needs. This may involve multiple/split applications of fertilizers and/or manures. This measure reduces the potential for significant leaching events and allows for later adjustments based on modified yield expectations. Consideration of climatic variations and weather forecasts, such as favouring manure spreading during cooler weather, is crucial for optimal timing. It is advisable to refrain from simultaneously applying organic slurries and inorganic fertilizers, as this practice can lead to an increase in N_2O and nitric oxide (NO) emissions and N leaching.

	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
C11 Supply nutrients at the appropriate rate	1	1	1	1	1	1	Robust	Intermediate

Under supply of N will result in reduced crop yields and soil organic matter and can lead to N mining of the soil. Over supplying of N can also result in reduced crop yields and profits and surplus available soil N, increasing the risk of losses to air and water. Supplying N to match crop requirements at an environmentally and economically sustainable level requires knowledge of crop N demand in relation to N content of organic manure, inputs through biological nitrogen fixation and inputs from fertilizer products and crop N demand.

Measure	**Impact**						**Reliability**	**Tech. rqmt**
	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
C12 Precision placement of fertilizer	1	1	x	x	2	x	Robust	Intermediate

Precision placement of fertilizer improves N and P uptake, minimises N losses to the air and reduces losses of both N and P to water. By optimizing nutrient uptake efficiency, this method can enhance plant growth and agricultural productivity, whilst requiring lower overall N and P input compared to broadcast spreading. When fertilizers are placed deep into the soil, NH_3 volatilisation can be reduced by up to 95%. This targeted placement minimises environmental impact, promoting sustainable N and phosphorus management practices that balance crop nutrient needs, economic efficiency and environmental conservation.

	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
C13 Replace urea with an alternative nitrogen fertilizer	1	1	x	x	3	3	Robust	Intermediate

Using a fertilizer form and application method appropriate to soil type is critical for efficient N uptake and to minimise losses. Ammonia emissions are much lower from NH_4NO_3 than from urea fertilizer. Following land application, urea will undergo hydrolysis to form ammonium carbonate, locally increasing pH and favouring NH_3 emission. By contrast, for fertilizer forms such as NH_4NO_3, ammonium will be in equilibrium at a much lower pH, greatly reducing the potential for NH_3 volatilisation. In calcareous and semi-arid soils, the replacement of urea by NH_4NO_3 or calcium ammonium nitrate usually also leads reduction in N_2O and NO_X emissions, though the opposite can happen in some situations.

	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
C14 Nitrification inhibitors	2	4	1	1	1	1	Robust	Intermediate

Nitrification inhibitors can be incorporated into NH_3 or urea-based fertilizer products, to slow the rate of conversion of NH_4+ to NO_3^-. These have been shown to reduce emissions of N_2O and can also be expected to reduce emissions of NO_X and N_2 and NO_3^- leaching. The performance of enhanced efficiency fertilizers varies widely due to differences in cropping systems, climate, or soil conditions, emphasising the need for local assessments to ensure suitability. While more usually associated with chemical fertilizers, nitrification inhibitors can also be added to livestock slurries just before application to land to delay the conversion of the slurry NH_4+ content to NO_3^-, which is more susceptible to Nr losses through denitrification, run-off and leaching. Potential long-term effects of nitrification inhibitors on non-target organisms should be considered.

Measure	Impact						Reliability	Tech. rqmt
	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
C15 Urease inhibitors	1	1	2	2	3	2	Robust	Intermediate

Urease inhibitors slow the hydrolysis of urea by inhibiting the urease enzyme in the soil. This allows more time for urea to be incorporated in the soil and for plant uptake thereby reducing the potential for NH_3 emissions. In some studies (e.g., under nitrifying conditions), urease inhibitors have also been found to decrease soil N_2O and NO_x emissions. Utilising urease inhibitors to reduce NH_3 losses during the application of cattle and pig manure is not anticipated to yield significant benefits. This is because the majority of the excreted urea is likely to have already undergone hydrolysis to form ammonium during livestock housing and manure storage.

	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
C16 Controlled-release fertilizer technologies	2	2	2	2	2	2	Robust	Intermediate

Controlled-release fertilizers, also called enhanced efficiency fertilizers, can improve synchrony between N supply from the fertilizer and uptake by the crop and thus reduce N losses. Special coatings on fertilizers can slow the release of nutrients to the soil over several months (e.g., sulphur or polymer coating). The gradual release of nutrients is associated with lower leaching and gaseous N losses. Organic N products with low water solubility such as isobutylidene diurea, crotonylidene diurea and methylene-urea polymers are also considered as slow-release fertilizers. While some of these fertilizers can be economically prohibitive, ongoing developments include designing cost-effective formulations using enzyme inhibitors with adaptable chemical structures and biodegradable coatings responsive to plant rhizosphere signalling molecules (Lam et al., 2022). The performance of enhanced efficiency fertilizers varies widely due to differences in cropping systems, climate or soil conditions, emphasising the need for local assessments to ensure suitability.

3.4 Soil management measures

Soil inoculation with plant-growth-promoting rhizobacteria promotes biological N fixation (Kuan et al., 2016; Vejan et al., 2016) and may reduce N_2O losses (Itakura et al., 2013). Lowering soil acidity by mixing gypsum or lime into soils before fertilizer or manure application can increase the abundance of microorganisms responsible for N fixation (Bossolani et al., 2020) crop growth and nutrient utilisation. However, it can also increase NH_3 volatilisation (Bossolani et al., 2020). Biochar addition to the soil can increase soil C storage and cation exchange capacity. This enables soils to hold more NH_4^+, decreasing NH_3 emissions, slowing nitrification and denitrification and offering potential reductions in N_2O, NO_X and N leaching (Dai et al., 2020). Surface mulching creates favourable conditions for crops through moisture conservation, improvement to soil fertility and weed suppression, thereby improving N uptake from soils through increased crop yield.

Reducing or avoiding soil tillage has been promoted as an alternative land management practice, to reduce gaseous N losses compared to conventional tillage (Liu et al., 2013; Peigné et al., 2007). However, its capacity to mitigate NO_3^- losses remains controversial and should therefore be complemented with other practices to improve soil N retention such as cover crops, reduced N rate and split N application, guided by local assessments (Daryanto et al., 2017). Soil tillage may remediate compacted subsoils, and thereby increase the access of plant roots to N and water in the subsoil, improve drainage and minimise risks of N losses via denitrification.

An overview of soil management measures is provided below.

Measure	Impact						Reliability	Tech. rqmt
	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
C17 Soil inoculation with rhizobacteria	3	2	2	x	x	x	Promising	Intermediate

Soil inoculation with rhizobacteria is a sustainable agricultural practice aimed at promoting biological N fixation, thereby increasing natural N inputs and diminishing the reliance on chemical or inorganic fertilizers. This process involves establishing a beneficial relationship between certain bacteria and plant roots, enhancing the plants' ability to fix atmospheric N. The biological N fixation facilitated by rhizobacteria can be seen as a natural form of slow-release fertilizer. Unlike conventional fertilizers, this approach minimises peaks in N emissions, particularly NH_3, associated with fertilizer applications, and so can be expected to reduce N losses.

Measure	Impact						Reliability	Tech. rqmt
	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
C18 Lower soil acidity with lime/gypsum amendments	2	4	2	x	1	x	Promising	Intermediate

Reducing soil acidity through the incorporation of gypsum or lime before fertilizer or manure application can enhance the proliferation of microorganisms involved in N fixation and reduce N_2O emissions and NO_3^- leaching. This practice may also elevate NH_3 volatilisation. Soil pH can impact nutrient uptake for grazing livestock. In instances of excessive soil acidity, trace minerals become less accessible to plants, leading to diminished benefits for animals during grazing. This approach underscores the intricate equilibrium in soil management, where adjustments in acidity, not only affect N-fixing microorganisms, but also influence nutrient availability for both plants and livestock.

Measure	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
C19 Biochar application	2	2	x	x	x	x	Promising	Intermediate

Biochar addition to the soil not only provides an opportunity to increase soil C storage and water-holding capacity, but also increases soil cation exchange capacity. This enables soils to hold more ammonium potentially decreasing NH_3 emissions and slowing nitrification and denitrification, offering potential reductions in N_2O, NO and N_2 emissions as well as Nr losses to water. Further research regarding the efficacy of this approach with various forms of N is still required.

Measure	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
C20 Surface mulching	3	x	x	x	3	x	Promising	Intermediate

Surface mulching involves applying a layer of material on the surface of the soil around plants and includes organic mulches such as wood chip/bark, straw/hay, leaves and inorganic mulches such as plastic sheeting and gravels/stones. Surface mulching is a comprehensive N management strategy, aiming for moisture conservation, fertility improvement and weed suppression. By creating favourable conditions for crop growth, it enhances N uptake with increased yields. This approach ensures efficient water use, supports nutrient-rich soil and prevents weed competition, contributing to sustainable agriculture.

Measure	Impact						Reliability	Tech. rqmt
	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
C21 Reduced tillage or no-tillage	2	x	1	x	x	x	Robust	Intermediate

Intensive tillage can increase N leaching and soil erosion resulting in the loss of N-rich topsoil. Reduced or no-tillage mitigates these risks and also influences the abundance of nitrifying and denitrifying microbial communities, reducing N_2O losses from agricultural soils. Traditional tillage accelerates N mineralisation by incorporating crop residues into the plough layer; however, over the long term, it may deplete soil organic matter, affecting N retention capacity. Conversely, no-tillage maintains crop residues on the surface, leading to slower decomposition rates. The impact of tillage on N management is context-dependent, underscoring the importance of local assessments in determining tillage strategies. Soil tillage may remediate compacted subsoils and thereby increase the access of plant roots to N and water in the subsoil. This approach can improve drainage and minimising risks of N losses via denitrification.

3.5 Crop management measures

Conservation cover crops, which follow the main crop, can decrease 'available' soil N levels in high-risk N leaching periods by utilising post-harvest decomposition and mineralisation. This approach boosts soil organic C, enhancing Nr retention, reducing erosion and limiting nutrient leaching. Including N-fixing crops (e.g., clovers) in mixed cropping/intercropping or rotation can elevate N levels, reducing the need for N application. Ploughing-in crop residues enhances soil structure and can help mitigate NH3 emissions. Perennial crops like grasslands and grass-clover mixtures, along with 'set-aside' areas (e.g., unfertilised grasslands), minimise environmental Nr losses by immobilising Nr in biomass, offering higher storage capacity and a lengthier N uptake period compared to annual plants.

Fertigation (i.e., fertilizer N dissolved in irrigation water) combined with split application (i.e., applying fertilizers in multiple doses or stages throughout the growing season) can help minimise evaporative losses of water and losses of N to air and water. Irrigation water recycling (i.e., capturing and storing water drained from fields to re-irrigate crops) can help reduce fertilizer application through recycling of captured nutrients (Carruth et al., 2014; Reinhart et al., 2019). Crop yield largely defines N uptake and hence factors that may limit crop growth must be addressed simultaneously (e.g., water and nutrient availability and pests, weeds and diseases) (Altieri et al., 2012; Chen et al., 2011; Vanlauwe et al., 2010).

An overview of crop management measures is provided below.

Measure	**Impact**						**Reliability**	**Tech. rqmt**
	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
C22 Conservation cover crops	2	3	x	x	2	x	Robust	Basic

Conservation cover crops (or ‘catch crops’), that follow the main crop, can help reduce available soil N levels during high-risk periods for NO_3^- leaching by taking up N originating from post-harvest decomposition and mineralisation. The extent to which N emissions are reduced and NUE increased over the whole cropping cycle depends largely on effective management of the cover crop residues and appropriate tuning of fertilisation rates to the subsequent crop. The approach also reduces the risk of erosion and other soil/nutrient transport to streams.

	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
C23 Perennial crops and set-aside	1	3	2	2	1	2	Robust	Basic

Introducing perennial crops, such as grass or grass-clover mixtures, can reduce the risk of Nr losses through the immobilisation of Nr in plant biomass and litter. Perennials typically have a longer N uptake period and capacity for N storage in biomass/litter than annual plants. This measure also increases soil N and C stocks and subsequently Nr retention capacity. Set-aside grassland (e.g., unfertilised grasslands) can remove NO_3^- from lateral soil water flows and serve as protective buffers to adjacent aquatic systems. The effectiveness of this measure depends on the subsequent reduction of N inputs in the landscape.

	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
C24 Crop rotation with nitrogen-fixing crops	2	2	2	2	2	3	Robust	Basic

Implementing crop rotation with N-fixing crops, such as legumes, is a strategic approach in N management. These plants fix atmospheric N_2, reducing the need for applied N (fertilizer or manure) and minimising associated N losses. Integrating legumes into a crop rotation or adopting inter-cropping techniques, like a grass-clover sward, enhances N efficiency. However, the incorporation of legumes into the soil as part of a rotation can result in a mineralisation pulse, potentially causing Nr emissions to the air and NO_3^- leaching to water. Careful management and monitoring are essential to optimize N benefits while minimising environmental impacts within this N-smart agricultural practice.

Measure **Impact** **Reliability** **Tech. rqmt**

C25 Select crop varieties with enhanced nitrogen use efficiency

Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
2	2	2	2	2	2	Promising	High

Crop genetic variants with heightened N use efficiency (NUE) enhance harvest outputs with reduced N inputs, minimising overall environmental losses. Tailored for optimal N utilisation, these varieties aim to increase yields while mitigating environmental impact. Their practical success depends on factors like soil conditions and climate. While promising for N-smart agriculture, ongoing research and careful implementation are essential for effectiveness and environmental compatibility in diverse agricultural contexts.

C26 Ploughing in crop residues

Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
1	1	3	3	2	3	Robust	Baisc

Incorporating crop residues by ploughing can enhance soil structure and mitigate NH_3 emissions by providing beneficial soil covering. However, ploughing in residues may elevate losses of other N compounds, including N_2O, N_2, NO_x and NO_3^-, due to increased nitrification and denitrification. This risk can be effectively mitigated by adjusting fertilizer inputs to compensate for the N released through the incorporation of crop residues. Precision in fertilizer management is crucial to align inputs with the N dynamics resulting from ploughing, ensuring sustainable agricultural practices. Careful consideration of this measure, balancing the benefits of improved soil structure against the potential N losses, is essential for optimizing N management and minimising environmental impact.

C27 Zaï or Tassa farming techniques

Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
x	3	x	x	1	4	Unproven	Basic

Zaï or Tassa is a cropping farming technique to dig pits (20-30 cm long and deep and 90 cm apart) in the soil during the pre-season to catch water and concentrate compost. The technique is traditionally used in western Sahel (e.g., Burkina Faso, Niger, Mali) to restore degraded drylands and increase soil fertility. The incorporation of organic matter into the pits fosters microbial activity, promoting nutrient cycling. This can enhance N availability to crops, reducing reliance on external N inputs. The water-retaining attributes of these pits aid in maintaining optimal soil moisture, facilitating efficient nutrient uptake by plants.

Measure	Impact						Reliability	Tech. rqmt
	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
C28 Fertigation	2	2	x	x	2	x	Promising	Basic

In regions affected by drought or constrained soil water availability, the dual management of water and N use is imperative. Employing drip irrigation alongside the split application of N dissolved in the irrigation water, known as drip fertigation, offers precise application in both spatial and temporal dimensions. This approach minimises evaporative water losses and reduces N losses to the air and water, significantly augmenting N use efficiency. Drip fertigation allows for targeted delivery of N to the root zone, optimizing nutrient uptake by crops while minimising environmental impact.

Measure	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
C29 Irrigation water/ nutrient capture and reuse	1	x	x	x	1	x	Robust	Basic

Irrigation water/nutrient capture and reuse involves the collection and recycling of irrigation water from fields along with associated nutrients, presenting a sustainable approach to water and N management in agriculture. By implementing efficient water and nutrient capture systems, farmers can reduce the risk of N leaching into water bodies. Additionally, this measure promotes the recycling of essential nutrients, particularly N, fostering a closed-loop system that minimises the need for external inputs. Properly managed, irrigation water/nutrient capture and reuse contribute to enhanced N use efficiency, reduced environmental impact and sustainable agricultural practices that align with the principles of resource conservation and ecosystem protection.

3.6 Forestry management measures

Implementing forestry management measures to enhance N management involves a comprehensive strategy as with crop management. Agroforestry, which involves integrating trees with crops, can help in N removal, erosion control, wind protection and to support biodiversity (Nerlich et al., 2013; Ranjan, 2021; Zhu et al., 2020). Additionally, initiatives such as afforestation and tree conservation play pivotal roles in augmenting soil quality and mitigating emissions (Schmidt et al., 2020). Reduction in the burning of forestry, timber and crops will reduce emissions of NO_x associated with biomass combustion (Koppmann et al., 2005). The holistic approach to forestry management, integrating agroforestry practices, afforestation, conservation efforts and agroecosystem diversification, emerges as a potent and multifaceted strategy. This not only optimizes N dynamics within ecosystems, but also aligns with broader environmental sustainability goals, making it a pivotal step toward a more balanced and resilient ecological landscape.

An overview of forestry management measures is provided below.

Measure	**Impact**						**Reliability**	**Tech. rqmt**
	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
C30 Increase agroforestry/ trees/hedges in the landscape	2	2	2	2	2	3	Promising	Basic

Introducing agroforestry, such as blocks of trees or alternating rows of trees with annual crops in the landscape, can help remove surplus Nr from neighbouring arable fields, minimise erosion, provide wind shelter and fosters biodiversity. Afforestation and planting of strips of trees around agricultural fields can reduce NO_3^- leaching by up to 82% compared to monocultures. Introducing fertilizer trees, particularly N-fixing leguminous varieties, enhances soil N supply, increase soil organic matter and improve productivity on degraded land. Demonstrating significant yield increases, these trees benefit crops like maize, millet and sorghum even with reduced synthetic fertilizer doses (25%–50% reduction of recommended dose). Success hinges on improved nutrient cycling, increased availability of macronutrients (N, P, K), cations, enhanced biological activity and positive impacts on soil pH, organic matter, physical properties and water relations.

Measure	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
C31 Zero burning of forestry and crop biomass	1	1	1	1	x	x	Robust	Basic

Avoiding the burning of forestry and crop biomass is critical for reducing emissions of NO_x, which contribute to air pollution. A zero-burning approach is essential for effective N management, preventing adverse impacts on air quality, human health and ecosystems. Additionally, it plays a crucial role in reducing CO_2 emissions, aligning with broader conservation goals and promoting sustainable land management practices.

3.7 Summary table of measures to improve nitrogen management in crop systems

The following table offers a concise overview of these measures.

Table 3.1 Measures for better N management in crop farming. The 'impact' on N emissions (i.e., 1 = large reduction, 2 = medium reduction, 3 = small reduction, 4 = potential increase and X = unclear or unknown effect), 'reliability' and 'technological requirement' (i.e., expertise and/or specialized equipment) are indicated for each measure. See Box 1.1 for further details on these indicators. For further guidance on implementation, efficiency and the cost, risks and benefits of implementing measures, see the INMS Nitrogen Measures Database – www.inms.international/measures.

Measure sub-category	Measure reference and name		Net effect	NH$_3$	N$_2$O	NO$_x$	Nr to water	N$_2$	Reliability	Technical Rqmt
Key actions for better nitrogen management in crop farming										
Soil and crop nitrogen testing	C1	Leaf colour chart/nitrogen sufficiency chart	2	2	2	2	2	2	Promising	Basic
	C2	Hand-held leaf chlorophyll content sensors	2	2	2	2	2	2	Promising	High
	C3	Remote sensor-based crop nutrient testing	2	2	2	2	2	2	Promising	High
	C4	Soil nutrient testing	1	1	1	1	1	1	Robust	High
	C5	Plant tissue nutrient analysis	1	1	1	1	1	1	Robust	High
Fertilizer and manure application measures	C6	Diluting slurry before field application	2	1	4	4	4	4	Promising	Intermediate
	C7	Low-emission slurry application	1	1	x	x	x	x	Robust	Intermediate
	C8	Rapid manure incorporation with soil	1	1	x	x	x	x	Robust	Intermediate
	C9	Limit/avoid fertilizer use in high-risk areas	2	3	2	2	2	2	Robust	Basic
	C10	Timed placement of nutrients	2	2	2	2	2	2	Robust	Intermediate
	C11	Supply nutrients at the appropriate rate	1	1	1	1	1	1	Robust	Intermediate
	C12	Precision placement of fertilizer	1	1	x	x	2	x	Robust	Intermediate
	C13	Replace urea with an alternative nitrogen fertilizer	1	1	x	x	3	3	Robust	Intermediate
	C14	Nitrification inhibitors	2	4	1	1	1	1	Robust	Intermediate
	C15	Urease inhibitors	1	1	2	2	3	2	Robust	Intermediate
	C16	Controlled release fertilizer technologies	2	2	2	2	2	2	Robust	Intermediate

Measure sub-cateogory	Measure reference and name	Net effect	NH$_3$	N$_2$O	NO$_x$	Nr to water	N$_2$	Reliability	Technical Rqmt
Soil management measures	C17 Soil inoculation with rhizobacteria	3	2	2	x	x	x	Promising	Intermediate
	C18 Lower soil acidity with lime/gypsum amendments	2	4	2	x	2	x	Promising	Intermediate
	C19 Biochar application	2	2	x	x	x	x	Promising	Intermediate
	C20 Surface Mulching	3	x	x	x	3	x	Promising	Intermediate
	C21 Reduced tillage or no-tillage	2	x	1	x	x	x	Robust	Intermediate
Crop management measures	C22 Conservation cover crops	2	3	x	x	2	x	Robust	Basic
	C23 Perennial crops and set-aside	1	3	2	2	1	2	Robust	Basic
	C24 Crop rotation with nitrogen fixing crops	2	2	2	2	2	3	Robust	Basic
	C25 Select crop varieties with enhwanced nitrogen use efficiency	2	2	2	2	2	2	Promising	High
	C26 Ploughing in crop residues	1	1	3	3	2	3	Robust	Basic
	C27 Zaï or Tassa farming techniques	x	3	x	x	1	4	Unproven	Basic
	C28 Fertigation	2	2	x	x	2	x	Promising	Basic
	C29 Irrigation water/nutrient capture and reuse	1	x	x	x	1	x	Robust	Basic
Forestry mgmt measures	C30 Increase agroforestry/trees/hedges in the landscape	2	2	2	2	2	2	Promising	Basic
	C31 Zero burning of forestry and crop biomass	1	1	1	1	x	x	Robust	Basic

4

Key actions for better nitrogen management in livestock farming

4.1 Overview of nitrogen management in livestock farming systems

Measures to reduce N loss from livestock farming largely focus on improving animal productivity and influencing manure composition through diet optimization (Figure 4.1), and the storage and handling of manures/litter. Fundamental steps include optimizing herd management (through breeding, precision feeding, disease and fertility control, and indoor-climate control), minimising air exposure of manures/slurries to reduce NH_3 emissions, lowering pH and temperature, and decreasing organic C content to reduce emissions of N_2O, NO_X and N_2. Slowing hydrolysis of urea ($(NH_2)2CO$) and uric acid ($C_5H_4N_4O_3$), along with reducing nitrification, may further enhance NUE and reduce N losses. Measures to reduce N losses from livestock farming (see Table 4.1) are grouped into:

i) livestock productivity and dietary measures,

ii) grazing management measures,

iii) animal housing measures and

iv) manure collection, storage and processing measures.

These groups represent stages in the flow of N and other nutrients, with significant synergy between them.

While the following sections provide brief summaries, more detailed descriptions including access to relevant literature are provided in the INMS Nitrogen Measures Database.

4.2 Livestock productivity and dietary measures

Increasing livestock productivity through breeding, precision feeding, timely disease and fertility control and indoor-climate control can reduce the amount of feed needed to produce one unit of animal product. It also decreases the amount of manure N produced and the N losses per unit of animal product. Thus, optimizing the productivity of livestock can decrease N emissions per unit of product (i.e., milk, egg or meat) (Sutton et al., 2022). Increasing the longevity of dairy cattle, sows an d mother hens (e.g., through better diet and housing conditions), will reduce N losses per product as fewer replacement animals are needed (Sutton et al., 2022). Implementing these measures necessitates a comprehensive approach, including animal care, nutrition, genetics and management practices, to ensure animal welfare. Adjusting the crude protein content in the diets of cattle, pigs and poultry, to closely match their growth needs will minimise the excretion of excess N, thereby reducing N emissions along the whole manure management chain (Sajeev et al., 2018). Considerations for low-protein animal feeding include a potential increase in enteric CH_4 emissions from ruminants (Dijkstra et al., 2011), and the need for synthetic amino acids supplements for pigs and poultry (Kim et al., 2006; Liu et al., 2017).

An overview of livestock productivity and dietary measures is provided below.

Measure	Impact						Reliability	Tech. rqmt
	Net Effect	NH_3	N_2O	NO_x	N_r to water	N_2		
A1 Optimize the protein intake of cattle	1	1	1	x	1	1	Robust	Intermediate

Optimizing crude protein content in cattle diets aligns with effective N emission reduction, achieved by adjusting the energy/protein ratio, leading to decreased crude protein levels. This strategy is proven to diminish surplus N excretion and reduce N emissions throughout manure management. However, implementation in grassland-based ruminant systems faces constraints, particularly with older grass affecting feeding quality. For dairy cattle, maintaining crude protein below 15%–16% in dry matter is recommended, with lactating cattle needing higher nutrient levels due to milk production demands. Phase feeding, reducing protein content gradually, is suggested for both dairy and beef cattle, with varying levels tailored to specific stages and production goals. While recommended ranges provide targets, adjustments may be needed based on local conditions. Despite challenges, aligning diet protein with growth needs remains pivotal for sustainable N management in cattle farming.

Measure **Impact** **Reliability** **Tech. rqmt**

A2 Optimize the protein intake of pigs

Net Effect	NH_3	N_2O	NO_x	N_r to water	N_2	Reliability	Tech. rqmt
1	1	1	x	1	1	Robust	Basic

Efficient N management in animal farming involves aligning protein levels in animal diets closely with growth requirements, minimising N excretion without compromising productivity or welfare. A 1% absolute reduction in dietary crude protein for finishing pigs can yield a relative 10% decrease in total ammoniacal N concentration and a subsequent relative 10% reduction in NH_3 emissions from pig slurry. Successful implementation relies on meticulous consideration of nutritional needs, precise feed formulation and diligent monitoring of pig health to ensure both welfare and productivity. Strategic attention to amino acid composition, especially lysine, is vital, addressing varying protein needs among young, high-productivity, and lactating animals. Recommendations for crude protein content (% total feed dry matter) in lactating sows range from 16%-18%, gestating sows 13%-16%, and piglets/weaners 18%-22%, reflecting an adaptive approach to N management in diverse pig categories.

A3 Optimize the protein intake of poultry

Net Effect	NH_3	N_2O	NO_x	N_r to water	N_2	Reliability	Tech. rqmt
1	1	1	x	1	1	Robust	Basic

Precision adjustment of crude protein (CP) content in poultry diets to align with growth requirements emerges as a pivotal strategy for N emission mitigation. Notably, reducing CP content from 19% to 17% (% of dry matter) in broiler diets aged 0 to 21 days demonstrated a substantial impact—yielding a 29% reduction in N excretion and a 7% increase in N retention relative to N intake. This targeted dietary modification proves to be an efficient approach for managing N emissions in poultry farming. Although the potential for N excretion reduction through dietary measures is more constrained in poultry compared with pigs, the observed improvements underscore the significance of fine-tuning nutritional strategies to enhance N management in poultry production. Such precision feeding practices play a crucial role in achieving optimal efficiency, while addressing environmental concerns associated with N emissions.

A4 Increase longevity of dairy cattle

Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
2	2	3	x	3	2	Promising	Basic

Prolonging the productive years of each cow diminishes the demand for replacement animals, subsequently reducing the N footprint associated with their upkeep. This approach centres on optimizing milk production cycles and yields per cow, thereby reducing the need for frequent replacement animals and lowering N losses linked to their production. Strategies for achieving longer lifespans involve considerations such as nutrition, housing conditions, genetics and health management practices. This measure aligns with principles of sustainable agriculture, concurrently bolstering N efficiency and enhancing the overall environmental and economic sustainability of dairy operations. The strategy underscores a systemic approach, offering benefits such as lowered N losses, improved N use efficiency and reduced reliance on replacement animals, contributing to a more sustainable and environmentally conscious dairy production system.

Measure	Impact						Reliability	Tech. rqmt
	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
A5 Increase productivity of dairy and beef cattle	2	2	3	x	3	2	Promising	Basic

Enhancing dairy and beef cattle productivity by increasing milk yield or daily weight gain has the potential to reduce CH_4 and potentially N_2O emissions per kg of product, offering a sustainable approach to N management. The ability of cattle to convert protein from roughage, unsuitable for direct human consumption, into high-value protein is resource-efficient and benefits biodiversity. While productivity gains can significantly cut N emissions per unit of product, care must be taken to avoid overloading cattle with concentrates, respecting their digestive limitations. The delicate interplay between emission reduction and cattle's physiological limits underscores the need for a comprehensive assessment to determine optimal productivity levels.

4.3 Grazing management measures

Extending cattle grazing time, both daily and seasonally, can reduce NH_3 emissions by increasing the proportion of excreted N that is returned to the soil, in comparison to housed animals (Webb et al., 2005). Grazing should be avoided in areas with a high risk of N losses, which include those with high connectivity to the vulnerable surface and/or groundwaters, waterlogging, poaching and compaction (Elrashidi et al., 2004; Wang and Li, 2019). Rotational grazing can help to reduce NH_3, N_2O and N leaching associated with the accumulation of manure and urine onto grasslands (Luo et al., 2010; Owens and Bonta, 2004; Selbie et al., 2015).

An overview of grazing management measures is provided below.

Measure	Impact: Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
A6 Extend cattle grazing time (daily and seasonally)	2	1	4	4	4	4	Promising	Basic

Reducing NH_3 emissions from grazing livestock is achievable through efficient urine infiltration into the soil. Rotational grazing, especially with prolonged grazing periods under suitable conditions, enhances N management by reintroducing excreta into the soil. While this approach lowers NH_3 emissions, it introduces a trade-off, potentially elevating NO_3^- leaching and denitrification losses. The risk arises when excess N isn't efficiently taken up by vegetation or retained in the soil, often due to over-grazing, leading to elevated NO_3^- concentrations. The extended grazing period, if not carefully managed, may result in unintended increases in other N species emissions. Despite being a low-tech measure, extending the grazing season requires careful management to balance the benefits of reduced NH_3 emissions with potential risks to other N species.

Measure	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
A7 Rotational grazing	2	3	2	2	1	2	Robust	Basic

Rotational grazing involves cyclic movement of livestock through pasture sections with recovery periods, particularly for sheep and cattle. In contrast to continuous grazing, this approach evenly distributes N-rich excreta, minimising localised saturation and subsequent leaching risks. By promoting nutrient cycling, rotational grazing contributes to the breakdown and incorporation of N into the soil during rest periods, reducing the likelihood of nutrient runoff into water bodies. The practice fosters healthier vegetation growth, robust root systems, improved soil structure and water-holding capacity, all of which can enhance N uptake efficiency by plants. Recognised as a robust and low-tech measure, rotational grazing proves effective in curbing N losses from cattle farming systems. However, its efficiency can vary depending on local conditions, management practices and landscape characteristics.

Measure	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
A8 Avoid grazing high-risk nitrogen loss areas	2	3	2	2	1	2	Robust	Basic

High-risk areas such as those with high connectivity to vulnerable surface and groundwater sources, can intensify N losses through processes like excreta runoff and denitrification, exacerbated by waterlogging, poaching and compaction. Optimizing N conservation requires preventing cattle grazing in these high-risk areas through measures like fencing or meticulous management. The potential for phosphorus and pathogen losses from excrement and urine through runoff is also heightened in these zones. This proactive approach minimises N losses and environmental impacts, fostering sustainable N management practices. Acknowledged as a robust and low-tech measure, it proves efficient in reducing various N emissions, including NH_3 volatilisation, NO_3^- leaching, N_2O emissions, nutrient runoff and soil compaction. The effectiveness of such grazing management measures depends on local conditions, management practices and landscape characteristics.

4.4 Animal housing measures

Treatment of exhaust air from livestock housing by acid scrubbers can achieve close to 100% reduction in atmospheric NH_3 emissions (Melse and Ogink, 2005; Starmans and Van der Hoek, 2007). Similarly, bio-scrubbers and bio-trickling reactors can achieve ~70% reduction in NH_3 emissions (Melse and Ogink, 2005). Both systems reduce odour and particulate matter emissions and provide opportunities for N recovery and recycling (Hadlocon et al., 2015), but require maintenance and are energy-demanding.

In animal houses with traditional slatted floors, barn climatization with slurry cooling, roof insulation and/or automatically controlled natural ventilation can reduce NH_3 emissions due to reduced temperature and air velocities (Sutton et al., 2022). Regular removal of slurry and manures from flooring and under the slats in animal housing, to a covered outside store, can substantially reduce NH_3 emissions by reducing the emitting surface and the slurry storage temperature (Philippe et al., 2011). Using 'toothed' scrapers running over a grooved floor (Swierstra et al., 2001) or robotic scrapers (Alessandro et al., 2018) can optimize the removal of manure and slurry. Where immediate removal to covered storage cannot be achieved, an increase in bedding material that can absorb urine in cattle and pig housing can protect urine from air turbulence/gas transfer thus reducing NH_3 (Gilhespy et al., 2009; Misselbrook and Powell, 2005). However, adding straw means adding energy and O_2, which increases opportunity for nitrification and denitrification and therefore can increase the risk of N_2O emissions.

Flooring can be designed to reduce the emitting surface area of slurry and aid collection into a covered outside store thereby reducing potential NH_3 emissions (Poteko et al., 2019). Examples include convex floors and slurry channels with slanted walls (Philippe et al., 2011). Innovations in flooring systems for broilers (i.e., partially perforated flooring systems and zero litter flooring systems) have achieved up to 50% reductions in NH_3 emissions, with improvements to animal welfare (Adler et al., 2021; Boggia et al., 2019).

An overview of animal housing measures is provided below.

Measure	**Impact**						**Reliability**	**Tech. rqmt**
	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
A9 Use of acid air scrubbers in cattle housing	2	1	x	x	x	x	Robust	High

Efficient removal of NH_3 from exhaust air in livestock operations, particularly in mechanically ventilated barns, can be achieved through filters or scrubbers, such as water or acid-based systems. While prevalent in pig and poultry farming, this measure is less common in cattle farming. Despite promising results in curtailing nitrogen dioxide and NOx emissions, challenges arise from high costs, technical complexities and dust-related issues, limiting broader applicability. The method also diminishes odour and particulate matter and offers opportunities to recover Nr for reuse as fertilizer.

Measure	Impact						Reliability	Tech. rqmt
	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
A10 Use of acid air scrubbers in pig housing	1	1	2	2	3	3	Robust	High

Acid scrubbers, primarily using sulphuric acid, have been demonstrated to be practical and effective at reducing N emissions in the exhaust air of large-scale livestock operations. Acid scrubbers can reduce NH_3 emissions by varying amounts, from 40% to 100%, with an average reduction of 96%. However, practical implementation faces limitations, including high costs. Despite these challenges, this measure is robust for N emissions reduction. In addition, odour removal through acid scrubbers ranges from 3% to 51%. The method offers opportunities to recover Nr for reuse as fertilizer.

Measure	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
A11 Use of acid air scrubbers in poultry housing	1	1	2	2	3	3	Robust	High

Acid scrubbers, mainly employing sulphuric acid, have demonstrated effective at mitigating NH_3 emissions from large-scale poultry houses with mechanical ventilation. When integrated into new poultry housing structures, these scrubbers showcase remarkable NH_3 removal efficiencies, exceeding 90% based on pH-set values. The implementation of these purification techniques encounters challenges, including elevated costs, technical intricacies and dust-related issues specific to poultry barns. Nevertheless, the approach is considered robust for reducing N emissions, offering a potential solution for poultry farming sustainability. Acid scrubbers in poultry barns show significant reductions in NH_3 emissions, ranging from 40% to 100%. The method also reduces odour and particulate matter and offers opportunities to recover Nr for reuse as fertilizer.

Measure	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
A12 Use of biological air scrubbers in pig housing	2	1	4	3	4	4	Robust	High

The implementation of biological air scrubbers, or biotrickling filters, presents a promising strategy for enhancing N management in pig housing, demonstrating success in reducing NH_3 emissions, fine dust and odour. These systems employ microbial processes to convert NH_3 into less volatile forms, contributing to improved air quality within pig facilities. Advanced multi-stage scrubbers address elevated dust loads, however, there's a potential trade-off between NH_3 reduction and increased N losses like N_2O and NO_x. The recovery of collected Nr may offset this rise, reducing the need for additional N fixation in chemical fertilizer production. Careful consideration of operational parameters is crucial for a balanced approach. Biological air scrubbers have shown a 70% reduction in NH_3 emissions, with odour removal ranging from 29% (increase) to 87% (decrease).

Measure **Impact** **Reliability** **Tech. rqmt**

A13 Use of biological air scrubbers in poultry housing

Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
2	1	4	3	4	4	Robust	High

The implementation of biological air scrubbers, known as bio-trickling filters, emerges as a promising strategy for improving N management in poultry housing. These systems, successfully applied internationally, not only effectively reduce NH_3 emissions but also address concerns related to fine dust and odour. Bio-trickling filters achieve this by facilitating microbial conversion of NH_3 into less volatile forms, thereby enhancing air quality in poultry facilities. While advanced multi-stage scrubbers combat elevated dust levels, the use of bio-filters may introduce a trade-off, potentially increasing other N losses like N_2O and NOx. The potential recovery and recycling of collected reactive nitrogen could offset these increases, reducing the need for additional fresh nitrogen fixation in chemical fertilizer production. These scrubbers have demonstrated a 70% reduction in NH_3 emissions, alongside dust and odour removal.

A14 Reduce indoor temp. and airflow in cattle housing

Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
2	1	3	x	x	x	Robust	Intermediate

In cattle housing, lowering indoor temperature can potentially reduce NH_3 emissions, as higher temperatures increase the volatilisation of NH_3 from manure and urine. The actual reduction depends on temperature change and housing specifics, with a few degrees potentially leading to a 5%-20% NH_3 emission decrease. Similarly, decreasing airflow in cattle housing can influence NH_3 emissions. Adequate ventilation is crucial for air quality and animal health, but excessive reduction can lead to poor air quality and negative effects on cattle. The impact on NH_3 emissions varies with the extent of airflow reduction, making it challenging to provide a specific percentage reduction without knowing the exact conditions. However, significant reductions in airflow may result in notable changes in emissions. While feasibility depends on bioclimatic factors, prioritising animal comfort is paramount.

A15 Reduce indoor temp. and airflow in pig housing

Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
2	2	x	x	x	x	Robust	Intermediate

Climate control measures in pig housing, like slurry cooling and controlled ventilation, reduce NH_3 and CH_4 emissions. Lowering barn temperature minimises temperature-dependent NH_3 production from manure. Ammonia emission reduction by adjusting indoor temperature and airflow in pig housing depends on factors like initial conditions, temperature change and ventilation. Using fans for surface cooling can achieve a 45%-75% reduction, especially cost-effective with redirected heat. Estimates suggest a 5%-20% reduction in NH_3 emissions by lowering temperature and a variable impact on airflow. Changes require careful monitoring, considering pig age, health and diet and aligning with welfare and environmental standards. Feasibility depends on various factors, prioritising animal welfare.

Measure	Impact						Reliability	Tech. rqmt
	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
A16 Increase in bedding material in cattle housing	3	3	3	x	x	x	Robust	Baisc

This measure involves increasing bedding materials, such as straw or sawdust, to efficiently absorb urine. These materials capture and immobilise N, preventing immediate NH_3 release. This approach not only improves air quality and human health by reducing NH_3 emissions but also retains N within the system, potentially benefiting soil nutrient cycling and crop productivity. However, adding straw means adding energy and O_2, which increases opportunity for nitrification and denitrification and therefore can increase the risk of N_2O and NO_x emissions. The choice of bedding material significantly influences emissions, with physical properties like urine absorbance capacity and bulk density playing a crucial role. Studies suggest that optimal results may be achieved by using targeted additional straws, specifically in soiled areas for cattle.

Measure	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
A17 Increase in bedding material in pig housing	3	3	3	x	x	x	Robust	Basic

Bedding materials, like straw or sawdust, can efficiently absorb urine in pig housing. These materials capture and immobilise N, preventing immediate release as NH_3. This bedding approach not only improves air quality, minimising negative impacts on human health but also retains N within the system, potentially benefiting soil nutrient cycling and crop productivity. It's considered a dependable, low-tech method to reduce N emissions, positively interacting with animal welfare. The choice of bedding material significantly influences emissions, with physical properties like urine absorbance capacity and bulk density playing a crucial role.

Measure	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
A18 Remove cattle slurry from under slats to outside store	2	2	x	x	x	x	Robust	Baisc

Regular and clean removal of cattle slurry (e.g., without smearing and hence increasing emitting surface area) from under slatted floors, using vacuum or gravity systems, can reduce NH_3 emissions by around 25%. However, the percentage reduction in NH_3 emissions varies based on factors like facility size, animal count and management practices. Strategically located outlets connect to a sewerage system and a slight vacuum expels the slurry once or twice a week. This practice reduces emitting surface area, lowers slurry storage temperature and transfers slurry to an outside store swiftly, minimising N-rich residue accumulation and CH_4 emissions.

Measure **Impact** **Reliability** **Tech. rqmt**

A19 Remove pig slurry from under slats to outside store

Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
2	2	x	x	x	x	Robust	Basic

Regular and clean removal pig slurry from under slatted floors (e.g., without smearing and hence increasing emitting surface area), using vacuum or gravity systems, can reduce NH_3 emissions by around 25%. However, the percentage reduction in NH_3 emissions varies based on factors like facility size, animal count and management practices. Outlets strategically located below the floor connect to a sewerage system and vacuum removal creates a slight vacuum for slurry expulsion once or twice a week. This practice reduces NH_3 emissions by minimising the emitting surface and lowering slurry storage temperature. Transferring slurry promptly to an outside store minimises N-rich residue accumulation, mitigating NH_3 release. Additionally, storing manure outside under cooler conditions reduces CH_4 emissions.

A20 Regular cleaning of floors in animal housing

Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
2	2	x	x	x	x	Robust	Basic

Thoroughly cleaning walking areas in livestock housing can minimise N-rich manure accumulation, reducing NH_3 emissions. Cleaning considered a 'basic' practice, can use manual tools or employ technological options like self-propelled scrapers or automated robots. This simple yet effective method curtails environmental N losses, addressing NH_3 emission concerns and enhancing nutrient utilisation. The percentage reduction in NH_3 emissions varies based on factors such as cleaning practices, facility size and initial NH_3 levels.

A21 Livestock housing floor design to reduce nitrogen emissions

Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
1	1	x	x	x	x	Robust	Intermediate

Flooring plays a crucial role in N management by promoting effective drainage and reducing exposed surface areas of slurries, curbing NH_3 emissions. Various designs, including grooved, slatted, perforated and composite flooring, cater to different livestock needs. These designs balance comfort and waste management, mitigating NH_3 buildup, especially in enclosed facilities. Regular cleaning and removal of manures further enhance the efficacy of flooring systems. Technological requirements for implementing these designs range from basic to intermediate. Slatted concrete floors exhibit a 25% to 46% reduction in NH_3 emissions than level solid floors without urine drainage. Integrating smart flooring designs enhances NH_3 control, fostering a healthier environment for animals and workers.

4.5 Manure collection, storage and processing measures

Segregating faeces and urine in livestock housing means keeping solids and liquids separate from the outset. This can mitigate urea hydrolysis, provided that urease activity can be promptly diminished where the urine is deposited. This results in a slowly degrading liquid rich in NH_4^+ that effectively permeates the soil (Ndegwa et al., 2008; Panetta et al., 2005).

Drying and pelletizing manure solids yield a stable, odourless slow-release fertilizer or biogas feedstock, but energy-intensive drying may increase NH_3 emissions unless filtered or acidified (Al Seadi et al., 2013; Pampuro et al., 2017; Wahyu Purnomo et al., 2017). Ventilating deep-pit poultry barns and storing manures under dry conditions lower NH_3 emissions, and can also reduce nitrification and denitrification, mitigating N_2O, NO_X, and N_2 emissions. Where manure and slurries are not immediately returned to soils, they must be appropriately stored. Covering manures, slurries or biogas digestates is a simple and effective way of reducing NH_3 losses (Kupper et al., 2020). Options include metal or concrete tanks with solid lids, floating covers on lagoons, slurry bags and dispersed coverings of peat, clay, zeolite or phosphogypsum (which have an affinity for NH_4^+) (Sutton et al., 2022). An impermeable base is also necessary to avoid the leaching of dissolved N. Where slurries have a high dry matter content, they may form a natural crust during storage, which is associated with substantially reduced NH3 emissions, although N_2O production may be enhanced (Petersen and Sommer, 2011).

The addition of certain additives to the slurry, such as clays, zeolites and biochar, can adsorb NH_4^+ on a chemical, physical, or biological basis, thereby reducing NH_3 emissions (Kocatürk-Schumacher et al., 2019, 2017; Lefcourt and Meisinger, 2001). Reducing the pH of stored slurry, through the addition of strong acids (e.g., sulphuric acids) can reduce NH_3 emissions by up to 90% (Fangueiro et al., 2015), and may reduce CH_4, N_2O and N_2 emissions (Sutton et al., 2022). Other acidifying substances e.g., alum or poly-$AlCl_3$, may also be used (Anderson et al., 2020).

In a novel variant of measures to reduce pH, electricity is used to produce a plasma, which oxidises N_2 to NO and hence to nitrgoen dioxide (NO_2), which converts in the slurry to produce nitric acid (HNO_3). The subsequent pH-drop significantly reduces NH_3 emissions and can substantially reduce microbial N2O and CH_4 losses (Graves et al., 2019).

An overview of manure collection, storage, and processing measures is provided below.

Measure	**Impact**						**Reliability**	**Tech. rqmt**
	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
A22 Segregation of urine and faeces in cattle houses	2	1	x	x	x	x	Promising	Intermediate

This approach reduces NH_3 emissions by diminishing urea hydrolysis facilitated by urease in faeces. Slatted floors or grooved systems are common in cattle housing to segregate urine, preventing its mixing with faeces. This segregation not only curtails NH_3 release within the housing environment but also offers advantages during land-application, minimising N loss. Around 80% of dairy cattle N intake is expelled through urine and faeces, so segregating these components helps mitigate urea hydrolysis and subsequent NH_3 emissions. Studies show varied reductions (5% to 99%) in NH_3 emissions through urine-faeces segregation, emphasising its effectiveness. Beyond housing, this measure optimizes N utilisation, reduces NH_3 emissions more widely.

Measure	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
A23 Mechanical solid/ liquid slurry separation	2	2	2	x	x	1	Promising	High

Mechanical slurry separation, involving the mechanical division of slurry into solid and liquid fractions, presents a pragmatic approach to N management. The liquid portion, enriched with ammonium, results in reduced NH_3 emissions when efficiently applied to soil, enhancing nutrient utilisation and crop yields. This process involves using devices like press screws or decanter centrifuges to obtain a stackable solid fraction and a more fluid liquid fraction, facilitating slurry handling. The solid fraction, comprising concentrated nutrients and organic matter, can serve as a slow-release fertilizer or biogas substrate. While mechanical separation shows no direct environmental advantages, appropriate storage of separated fractions can mitigate NH_3 emissions. Caution is needed to prevent NH_3 and methane losses from the solid fraction, emphasising the importance of appropriate storage and handling. Overall, mechanical slurry separation contributes to optimizing nutrient utilisation, mitigating environmental impacts and improving overall manure management.

Measure	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
A24 Rapid drying of poultry manure	1	1	2	2	2	2	Robust	Intermediate

Rapid drying of poultry litter is achieved through ventilation systems or removal belts, this process minimises hydrolysis of uric acid to NH_3. The primary focus is on mitigating NH_3 emissions. Dried poultry litter, rich in uric acid, offers higher fertilizer value for farmers, promoting efficient land application with reduced doses. Aviary systems with manure belts show over 70% reduction in NH_3 emissions compared to traditional deep litter housing. Drying to 60-70% dry matter content is crucial to limit subsequent NH_3 generation, though caution is needed to prevent elevated emissions during intensive ventilation.

Measure	Impact						Reliability	Tech. rqmt
	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
A25 Manure storage under dry conditions	2	2	2	2	2	2	Robust	Intermediate

Maintaining solid manure in dry conditions is crucial for N management, impacting various N compounds and emissions. Dry storage minimises processes like mineralisation and denitrification, reducing N_2O, NOx, N_2 and NO_3^- leaching. Storage methods, such as covered piles or roofed storage, significantly cut N losses. Particularly pertinent in poultry operations, leaving poultry litter uncovered exposes it to rainfall, potentially causing up to 30% N loss, mainly via NH_3 volatilisation. Conversely, covered storage reduces moisture to 16-19%, cutting N losses to 17%, including 13% from NH_3. This practice is a simple and effective strategy for sustainable N management.

Measure	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
A26 Manure storage: solid base, permeable (dispersed/floating) covering	2	2	x	x	1	x	Robust	Intermediate

Reducing NH_3 emissions in agriculture is achieved through manure storage under permeable covers, like peat or plastic tiles, which resist volatilisation. Impermeable bases, such as clay liners, prevent NO_3^- leaching, retaining N in the storage system. These measures offer promising options for N loss reduction, requiring intermediate technology. Proper maintenance is vital for system integrity and leakage prevention, ensuring sustained N management benefits. Multiple covering methods, including peat, biochar, wood chips, vegetable oils, floating plastic tiles and high-density polyethylene (HDPE) geometric shapes show significant reductions in NH_3 emissions, providing flexibility for farm-specific conditions. Selecting suitable methods depends on factors like farm practices and infrastructure, emphasising the need for consistent maintenance to uphold efficiency.

Measure	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
A27 Manure storage: solid base, impermeable cover	1	1	3	x	1	3	Robust	Intermediate

Covered storage with solid lids and impermeable bases is a crucial strategy for N management in agriculture, reducing NH_3 emissions and preventing NO_3^- leaching. Materials like metal or concrete tanks with wood or polyvinyl chloride (PVC) covers resist volatilisation, limiting emitting surfaces. Peat and zeolite covers, when well-maintained, result in negligible NH_3 emissions. Besides reducing NH_3, covers retain volatile compounds, lowering malodorous fumes. An impermeable base prevents NO_3^- leaching, mitigating nutrient runoff. This robust, basic-to-intermediate technology requires rigorous maintenance to prevent leakage and ensure sustained benefits. Various covering methods, including structural and synthetic options, significantly cut NH_3 emissions, offering flexibility based on farm conditions. Consistent upkeep is vital for continued N management effectiveness.

Measure	Impact						Reliability	Tech. rqmt
	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
A28 Manure storage: solid base with walls	2	4	4	4	1	4	Promising	Basic

Storing manure on impermeable bases, like concrete or synthetic liners, effectively prevents NO_3^- leaching - a robust method achievable with basic technology. However, without proper covering, significant gaseous N emissions may occur, emphasising the need to limit ammonium-rich exposure for NH_3 reduction. Solid covers, including metal or concrete tanks, play a vital role in retaining volatile compounds and reducing malodorous fumes. Covered storage surpasses non-covered systems in N management, preventing higher N losses. Various covering options exist, with method selection depending on farm conditions and consistent maintenance crucial for sustained N management benefits.

Measure	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
A29 Manure storage: solid base, natural crust	2	2	4	x	1	3	Promising	Basic

Manure storage is crucial for N management, mitigating losses via NH_3 emissions and NO_3^- leaching. Uncovered systems, like natural crust formation, lead to higher N losses than covered methods. Natural crusts, common in cattle slurry, inconsistently reduce NH_3 emissions due to variable factors. A solid base (basic technology) beneath storage prevents NO_3^- leaching, safeguarding N. While natural crusts may reduce NH_3 for specific manures, they lack consistent control and cracks can readily form, leading to the release of both CH_4 and NH_3. Effective covering systems are recommended for reliable NH_3 reduction. Method selection depends on farm conditions and consistent maintenance is vital for sustained N management benefits.

Measure	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
A30 Zeolite and/or biochar additives to slurry	2	2	2	x	x	x	Promising	Basic

Efficient N management in agriculture involves employing additives to mitigate NH_3 emissions from manures. Zeolite, clay minerals, biochar, plant-based materials, chemical amendments, nitrification inhibitors, gypsum, amino acids, urea derivatives, microbial additives and encapsulation technologies are notable options. These additives act through adsorption, acidification or nitrification inhibition, reducing NH_3 volatilisation. Effectiveness depends on factors like manure composition and environmental conditions, demanding careful consideration and scientific evaluation. While promising for N loss reduction, economic implications arise, especially with mineral additives requiring substantial volumes (e.g., 25 kg zeolite per m3 slurry to absorb 55% of ammonium). Research gaps persist regarding the additives' effectiveness across diverse agricultural contexts.

Measure	Impact: Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
A31 Alum treatment of poultry litter	1	1	2	x	3	2	Robust	Basic

Addressing NH_3 emissions from poultry litter is crucial for poultry farming's environmental and health aspects. The application of alum $[Al_2(SO_4)_3 \cdot 12H_2O]$ to poultry litter emerges as a reliable and basic method to mitigate NH_3 volatilisation in poultry barns. This treatment demonstrates economic efficiency, reducing poultry litter NH_3 emissions by approximately 50%. Basic technological steps involve breaking up the litter and mixing it with alum. Combining alum treatment with proper ventilation, litter management and biosecurity measures enhances its effectiveness. This approach is particularly beneficial when considering the health of young birds, highly sensitive to harmful NH_3 emissions. Moreover, alum-treated litter becomes a more valuable fertilizer material due to increased N content. While alum is commonly used for litter, studies indicate its potential to reduce NH_3 emissions from cattle slurry, showcasing versatile applications in N management practices.

Measure	Impact: Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
A32 Acidification of slurry during storage	1	1	2	x	3	2	Robust	Intermediate

Acidifying stored slurry, achieved by lowering pH below 6.5, proves reliable and effective, reducing NH_3 emissions by up to 98%. Various acids, including sulfuric, nitric and hydrochloric acid, are employed for this purpose, with technological requirements ranging from basic to high, depending on the system's complexity. Safety procedures are essential for acid addition. The efficiency of this measure varies, with strong acids like sulfuric and hydrochloric acid proving the most effective, achieving reductions ranging from 50%-98%. Slurry acidification can surpass or match the efficiency of alternative methods, such as covering or manure injection.

Measure	Impact: Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
A33 Acidification of slurry during application	1	1	3	3	x	3	Robust	Intermediate

During and after slurry application to soil, over 50% of applied N can be lost, with nearly half occurring within the first 24 hours. Acidification of slurry during application proves a reliable and effective measure, achieving up to 80% reduction in NH_3 emissions by lowering pH below 6.5. Various acids, including sulfuric, nitric and hydrochloric acid, are utilised, with technological requirements ranging from basic to high. The efficiency of this measure, impacting factors like manure type, pH, acid type, storage conditions and temperature, varies, but studies indicate slurry acidification can be as or more efficient than alternative methods like covering or manure injection.

Measure	Impact						Reliability	Tech. rqmt
	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
A34 Anaerobic digestion of manure	1	1	2	x	1	2	Robust	High

Anaerobic digestion involves breaking down organic materials, like slurry and manure, by bacteria to produce CH_4 (biogas) offering an eco-friendly alternative to fossil energy. However, the resultant digested slurry has heightened ammonium content and pH, elevating the risk of NH_3 emissions. To address this, covered storage and low-emission manure spreading are imperative. Integrated into a comprehensive strategy, anaerobic digestion effectively reduces NH_3, N_2O and N_2 losses, presenting opportunities for advanced nutrient recovery. This holistic approach highlights the diverse benefits of anaerobic digestion, not only in mitigating greenhouse gas emissions, but also in promoting effective N management.

Measure	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
A35 Manure composting	x	4	4	4	x	4	Promising	Basic

Manure composting yields a stable, odour-free and bio-based fertilizer with reduced moisture content, retaining most initial nutrients and free from pathogens and seeds. However, NH_3, N_2O, NOx, N_2, CO2 and CH_4 losses may rise, diminishing the N fertilizer value. Composting on porous substrates poses a risk of increased N leaching. Employing covered composting methods can help alleviate some of these adverse effects.

Measure	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
A36 Plasma treatment of slurry	2	1	3	x	x	x	Robust	High

Using a compact plasma unit, slurry undergoes NO_3^- enrichment, matching NH_4+ concentrations. The ensuing stable pH decline substantially reduces NH_3 emissions. The plasma treatment not only hinders microbial activity, persisting through storage to reduce microbial N_2O and CH_4 losses, but also enhances the N content in liquid organic fertilizer. This dual impact contributes to a more precise fertilizer application, reducing NH_3 loss uncertainties and allowing better estimation of slurry N content. The technology's broader implications include a notable reduction in CH_4 production, curbing N_2O release and decreasing reliance on fossil-based fertilizers.

Measure	Impact						Reliability	Tech. rqmt
	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
A37 Drying and pelletizing of manure solids	4	4	x	x	x	x	Promising	High

Drying and pelletizing solid manures, slurry or digestate solids can yield a stable and odourless biobased fertilizer, although the energy-intensive drying process tends to be costly. The expense may be mitigated if excess energy, such as that from a biogas plant's combined heat and power engine, is readily available. However, NH_3 loss increases unless exhaust filtering or scrubbing is applied, or solids are acidified before drying. Pelletization, often combined with drying for ease of handling, allows the resulting pellets to be marketed as an organic matter and phosphorus-rich soil amendment. Acidification before drying can enhance the product's N availability for plants. Despite the benefits, careful consideration of the costs and NH_3 management is essential in implementing this process.

4.6 Summary table of measures to improve nitrogen management in livestock systems

The following table offers a concise overview of these measures.

Table 4.1 Measures for better N management in livestock farming. The 'impact' on N emissions (i.e., 1 = large reduction, 2 = medium reduction, 3 = small reduction, 4 = potential increase and X = unclear or unknown effect), 'reliability' and 'technological requirement' (i.e., expertise and/or specialized equipment) are indicated for each measure. See Box 1.1 for further details on these indicators. For further guidance on implementation, efficiency and the cost, risks and benefits of implementing measures, see the INMS Nitrogen Measures Database – www.inms.international/measures.

Measure sub-cateogory	Measure reference and name		Net effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Technical Rqmt
Livestock dietary and productivity measures	A1	Optimise the protein intake of cattle	1	1	1	x	1	1	Robust	Intermediate
	A2	Optimise the protein intake of pigs	1	1	1	x	1	1	Robust	Basic
	A3	Optimise the protein intake of poultry	1	1	1	x	1	1	Robust	Basic
	A4	Increase longevity of dairy cattle	2	2	3	x	3	2	Promising	Basic
	A5	Increase productivity of dairy and beef cattle	2	2	3	x	3	2	Promising	Basic
Grazing mgmgt measures	A6	Extend cattle grazing time (daily and seasonally)	2	1	4	4	4	4	Promising	Basic
	A7	Rotational grazing	2	3	2	2	1	2	Robust	Basic
	A8	Avoid grazing high-risk nitrogen loss areas	2	3	2	2	1	2	Robust	Basic
Animal housing measures Animal housing measures	A9	Use of acid air scrubbers in cattle housing	2	1	x	x	x	x	Robust	High
	A10	Use of acid air scrubbers in pig housing	1	1	2	2	3	3	Robust	High
	A11	Use of acid air scrubbers in poultry housing	1	1	2	2	3	3	Robust	High
	A12	Use of biological air scrubbers in pig housing	2	1	4	4	3	4	Robust	High
	A13	Use of biological air scrubbers in poultry housing	2	1	4	4	3	4	Robust	High
	A14	Reduce indoor temp. and airflow in cattle housing	2	1	3	x	x	x	Robust	Intermediate
	A15	Reduce indoor temp. and airflow in pig housing	2	2	x	x	x	x	Robust	Intermediate
	A16	Increase in bedding material in cattle housing	3	3	3	x	x	x	Robust	Basic
	A17	Increase in bedding material in pig housing	3	3	3	x	x	x	Robust	Basic
	A18	Remove cattle slurry from under slats to outside store	2	2	x	x	x	x	Robust	Basic
	A19	Remove pig slurry from under slats to outside store	2	2	x	x	x	x	Robust	Basic

Measure sub-cateogory	Measure reference and name	Net effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Technical Rqmt
(cont.)	A20 Regular cleaning of floors in animal housing	2	2	x	x	x	x	Robust	Basic
	A21 Livestock housing floor design to reduce nitrogen emissions	1	1	x	x	x	x	Robust	Intermediate
Manure collection, storage and processing measures	A22 Segregation of urine and faeces in cattle houses	2	1	x	x	x	x	Promising	Intermediate
	A23 Mechanical solid/liquid slurry separation	2	2	2	x	x	2	Promising	High
	A24 Rapid drying of poultry manure	1	1	2	2	2	2	Robust	Intermediate
	A25 Manure storage under dry conditions	2	2	2	2	2	2	Robust	Intermediate
	A26 Manure storage: solid base, permeable (dispersed/floating) covering	2	2	x	x	1	x	Robust	Intermediate
	A27 Manure storage: solid base, impermeable cover	1	1	3	x	1	3	Robust	Intermediate
	A28 Manure storage: solid base with walls	2	4	4	4	1	4	Promising	Basic
	A29 Manure storage: solid base, natural crust	2	2	4	x	1	3	Promising	Basic
	A30 Zeolite and/or biochar additives to slurry	2	2	2	x	x	x	Promising	Basic
	A31 Alum treatment of poultry litter	1	1	2	x	3	2	Robust	Basic
	A32 Acidification of slurry during storage	1	1	2	x	3	2	Robust	Intermediate
	A33 Acidification of slurry during application	1	1	3	3	x	3	Robust	Intermediate
	A34 Anaerobic digestion of manure	1	1	2	x	1	2	Robust	High
	A35 Manure composting	x	4	4	4	x	4	Promising	Basic
	A36 Plasma treatment of slurry	2	1	3	x	x	x	Robust	High
	A37 Drying and pelletizing of manure solids	4	4	x	x	x	x	Promising	High

5

Key actions for better nitrogen management related to land-use, landscapes and waterbodies

5.1 Overview of nitrogen management related to land-use and landscapes

Landscape planning can be used to make land-use decisions that support N recycling through the better integration of arable and livestock agriculture, by slowing the rate of N losses through drainage and erosion control (Figure 5.1), and by the use of trees and plants to capture atmospheric and leaching Nr losses to waterbodies. Measures (see Table 5.1) are grouped into:

i) drainage and erosion control,

ii) landscape planning measures, and

iii) waterbody management measures.

While the following sections provide brief summaries, more detailed descriptions including access to relevant literature are provided in the INMS Nitrogen Measures Database.

5.2 Drainage and erosion control measures

Establishing streambank fencing with buffer zones (>5-10 m) in pasture areas bordering rivers prevents direct livestock excretion into streams, reducing riverbank erosion and sedimentation (Grudzinski et al., 2020; O'Callaghan et al., 2019). If fencing is absent, providing alternative/off-stream watering sources is essential. Improving field drainage to prevent waterlogging can mitigate N_2O and N_2 emissions. However, shorter nutrient residence times in the soil may increase NO_3^- runoff into streams. Flow control structures, like vegetated channels, enhance N removal through plant-mediated denitrification, maximizing remediation by extending water residence time (Figure 5.1) (Montakhab et al., 2012; Strock et al., 2007). Similarly, riparian buffers (e.g., the vegetated region adjacent to streams and wetlands) are effective at intercepting airborne NH_3 or NO_3^- leaching to surface waters (Mayer et al., 2007; Walton et al., 2020). Organic matter (e.g., woodchips) can be placed in trenches at key points in the landscape to promote denitrification and enhance the removal of NO_3^- from ground/surface waters. This approach can help improve water quality but wastes Nr resources (lost as N_2) and potentially increases N_2O and CH_4 emissions (Sutton et al., 2022). Urban stormwater treatment through dry detention ponds and bioretention cells (BRCs) varies in N removal effectiveness, influenced by design type (Morse et al., 2017). (Waller et al., 2018) found denitrification potential increases with organic C and inorganic N concentrations in the soil media, while it decreases when grass is planted in BRCs compared to other types of vegetation.

An overview of drainage and erosion measures is provided below.

Measure	**Impact**						**Reliability**	**Tech. rqmt**
	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
L1 Off-stream watering facilities/alternative watering facilities	2	3	2	2	1	2	Robust	Basic

Off-stream watering facilities, also known as alternative watering facilities, are structures designed to provide water to livestock away from streams, rivers and other water bodies. Nitrogen emissions may occur when livestock have direct access to water bodies, leading to nutrient runoff and potential water pollution. The use of off-stream watering facilities helps manage these issues by providing an alternative water source away from natural water bodies, reducing the direct contact of livestock with these environments.

Measure	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
L2 Streambank fencing	2	3	2	2	1	2	Robust	Basic

In pastures adjacent to rivers streambank fencing with buffer distances >5-10 m, will stop livestock from excreting N-rich manures and urine directly into streams and reduce erosion of riverbanks and sediments. In addition, allowing a buffer zone of vegetation to grow between the fence and the stream can function to capture nutrients. Streambank fencing is a simple, effective way for farmers to improve water quality in the streams flowing through their farms.

Measure	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
L3 Trenches of organic matter to capture nitrate in runoff	4	3	4	4	1	4	Unproven	Basic

Implementing trenches of organic matter, such as woodchips, strategically placed in the soil at vital landscape points aids in denitrification. This process enhances the removal of NO_3 – from ground and surface waters, contributing to improved water quality. However, it's essential to acknowledge that this approach has potential drawbacks. While it effectively reduces NO_3 – levels, it results in N_2 emissions (wasting Nr resources), with the associated risk of increased N_2O and CH_4 emissions. Therefore, careful consideration is needed to weigh the benefits of enhanced water quality against the environmental impact of gas emissions associated with this N management measure.

Measure	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
L4 Dry detention and bio-retention basins	3	3	2	2	4	2	Unproven	Basic

Dry detention ponds and bioretention cells (BRCs) are effective tools for treating urban stormwater, but N removal by these systems is highly variable and influenced by design type. Denitrification potential increases with organic C and inorganic N concentrations in the soil media, while it decreases when grass is planted in BRCs compared to other types of vegetation.

Measure	Impact						Reliability	Tech. rqmt
	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
L5 Field border buffer strips (e.g., vegetated open channels)	1	x	1	1	1	x	Promising	Basic

Improving field drainage to promote run-off and avoiding waterlogging may help mitigate N_2O and N_2 emissions. In contrast, shorter residence times of nutrients (in the soil) are likely to increase run-off of NO_3^- into stream waters. Flow control structures such as vegetated open channels can be used to increase retention time allowing for N removal from surface waters through plant-mediated denitrification. In these systems, N remediation capacity is maximized by increasing water residence time, enhancing biofilm development on macrophytes and appropriate management. Similarly, riparian buffers (e.g., the vegetated region adjacent to streams and wetlands) are effective at intercepting airborne NH_3 or NO_3^- leaching to surface waters. Organic matter (e.g., woodchips) can be placed in trenches at key points in the landscape to promote denitrification and enhance the removal of NO_3^- from ground/surface waters. This approach can help improve water quality but wastes Nr resources (lost as N_2) and potentially increases N_2O and CH_4 emissions.

5.3 Landscape planning measures

Spatial optimization of crop and animal production systems has the potential to increase crop productivity, decrease the needed cropland area for food production and decrease N losses from food production (Dai et al., 2023). Contour or strip farming can slow surface water flow, increase infiltration and reduce erosion which can reduce NO_3^- losses (Liu et al., 2013). This is especially relevant for mitigating the heightened denitrification potential frequently observed in (submerged) rice paddies, particularly prevalent in East and South Asia. Integrating arable and livestock farming offers opportunities to enhance nutrient recycling, reduce N pollution and increase farm – and landscape-scale NUE (Sutton et al., 2013a). It also lowers emissions linked to long-distance feed and manure transport. Implementing such a structural shift would likely require supportive economic and regulatory frameworks. Environmentally smart placement of livestock facilities and outdoor animals (i.e., away from sensitive terrestrial habitats or waterbodies) can reduce local Nr problems. In some cases, shelterbelts around point sources, like manure storage areas, can mitigate atmospheric Nr losses, albeit with potential N_2O emission risks. This approach may also reduce NO_3^- leaching losses but can risk increased N_2O emissions. Where resources allow, modelling nutrient retention at the landscape scale (e.g., digital 3D precision maps of soil N retention) can help to ensure the most effective measures are implemented where they are needed (Natho and Venohr, 2012; Sutton et al., 2013a). However, the technical requirements of this approach may constrain its applicability across diverse regions.

An overview of landscape planning measures is provided below.

Measure **Impact** **Reliability** **Tech. rqmt**

L6 Contour farming/strip farming

Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
x	x	x	x	1	x	Robust	Intermediate

Crop row ridges built by tilling and planting on the contour create hundreds of small dams. These ridges or dams slow water flow and increase infiltration, which reduces erosion. Can also be used with strip cropping, whereby the crop is alternated with strips of meadow or small grain planted on the contour. The small grain/meadow strip slows runoff, increases infiltration, traps sediment and provides overall cover. In doing so, this measure can reduce nutrient losses associated with runoff, such as NO_3^- leaching losses.

L7 Digital planning of land-use based on a suitability assessment

Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
1	2	2	2	1	2	Promising	High

Digital planning of land use, grounded in a thorough land suitability analysis, is crucial for fostering sustainable agricultural production. By incorporating 3D precision maps that assess soil N retention, this approach becomes instrumental in optimizing fertilizer utilisation, thereby curbing N leaching and minimising Nr losses. Land suitability analysis encompasses a broad evaluation of criteria, including soil quality, terrain characteristics, as well as socio-economic, market and infrastructure factors. This comprehensive assessment not only aids in enhancing nutrient retention at the landscape level but also contributes to improving water quality in both surface and groundwater, all while effectively reducing gaseous Nr losses. Successful implementation of this digital strategy often relies on robust support from detailed modelling processes.

L8 Integrating arable and livestock farming

Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
1	1	1	1	1	1	Promising	Basic

Mixed farming, integrating arable and livestock activities at both farm and landscape scales, can aid a sustainable approach to agriculture. This system seamlessly combines crop cultivation with livestock management, creating synergies that enhance N management. By connecting N inputs and surpluses, it effectively reduces overall N pollution and boosts NUE on both farm and landscape levels. Moreover, emissions linked to the transportation of feed and manure over long distances are avoided, contributing to a more environmentally friendly operation. Additionally, mixed cropping-livestock systems offer the potential for the development of free-range livestock production alongside crops specially chosen to mitigate Nr losses. This integrated approach aligns with sustainable practices, fostering efficient N utilisation while minimising environmental impact.

Measure	Impact						Reliability	Tech. rqmt
	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
L9 Environmentally smart placement of livestock facilities and outdoor animals	2	2	3	3	2	3	Robust	Basic

Strategic placement of livestock facilities and outdoor animals away from sensitive terrestrial habitats or water bodies effectively minimises local N problems. This approach is particularly prevalent in planning procedures for new agricultural developments or expansions of existing farms. By proactively considering the ecological impact and potential N-related consequences, this method aligns with sustainable land use practices. It ensures that the presence of livestock does not adversely affect nearby environments, preserving the quality of terrestrial habitats and water bodies. This environmentally conscious placement strategy exemplifies a proactive approach to N management, contributing to the overall sustainability of agricultural operations.

Measure	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
L10 Shelterbelts around nitrogen point sources	x	2	4	4	x	3	Promising	Basic

Establishing broad shelterbelts, like woodlands, around N point sources offers a strategic measure to alleviate landscape dispersion of N in areas with concentrated emissions, such as manure storage or animal housing facilities. Trees act as bio-filters, effectively trapping some NH_3 and contribute to immobilising Nr into plant biomass and organic soil N stocks. While this approach has the potential to diminish losses from NO_3 – leaching, there is a risk of increased N_2O emissions. This method exemplifies a nuanced N management strategy, balancing the benefits of reduced NH_3 dispersion with careful consideration of potential trade-offs in terms of N_2O emissions.

5.4 Waterbody management measures

Constructed/treatment wetlands remove Nr from water bodies and wastewater treatment through denitrification to N2 (Huang et al., 2000; Vymazal, 2013), while other nutrients such as P accumulate. Nitrogen removal rates can vary by 25% to 85% between systems (Lee et al., 2009) but can be enhanced through engineering and management e.g., intermittent aeration and effluent recirculation (Ilyas and Masih, 2017). Planting macrophytes can maximize biomass growth, thereby removing Nr from the water. The biomass can be harvested and used, e.g., as a source of bioenergy (Röhl et al., 2019). Poorly managed systems may increase emissions of N2O and N2 (as well as CH4) if Nr is not fully used for plant growth (Sutton et al., 2022). Similarly, biological Nr removal can be enhanced in coastal waters by growing seaweed, eelgrass, oyster farming or shellfish aquaculture and N can be recovered into useful products (Carmichael et al., 2012; Mara et al., 2021; Rose et al., 2014).

Further research is needed to quantify the efficacy of such systems in mitigating coastal water pollution. Vegetated coastal wetlands also dissipate incoming wave energy, providing a transition zone between the erodible uplands and open water which can prevent nutrient-laden sediments from entering the waters (Onorevole et al., 2018). Structural tidal shoreline erosion controls (e.g., rigid, barrier-type structures) can indirectly enhance N removal by protecting coastal vegetation and shorelines from the action of waves, currents, tides, wind-driven water, runoff storms, or groundwater seepage that erodes shorelines (O'Meara et al., 2015).

The following text presents an overview of measures for sustainable N management in water bodies.

Measure	Impact						Reliability	Tech. rqmt
	Net Effect	NH$_3$	N$_2$O	NO$_x$	Nr to water	N$_2$		
L11 Planting wetland plants in riparian zones and wetlands	4	2	4	4	1	x	Robust	Basic

Strategically planted wetland vegetation optimizes biomass growth, removing Nr from water for potential bioenergy. Poor management can lead to increased N emissions if Nr isn't fully utilised. Riparian zones in agricultural landscapes provide vital ecosystem services, including nutrient and sediment retention, C sequestration and flood peak control. Nutrient attenuation in riparian zones varies between existing natural and new agricultural wetlands, with existing wetlands more vulnerable to nutrient loading. Agricultural wetlands designed for N removal and biodiversity enhancement generally show positive results, especially in landscapes with limited original wetland resources.

Measure

L12 Constructed wetlands for biological nitrogen removal

Impact						Reliability	Tech. rqmt
Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
4	3	4	3	1	4	Unproven	Basic

Constructed wetlands serve as effective tools for nutrient removal from water bodies and wastewater treatment. The fundamental principle guiding constructed wetlands is to create conditions conducive to denitrification, converting N compounds into N_2, while other nutrients accumulate within the wetland system. This approach is cost-effective, offering an affordable means of nutrient reduction. However, it has inherent drawbacks, such as the loss of Nr in the form of N_2, posing a potential waste. Additionally, there is a risk of elevated emissions of N_2 and CH_4. Furthermore, dissolved organic C and N may be lost to nearby watercourses during the process. Despite its cost-efficiency, careful consideration is needed to address the associated environmental risks and losses in nutrient resources.

L13 Biological nitrogen removal from coastal waters

Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
1	1	1	3	2	2	Promising	Intermediate

The utilisation of seaweed, eelgrass, oyster farming, or shellfish aquaculture has been suggested as a means to alleviate excess nutrient levels in coastal waters. Nitrogen is assimilated into the biomass of these organisms, which is then harvested. Although the fundamental concept of promoting Nr recovery into valuable products is promising, a more comprehensive understanding of the quantitative efficacy of this system is essential. Further empirical evidence is required to ascertain the performance and reliability of these approaches in mitigating coastal water pollution before they can be confidently employed as sustainable and effective solutions.

L14 Structural coastal erosion control

Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
2	3	3	3	2	2	Promising	High

Structural tidal shoreline erosion controls, like rigid barriers, indirectly aid N removal by safeguarding coastal vegetation from erosive forces. These measures shield shorelines from waves, currents, tides, wind-driven water, storm runoff and groundwater seepage, promoting a stable environment for N removal. While contributing to erosion control and enhanced N removal, further research is needed to precisely gauge the effectiveness of these structures and validate their suitability for sustainable coastal management.

5.4 Summary table of nitrogen management measures related to land-use, landscapes and waterbodies

The following table offers a concise overview of these measures.

Table 5.1 Measures for better N management related to land-use, landscapes and waterbodies. The 'impact' on N emissions (i.e., 1 = large reduction, 2 = medium reduction, 3 = small reduction, 4 = potential increase and X = unclear or unknown effect), 'reliability' and 'technological requirement' (i.e., expertise and/or specialized equipment) are indicated for each measure. See Box 1.1 for further details on these indicators. For further guidance on implementation, efficiency and the cost, risks and benefits of implementing measures, see the INMS Nitrogen Measures Database – www.inms.international/measures.

Measure sub-cateogory	Measure reference and name		Net effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Technical Rqmt
Key actions for better nitrogen management related to land-use, landscapes and waterbodies										
Drainage and erosion control	L1	Off-stream watering facilities/ alternative watering facilities	2	3	2	2	1	2	Robust	Basic
	L2	Streambank fencing	1	3	2	2	1	2	Robust	Basic
	L3	Trenches of organic matter to capture nitrate in runoff	4	3	4	4	1	4	Unproven	Basic
	L4	Dry detention and bio-retentions basins	2	3	2	2	4	2	Unproven	Basic
	L5	Field border buffer strips (e.g. vegetated open channels)	1	x	1	1	1	x	Promising	Basic
Landscape planning measures	L6	Contour farming/strip farming	1	x	x	x	1	x	Robust	Intermediate
	L7	Digital planning of land-use based on a suitability assessment	1	2	2	2	1	2	Promising	High
	L8	Integrating arable and livestock farming	1	1	1	1	1	1	Promising	Basic
	L9	Environmentally smart placement of livestock facilities and outdoor animals	2	2	3	3	2	x	Robust	Basic
	L10	Shelterbelts around nitrogen points sources	x	2	4	4	x	3	Promising	Basic
Waterbody management measures	L11	Planting wetland plants in riparian zones and wetlands	1	1	x	2	1	x	Robust	Basic
	L12	Constructed wetlands for biological nitrogen removal	4	3	4	3	1	4	Unproven	Basic
	L13	Biological nitrogen removal from coastal waters	2	3	3	3	2	2	Promising	Intermediate
	L14	Structural coastal erosion control	2	3	3	3	2	2	Promising	High

6

Key actions for better nitrogen management of wastewater and solid organic waste

6.1 Overview of nitrogen management of wastewater and solid organic waste

The key strategies to remove Nr from municipal/industrial wastewater is to convert it to N2 gas to the atmosphere and to concentrate and recover Nr for use as fertilizer (Winkler and Straka, 2019). Offsetting the energy consumption used to make synthetic N fertilizers by reusing Nr from waste streams supports a circular flow of the N cycle (Beckinghausen et al., 2020a). However, low N concentrations in influent wastewaters can make recovery via physico-chemical processes energy-intensive pointing to the need for continued innovation (Winkler and Straka, 2019). The emerging challenge is to recover Nr with low energy requirements. Recent innovations to enhance N recovery can reduce energy costs and negative environmental impacts and offer value-added products (Capodaglio et al., 2015). Here we discuss common measures to address N in wastewater and solid organic residues (Table 6.1), grouped into

i) biological removal of N from wastewater,

ii) physicochemical, as well as

iii) biological removal and recovery of N from wastewater and organic residues.

However, in practice, efficient techniques commonly combine multiple measures across groupings.

While the following sections provide brief summaries, more detailed descriptions including access to relevant literature are provided in the INMS Nitrogen Measures Database.

6.2 Biological removal of nitrogen from wastewater

Removal of N from wastewater is commonly achieved using 'conventional' microbial nitrification/denitrification processes within activated sludge plants (Figure 6.1) (Capodaglio et al., 2015; Winkler and Straka, 2019). With the ultimate objective to produce N_2, nitrification converts NH_3 to NO_3^- aerobically, followed by denitrification; both stages produce N_2O as a by-product and intermediate substance, respectively (Massara et al., 2017). Energy-intensive processes are needed and denitrifying low organic C wastewater may require costly C additions (Sun et al., 2018). Efficiency depends on temperature, pH and substrate loading (Metcalf et al., 2003).

Alternative biological methods for N removal have been identified that, depending on the composition of the wastewater, require less energy and/or offer higher N removal efficiencies. These include anaerobic ammonium oxidation (anammox), Completely Autotrophic N removal Over Nitrite (CANON), simultaneous nitrification and denitrification, shortcut nitrification and denitrification, Oxygen-Limited Autotrophic Nitrification-Denitrification (OLAND) processes and aerobic deammonification (Rahimi et al., 2020; Zhu et al., 2008). Whilst there is variation in the types of microorganisms and processes used, in all these processes Nr is lost and wasted as N_2 (for recovery based options see Section 7.3).

The following text presents an overview of measures for biological removal of N from wastewaters.

Measure	**Impact**						**Reliability**	**Tech. rqmt**
	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
O1 Conventional nitrification/denitrification	2	x	x	x	1	4	Robust	High

Conventional microbial nitrification/denitrification systems typically include aeration tanks for aerobic nitrification, anoxic tanks for anaerobic denitrification, blowers for aeration and additional components such as settling tanks for solids separation and monitoring instruments for process control. Nitrification is achieved via oxidation of NH_3 to NO_2-, then to NO_3-, under aerobic conditions followed by denitrification, in which microbial organisms convert NO_3 – to N_2, via NO_2-, NO and N_2O under anaerobic conditions. Both stages create N_2O as a by – product and an intermediate substance, respectively. In most cases, significant energy costs for aeration, pumping and solids processing are required. Furthermore, denitrification of wastewater with low dissolved organic C may require costly C additions (e.g., methanol and ethanol). Efficiency is influenced by several factors including temperature, pH and substrate loading. This method does not recover Nr resources.

Measure	Impact						Reliability	Tech. rqmt
	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
O2 Anaerobic ammonium oxidation (anammox)	2	x	x	x	1	4	Robust	High

Anaerobic ammonium oxidation (anammox) is recognised in wastewater treatment for its capability to simultaneously remove NH_3 and NO_2 – with minimal or no greenhouse gas emissions, because the anammox reaction does not involve N_2O. This process demonstrates lower oxygen (O_2) demand and results in negligible sludge production composed with measure O1. Anammox bacteria fall into seven genera with around 22 species, including Candidatus Brocadia, Candidatus Kuenenia, Candidatus Scalindua. Typically, microbial communities are held in anoxic moving-bed – biofilm reactor-systems, where they exhibit efficient N removal activity within the temperature range of 10°C to 35°C. Despite challenges such as sensitivity to organic chemicals and competition with heterotrophic denitrifying bacteria in the presence of organic matter, anammox processes are considered a suitable for N removal in wastewater treatment while potentially contributing to reduced greenhouse gas emissions. This method does not recover Nr.

Measure	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
O3 Completely autotrophic nitrogen removal over nitrite (CANON)	2	x	x	x	1	4	Robust	High

The CANON process (Completely Autotrophic Nitrogen removal Over Nitrite) offers a unique approach to N removal in wastewater treatment by combining partial nitriation (i.e. nitritation; stopping the process at NO_2^- creation) and anammox in a single aerated reactor. In this system, nitrifying bacteria oxidise NH_3 to NO_2^- while consuming oxygen, creating anoxic zones for anammox bacteria to function and complete the N transformation. CANON has the potential to remove ammonium from wastewater in a single, oxygen-limited treatment step. The effectiveness of CANON as an industrial process depends on its ability to recover from major disturbances in feed composition. The process relies on the stable interaction between two bacterial populations: *Nitrosomonas*-like aerobic and *Planctomycete*-like anaerobic ammonium-oxidising bacteria. Challenges in implementing CANON in completely mixed activated sludge systems include a prolonged start-up period and low N removal rates due to the slow growth rate of anaerobic ammonium-oxidising bacteria. This method does not recover Nr resources.

Measure	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
O4 Simultaneous nitrification and denitrification (SND)	2	x	x	x	1	4	Robust	High

Simultaneous Nitrification and Denitrification (SND) is a promising biological N removal process, exhibiting cost-effectiveness through reduced structural footprint and minimal oxygen and energy demands compared to conventional methods (based on measure O1). SND involves concurrent nitrification and denitrification in a single reactor under optimal conditions, contributing to its efficiency and economic viability. Notably, SND requires less external C sources, lacks internal recirculation and maintains a diverse microbial population. Overcoming challenges, such as establishing stable aerobic and anoxic conditions within flocs and optimizing dissolved oxygen, is crucial in SND implementation. Innovative reactor configurations and diversified microbial communities have successfully achieved substantial C and N reduction in wastewater. Recent advancements in SND extend its utility to micropollutant removal, leveraging microaerobic and diverse redox conditions to enhance biotransformation. This method does not recover Nr resources.

Measure **Impact** **Reliability** **Tech. rqmt**

O5 Shortcut/partial nitrification and denitrification

Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
2	x	x	x	1	4	Robust	High

Shortcut/partial nitrification and denitrification streamline NH_3 conversion to N_2, bypassing intermediate N oxidation and reduction stages. The nitrite pathway halts nitrification at NO_2 – (nitritation), proceeding to reduce NO_2 – to N_2 through denitrification and/or anammox. Compared to the conventional NO_3 – pathway, the nitrite pathway offers approximately 40% C source savings, a 25% oxygen requirement reduction and a 60% denitrification rate improvement. These advances boost N removal efficiency, benefiting resource use and the environment. Optimizing these processes is crucial in wastewater treatment, leading to lower energy consumption, enhanced N removal rates and a more sustainable N management approach in treatment plants. This method does not recover Nr resources.

O6 Oxygen-limited autotrophic nitrification-denitrification (OLAND) processes

Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
2	x	x	x	1	4	Robust	High

Oxygen-limited autotrophic nitrification-denitrification (OLAND) processes represent an efficient biological method for N treatment in wastewater. OLAND integrates partial nitrification and anaerobic ammonium oxidation, operating as a completely autotrophic nitrification-denitrification system. This process offers numerous advantages, including low energy consumption, a high N removal rate and a compact system footprint. Particularly suitable for wastewater with low chemical oxygen demand/NH_4-N ratios, OLAND has emerged as a successful and practical biological N removal technology. The efficiency of the OLAND process to reduce nitrogen compounds, along with its economic and spatial advantages, makes it a suitable option for sustainable N management in wastewater treatment. That withstanding, this method does not recover Nr resources.

O7 Aerobic deammonification

Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
2	x	x	x	1	4	Robust	High

Aerobic deammonification, or aerobic ammonium oxidation, is a biological process in wastewater treatment that transforms NH_4^+ into N_2 under oxygen-rich conditions. This method, facilitated by specific bacteria, bypasses traditional nitrification stages, eliminating the conversion of NH_4^+ to NO_3^-. Unlike nitrification, aerobic deammonification avoids the formation of NO_2 – and NO_3^-, directly converting NH_4^+ to N_2. This approach proves advantageous when the primary goal is N_2 reduction, as it diminishes oxygen demand and prevents NO_3 – production—particularly crucial in environmentally sensitive contexts. Nevertheless, this method does not recover Nr resources.

6.3 Physicochemical removal and recovery of nitrogen from wastewater and organic residues

The preceding section discussed several methods that are available to clean water by converting N_r to N_2. While these have major benefits for mitigation of water pollution, they nevertheless waste substantial valuable N_r resources. This realisation is now leading to increased focus on methods that can both clean water and recover N_r for subsequent use.

Various methods can recover N_r from wastewaters and organic residues. A commonly used method is struvite ($NH_4MgPO_4 \cdot 6H_2O$) precipitation with magnesium addition, which can recover NH_4^+ and phosphate, but can involves significant chemical costs (Booker et al., 1999; Kumar and Pal, 2015). Struvite can serve as a slow-release fertilizer (El Diwani et al., 2007), in certain cases this can help offset some of the process costs. Physical adsorption of NH_3 using materials like zeolite, activated C, and biochar (Han et al., 2021) can be an energy-efficient and straightforward alternative method to recover N_r resources from wastewaters (Beckinghausen et al., 2020b; Sancho et al., 2017; Smith and Smith, 2019). Membrane systems, including filtration and gas permeable membranes, provide efficient NH_4^+ removal without heat (Adam et al., 2019; Karri et al., 2018). 'Vacuum' membrane distillation, using vacuum pressure for volatilised migration, has achieved an 85% recovery in anaerobic digestate and 96%-99% in industrial wastewater (Yang et al., 2017). When processing wastewaters with a high-solid content, thermal stripping processes may be more appropriate and can recover up to 95% of NH_3 when combined with acid absorption (Folino et al., 2020; Tian et al., 2019; Ukwuani and Tao, 2016). More selective recovery processes include electrocoagulation and electrodialysis, which can be used to separate ions without chemicals but require careful consideration of energy costs (Perera et al., 2019).

Choosing the most suitable method for a given system should be based on an assessment of the composition and nutrient content of the wastewater or residue, as well as relevant local factors such as budget, technical expertise, proximity to a recycling site, and local and national goals.

The following text presents an overview of measures for physicochemical removal and recovery of N_r from wastewater and organic residues.

Measure	**Impact**						**Reliability**	**Tech. rqmt**
	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
O8 Struvite precipitation from wastewater	1	2	x	x	1	x	Robust	High

Struvite is a form of N that can be precipitated from wastewater. Optimizing struvite recovery from wastewaters involves the precipitation of NH_3 and phosphate through the addition of magnesium.
Struvite serves as a slow-release fertilizer with agricultural benefits. Considerations include managing chemical costs, which can be addressed by optimizing nutrient recovery efficiency. This process contributes to sustainable N management in organic residues through dual Nr and P recovery.

Measure	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
O9 Ammonia stripping and acid absorption from wastewater	1	1	x	x	1	x	Robust	High

The balance of NH_3/NH_4+ in wastewaters is pH-dependent, with NH_3 in the liquid phase readily volatilising at pH >8. Ammonia stripping and acid absorption leverage this, creating conditions for NH_3 volatilisation followed by capture through acid scrubbing. Nitrogen recovery efficiencies vary significantly based on the specific technique and characteristics of the wastewater stream. This process provides a strategic approach to managing N in wastewaters, aligning with pH considerations for effective Nr recovery as NH_4^+. Although several possible acids may be used, sulfuric acid (H_2SO_4) is most frequent due to its low cost and stability.

Measure	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
O10 Bio-drying sludge with acid scrubbing of exhaust air	3	2	4	4	x	3	Robust	High

Bio-drying sewage sludge, coupled with acid scrubbing of exhaust air, is a N management strategy that employs controlled aerobic microbial activity. This dual process effectively reduces moisture content and stabilises organic matter in sewage sludge. Simultaneously, acid scrubbing is implemented on the exhaust air to minimise emissions, specifically targeting N compounds such as NH_3, N_2O and NO_X. By integrating these techniques, the approach not only optimizes sludge quality but also addresses N-related environmental concerns, enhancing overall N management in wastewater treatment.

Measure **Impact** **Reliability** **Tech. rqmt**

O11 Physical adsorption of nitrogen from wastewaters

Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
2	x	x	x	2	x	Robust	High

Physical adsorption of NH_4^+ from wastewaters is an effective N recovery process that is energy efficient and easy to operate. A range of adsorbent materials can be used, most commonly zeolite (natural and synthetic), however lignite, bentonite, clay, biochar, activated C and nanomaterials have also been used successfully. Loaded zeolite can be used as a soil additive, whilst regeneration of loaded zeolite can form rich NH_4^+/NH_3 concentrates (2-6 g NH_3 L^{-1}) which have potential use as a liquid fertilizer. Challenges include ion selectivity, regeneration requirements and adsorbent material costs. Pyrolyzed sewage sludge, agricultural residues and forestry wastes yield activated C and biochar. These materials, unlike minerals, provide sustainable benefits by recycling discarded residues and their nutrient content (e.g., C, P and K) through direct biochar application to soils.

O12 Membrane systems for treatment of nitrogen in wastewaters

Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
1	x	x	x	1	x	Robust	High

Membrane systems, including various filtration techniques such as microfiltration, ultrafiltration, nanofiltration and reverse osmosis, provide effective NH_4^+ removal from wastewater by utilising osmotic pressure and size disparities among ions and dissolved or suspended materials. Additionally, gas permeable membranes selectively capture NH_3 with a recovery efficiency of approximately 95%. Membrane distillation, a thermal process relying on vapor pressure across a hydrophobic porous membrane, is enhanced by 'vacuum' membrane distillation, utilising vacuum pressure or a sweeping gas instead of applied heat for efficient volatilised molecule migration. The technique, exemplified by an 85% recovery efficiency in anaerobic digestate and 96%-99% in industrial wastewater, improves N recovery, though operational complexity and cost highlight the need for further innovation to allow widespread implementation.

O13 Thermal stripping with nitrogen recapture from wastewaters

Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
1	1	x	x	1	x	Robust	High

Thermal stripping, coupled with N recapture from wastewater, involves elevating wastewater temperature to induce N compound volatilisation. Advanced technologies, including scrubbers, membrane separation and absorption towers, facilitate subsequent N recapture. This efficient process reduces N concentrations, addressing environmental and water quality concerns. Ongoing research focuses on refining N recovery efficiency and enhancing economic feasibility for recycled N as fertilizer. However, challenges such as elevated energy consumption and operational expenses require careful consideration for widespread implementation. Thermal stripping, utilising heat for separation without a stripping gas, offers benefits in handling waste with high solids concentrations, distinguishing it from membrane processes. Vacuum thermal stripping with acid absorption can recover 95% of NH_3 from urine as ammonium sulphate crystals. While NH_3 stripping with acid absorption is a simple and effective technique (See measure O9), common fouling, chemical costs, aeration expenses and potential NH_3 losses should be considered.

O14 Electrocoagulation systems for treatment of nitrogen in wastewaters

Measure	Impact						Reliability	Tech. rqmt
	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
O14 Electrocoagulation systems for treatment of nitrogen in wastewaters	1	1	x	x	1	x	Robust	High

Electrocoagulation is a versatile electrochemical process applied in various wastewater treatment scenarios. In the context of N management, electrocoagulation plays a role in destabilising particles and coagulating contaminants, including N compounds. While electrocoagulation is not typically used specifically for the direct recovery of nitrogen compounds, it can facilitate the removal of nitrogen in the form of NH_3 and NH_4^+. The process utilises an electric current and sacrificial electrode to form coagulants, facilitating the removal of a broad spectrum of contaminants. While it eliminates the need for chemical additions, careful consideration of energy costs is essential. Electrocoagulation is well-suited for scenarios where diverse pollutants need to be addressed, making it a versatile option for wastewater treatment.

O15 Electrodialysis systems for treatment of nitrogen in wastewaters

Measure	Impact						Reliability	Tech. rqmt
	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
O15 Electrodialysis systems for treatment of nitrogen in wastewaters	2	2	x	x	2	x	Robust	High

Electrodialysis is a specialized electrochemical process designed for ion removal, particularly targeting N compounds found in wastewater. In the case of N management, electrodialysis employs a cation-exchange membrane to allow positively charged ions, such as NH_4^+, to pass through selectively while blocking negatively charged ions like NO_3^-. This process is known for its energy efficiency, continuous operation and minimal waste production compared with some other treatment methods. Electrodialysis is especially effective where selective ion removal, such as NH_4^+, is the primary goal, providing an energy-efficient solution for wastewater treatment.

6.4 Biological nitrogen removal and recovery from wastewater and organic residues

Biological N removal and recovery include a range of electrical, bioreactor and decomposition-based approaches. In bio-electrochemical systems, microorganisms are used to catalyse reactions at the anode or cathode of an electrochemical cell for recovery of N_r compounds from wastewater. Nitrogen recovery mechanisms include ion exchange membranes and volatilisation followed by acid absorption (Wu and Modin, 2013). Performance is influenced by current density, pH and wastewater N concentration (Rodríguez Arredondo et al., 2017). Microbial fuel cells recover energy at the anode, while microbial electrolysis cells require energy input at the cathode (Wu and Modin, 2013). Microbial desalination cells and submerged membrane desalination cells can also be used for NH_4^+ recovery (Chen et al., 2015). Bipolar bio-electrodialysis produces hydrogen (offsetting energy costs) at the cathode and recovers NH_3 and sulphate. Challenges include membrane optimization, internal resistance and electrode conductivity for scale-up (Nancharaiah et al., 2016).

Biological N recovery from wastewater, via assimilation into biomass has been achieved using phototrophic bacteria, microalgae and cyanobacteria (Han and Zhou, 2022; Hülsen et al., 2018). Some species are best suited for wastewater with low N concentration as they experience growth inhibition or even toxicity in high NH_4^+ environments, but others like phototrophic purple bacteria can grow in high-strength wastewater (Winkler and Straka, 2019). As with biological N removal, the organisms used in these processes are sensitive to changes in influent characteristics and operational parameters. Advantages include cost (compared to chemical precipitation) and co-recovery of other nutrients (e.g., P and K) into products that can be used for animal feed and biofuels (Perera et al., 2019).

As described for aquaculture sludges (Section 7.3), recovery and recycling of nutrients from solid organic residues (e.g., sewage sludges, food and abattoir residues) can also be achieved using anaerobic digestion and aerobic composting (with appropriate storage to avoid N losses) (Wainaina et al., 2020).

The following text presents an overview of measures for biological N removal and recovery from wastewater and organic residues.

Measure	Impact						Reliability	Tech. rqmt
	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
O16 Microbial fuel cell for wastewater treatment	2	x	x	x	2	x	Robust	High

A Microbial Fuel Cell (MFC) is an innovative wastewater treatment technology that utilises microorganisms to convert organic matter into electricity. Bacteria within the MFC oxidise organic compounds, generating electrons for electricity production and enhancing the breakdown of Nr compounds like NH_3 and NO_3-, to N_2. This process effectively reduces N pollution in treated water but does not recover Nr resources. However, MFCs can also be tailored to recover valuable Nr compounds from the treated wastewater by using specific electrode materials or membranes. This targeted recovery enables the concentration of valuable Nr species, providing a sustainable and energy-efficient approach to wastewater treatment while facilitating the reuse of Nr resources, for example, in fertilizer production.

Measure	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
O17 Microbial electrolysis cell for wastewater treatment	2	x	x	x	2	x	Robust	High

The Microbial Electrolysis Cell (MEC) is a bio-electrochemical system employed in wastewater treatment, with a specific focus on N management. MECs utilise microorganisms to catalyse the electrolysis of organic matter, generating hydrogen gas and promoting N removal. Notably, N species such as NH_4 and NO_3 are impacted, facilitating their conversion to N_2. This process mitigates N pollution, a critical concern in wastewater. Benefits include enhanced energy recovery through hydrogen production and efficient N removal. However, challenges include system optimization, electrode material selection and potential scaling issues.

Measure	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
O18 Bio-electrodialysis for wastewater treatment	1	x	x	x	1	x	Robust	High

Bio-electrodialysis is an electrochemical wastewater treatment method that utilises ion-selective membranes and microbial activity to facilitate recovery of specific ions. Bio-electrodialysis targets NH_4 and NO_3 , aiming to convert them into N_2 through microbial processes. The system offers benefits such as efficient N removal and simultaneous energy recovery through ion migration. By contrast the approach does not focus on Nr recovery Challenges include membrane fouling, biofilm formation and system optimization complexities. Implementation necessitates careful consideration of membrane materials, microbial communities and operational conditions to maximize N removal efficiency, while addressing potential risks associated with bio-electrodialysis, such as system contamination or biofouling.

Measure	Impact						Reliability	Tech. rqmt
	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
O19 Membrane bioreactors for wastewater treatment	1	x	x	x	1	x	Robust	High

Membrane Bioreactors (MBRs) are advanced wastewater treatment systems integrating biological processes with membrane filtration. MBRs effectively target N compounds like NH_4 and facilitate their conversion to NO_3 through biological reactions. MBRs leverage membranes to separate biomass from treated water, enhancing nutrient removal. Key benefits include high-quality effluent, reduced footprint and enhanced nutrient control. Challenges include membrane fouling, energy consumption and initial capital costs. Implementation considerations involve membrane selection, aeration optimization and operational monitoring to mitigate risks associated with fouling and ensure system efficiency. This method does not recover Nr resources.

Measure	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
O20 Phototrophic bacteria and microalgae systems for wastewater treatment	1	1	x	x	1	x	Robust	Intermediate

Phototrophic bacteria and microalgae systems offer innovative approaches to wastewater treatment by harnessing photosynthesis for nutrient removal. In relation to N management, these systems target N species like NH_4 and NO_3, utilising phototrophic organisms to convert them into biomass or N_2. Benefits include efficient nutrient uptake, simultaneous CO_2 fixation and potential biofuel production. Challenges involve maintaining optimal growth conditions, preventing biomass washout and system scalability. Implementation requires careful consideration of light exposure, nutrient ratios and system design to optimize performance. Risks include potential nutrient imbalances, algal blooms and system stability. This method does not recover Nr resources.

Measure	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
O21 Anaerobic digestion of solid organic residues	2	2	x	x	2	x	Robust	High

Anaerobic digestion of organic residues is a biological process that decomposes complex organic matter in the absence of oxygen, producing biogas and nutrient-rich effluent. The same approach described in the context of animal manure is discussed in measure A34. In terms of N management, anaerobic digestion targets organic N compounds, converting them into NH_4 and subsequently into biogas, reducing the N load. Notable benefits include biogas generation for energy, waste volume reduction and pathogen inactivation. Challenges include process instability, longer retention times and potential inhibition of NH_3 volatilisation. Implementation considerations involve optimizing feedstock composition, temperature control, and reactor design to enhance digestion efficiency. One of the key opportunities of anaerobic digestions is the recover Nr and other nutrients for digestate, such as by NH_3 stripping (O9).

Measure	Impact: Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
O22 Covered composting of solid organic residues	2	2	x	x	2	x	Promising	Basic

Covered composting involves controlled organic matter decomposition under impermeable covers, efficiently managing N by converting organic compounds to NH_3 and NO_3 . The use of covers in this method (see measures A35 – uncovered composting) minimises odours and N losses, particularly NH_3, offering advantages over open composting with its risk of substantial N emissions. However, all composting practices, including covered composting, may induce nitrification and potential denitrification to N_2, offsetting some benefits. Challenges include maintaining optimal aeration to prevent prolonged anaerobic conditions and the associated production of malodorous and greenhouse gas by-products.

6.5 Summary table of measures for better nitrogen management of wastewater and solid organic waste

The following table offers a concise overview of these measures.

Table 6.1 Measures for better N management of wastewater and solid organic waste. The 'impact' on N emissions (i.e., 1 = large reduction, 2 = medium reduction, 3 = small reduction, 4 = potential increase and X = unclear or unknown effect), 'reliability' and 'technological requirement' (i.e., expertise and/or specialized equipment) are indicated for each measure. See Box 1.1 for further details on these indicators. For further guidance on implementation, efficiency and the cost, risks and benefits of implementing measures, see the INMS Nitrogen Measures Database – www.inms.international/measures.

Measure sub-cateogory	Measure reference and name		Net effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Technical Rqmt
Biological removal of nitrogen from wastewaters	O1	Conventional nitrification/ denitrification	2	x	x	x	1	4	Robust	High
	O2	Anaerobic ammonium oxidation (anammox)	2	x	x	x	1	4	Robust	High
	O3	Completely autotrophic nitrogen removal over nitrite (CANON)	2	x	x	x	1	4	Robust	High
	O4	Simultaneous nitrification and denitrification	2	x	x	x	1	4	Robust	High
	O5	Shortcut/partial nitrification and denitrification	2	x	x	x	1	4	Robust	High
	O6	Oxygen-limited autotrophic nitrification-denitrification (OLAND) processes	2	x	x	x	1	4	Robust	High
	O7	Aerobic dammonification	2	x	x	x	1	4	Robust	High

Measure sub-category	Measure reference and name		Net effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Technical Rqmt
Physicochemical removal/recovery of nitrogen from wastewaters and organic residues	O8	Struvite precipitation from wastewater	1	2	x	x	1	4	Robust	High
	O9	Ammonia stripping and acid absorption from wastewater	1	1	x	x	1	4	Robust	High
	O10	Bio-drying sludge with acid scrubbing of exhaust air	3	2	4	4	x	3	Robust	High
	O11	Physical adsorption of nitrogen from wastewaters	2	x	x	x	2	x	Robust	High
	O12	Membrane systems for treatment of nitrogen in wastewaters	1	x	x	x	1	x	Robust	High
	O13	Thermal stripping with nitrogen recapture from wastewaters	1	1	x	x	1	x	Robust	High
	O14	Electrocoagulation systems for treatment of nitrogen in wastewaters	1	1	x	x	1	x	Robust	High
	O15	Electrodialysis systems for treatment of nitrogen in wastewaters	2	2	x	x	2	x	Robust	High
Biological removal/recovery of nitrogen from wastewaters and organic residues	O16	Microbial fuel cell for wastewater treatment	2	x	x	x	2	x	Robust	High
	O17	Microbial electrolysis cell for wastewater treatment	2	x	x	x	2	x	Robust	High
	O18	Bio-electrodialysis for wastewater treatment	1	x	x	x	1	x	Robust	High
	O19	Membrane bioreactors for wastewater treatment	1	x	x	x	1	x	Robust	High
	O20	Phototrophic bacteria and microalgae systems for wastewater treatment	1	1	x	x	1	x	Robust	Intermediate
	O21	Anaerobic digestion of solid organic residues	2	2	x	x	2	x	Robust	High
	O22	Covered composting of solid organic residues	2	2	x	x	2	x	Promising	Basic

7

Key actions for better nitrogen management in aquaculture

7.1 Overview of nitrogen management in aquaculture

Nitrogen from excreted organic matter, fish waste, and uneaten feed can accumulate in aquaculture systems (Figure 7.1), and if not managed appropriately, can lead to water quality issues such as eutrophication, oxygen depletion and harmful algal blooms (Luo et al., 2018). Globally, aquaculture is contributing to a net increase in nutrient loading, which equates to approximately 0.9% of anthropogenic inputs to the global N cycle (Verdegem, 2013). Inefficiencies of N use occur at multiple levels within aquaculture production systems, stemming from the use of wild-caught fish to produce farmed fish; on average, 1.9 kg of wild fish are used to produce 1 kg of farmed fish (Naylor et al., 2000). The use of crude formulated feed can result in elevated levels of NH_4^+ excretion. The accumulation of 'total ammonia N' (e.g., NH_4^+ and NH_3 in water), is a major fish mortality risk in intensive aquaculture; NH_3 concentrations in water >1.5 mg L^{-1} are toxic to marine organisms (Avnimelech, 1999; Crab et al., 2007). Due to this toxicity, currently, N management in aquaculture is focused on NH_4^+ removal.

Measures that address nitrogen management in aquaculture (Table 6.1) are grouped into:

i) optimizing N inputs to aquaculture systems which must involve regular water quality monitoring to guide appropriate management action.

ii) biofiltration of aquaculture discharge waters and other N removal approaches,

iii) aquaculture with recovery of N into living biomass, and

iv) aquaculture sludge management measures.

It is important to note that N management practices in aquaculture may vary depending on the type of aquaculture system, the species being cultured and local environmental regulations. It should be noted that some aquaculture systems not only include feed inputs but also fertilizer inputs which are directly added to waterbodies. Such fertilizer inputs to waters are intended to stimulate algal growth as food for fish, and crustacean (e.g., prawns), but obviously risk pollution especially where used intensively.

While the following sections provide brief summaries, more detailed descriptions including access to relevant literature are provided in the INMS Nitrogen Measures Database.

7.2 Optimizing nitrogen inputs to aquaculture systems

Monitoring of water quality parameters including total ammonia N, NO_2^- and NO_3^- and organic N levels should be conducted regularly to identify potential pollution issues and guide appropriate management actions. Nutrient budgeting should be carried out to support the optimization of feed and fertilizer inputs to match the nutrient requirements of the cultured species and minimise excess nutrient accumulation. Adjusting the crude protein content in fish diets to closely match their growth needs, and following careful feeding practices to avoid losses, can help minimise excess feed and nutrient waste.

An overview of measures to optimize N inputs to aquaculture systems is provided below.

Measure	**Impact**						**Reliability**	**Tech. rqmt**
	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
Q1 Regular water quality monitoring	1	2	2	2	1	1	Robust	High

Water quality parameters such as NH_3/NH_4+, NO_2-, and NO_3 – levels can help identify potential Nr pollution issues and guide appropriate management actions. Monitoring can be done using on-site testing kits or by sending water samples to a laboratory for analysis. As a result of monitoring better informed discussions can be made on the amount of nutrients to be added to aquaculture systems.

Measure	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
Q2 Nutrient budgeting in aquaculture systems	1	2	2	2	1	1	Robust	High

Keeping track of nutrient inputs and outputs in an aquaculture system can help optimize nutrient management. This involves estimating the nutrient inputs from feed, fertilizers and other sources, as well as quantifying the nutrient outputs through harvest, water exchange and sediment removal. By maintaining a nutrient budget, aquaculturists can adjust feed and fertilizer inputs to match the nutrient requirements of the cultured species, minimising excess nutrient accumulation.

Measure	Impact						Reliability	Tech. rqmt
	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
Q3 Optimize protein intake of farmed aquatic species	1	2	2	2	1	1	Robust	Intermediate

Adjusting the crude protein content in fish diets to closely match their growth needs is an efficient measure to mitigate N emissions. Feeding measures include formulating diets based on digestible/available nutrients, using low-protein amino acid-supplemented diets and feed additives/supplements.

Measure	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
Q4 Minimise excess aquaculture feed and feed loss	1	2	2	2	1	1	Robust	Intermediate

Careful feeding practices can help minimise excess feed and nutrient waste, reducing the potential for N pollution. Avoid overfeeding and adjust feeding rates based on the nutritional needs of the cultured species, growth rates and environmental conditions. Using formulated feeds that are highly digestible and have optimised nutrient content can also help reduce nutrient discharge and waste of nutrients.

7.3 Biofiltration of aquaculture discharge waters and other nutrient removal approaches

The intensification of land-based aquaculture systems has been accompanied by technological developments to deal with the increasing quantities of total ammonia N. In conventional recirculating aquaculture systems (RAS), fixed-film biological filtration systems, such as trickling filters, bead filters or fluidised sand biofilters, provide a high-surface area for colonisation of chemolithotrophic bacteria which mediate the stepwise conversion of NH_4+, to NO_2^- and then to NO_3^- (Badiola et al., 2012; Ebeling et al., 2006). Rotating biological contactors operate on a similar principle but utilise a series of rotating discs for wastewater contact with a biological film. However, these methods often result in water discharge with elevated NO_3^- levels. To address this, RAS technologies incorporate denitrifying filters to convert NO_3^- to N_2 (Tal et al., 2006; J van Rijn et al., 2006). Additionally, prototype 'anammox' filters (i.e., anaerobic ammonium oxidation mediated by bacteria) hold the potential to convert NH_4+ to N_2 (albeit wasting a N_r resource), but have not yet been widely adopted for commercial use (Espinal and Matulić, 2019).

The following text presents a summary of measures that accomplish the biofiltration of discharge waters from aquaculture.

Measure	Impact						Reliability	Tech. rqmt
	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
Q5 Conventional recirculating aquaculture systems (nitrification only)	2	1	x	x	4	4	Robust	High

Conventional recirculating aquaculture systems (RAS) rely on mechanical filters for solids removal and the supply of oxygen to fixed-film biological filtration systems where chemolithotrophic bacteria mediate the stepwise conversion of NH_4^+ to NO_2^- and NO_3^- with the main aim of minimising the toxic effects of NH_3 in water. A range of different biological filters are used to reduce NH_3 discharge from waters. The most commonly used are trickling filters and bead filters, which provide a high-surface area for colonisation by ammonia-oxidising and nitrite-oxidising bacteria, while more technical systems employ fluidised sand biofilters. Use of chemolithotrophic bacteria in biological filters results in the production of high NO_3^- levels produced by nitrite-oxidising bacteria, in the final step of nitrification. A disadvantage of this approach is that it releases a substantial amount of NO_3^- to the environment which is both polluting and a waste of N_r resources.

Measure	Impact: Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
Q6 Rotating biological contactors (nitrification only)	2	1	x	x	4	4	Robust	High

Rotating Biological Contactors (RBCs) facilitate nitrification in wastewater treatment by providing a surface for the attachment and growth of bacteria. The rotating discs create an environment conducive to the formation of a biological film, supporting the conversion of NH_3 to NO_3^-. The continuous rotation optimizes microbial activity, enhancing the efficiency of the nitrification process. Through this mechanism, RBCs effectively reduce the presence of NH_3 in wastewater, contributing to N removal before discharge and aligning with environmental standards for water quality. As with W6, a disadvantage of this approach is the release of NO_3^- to the aquatic environment and waste of Nr resources.

Measure	Impact: Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
Q7 Recirculating aquaculture systems with integrated denitrifying filters	2	1	4	4	2	4	Robust	High

So called 'next-generation' recirculating aquaculture systems (RAS) technologies focus on reducing water usage from <1 to <0.01 m3 water kg-1 feed by incorporating further N transformation pathways. These pathways aim to eliminate NO_3^- produced from nitrification in biological filters by denitrification to N_2. Current developments integrate filtration systems for denitrification and anaerobic oxidation of NH_3 (anammox), aiming to convert NH_4^+ to N_2. Denitrifying filters use organic C sources, like methanol or aquaculture sludge, while this approach reduces NO_3^- pollution it lacks N recovery, thereby wasting valuable Nr resources. Anammox, performed by bacteria like Kuenenia stuttgartiensis, offers a cost-efficient alternative, saving 90% of operational costs by eliminating the need for additional C sources and producing less sludge. Though successful in prototypes, widespread adoption by commercial RAS companies is pending.

7.4 Aquaculture with recovery of nitrogen into living biomass

Ecologically based systems are designed to resemble natural aquatic environments that recycle nutrients through the food web. Microbial-based systems and integrated multi-trophic aquaculture (IMTA) are increasingly widespread. Aquaculture bioremediation technologies, such as proteinaceous bio-flocs technology (Avnimelech, 2014, 1999), aquaponics (Wongkiew et al., 2021) and periphyton treatment techniques (Azim et al., 2005; Martínez-Córdova et al., 2015), can be utilised for the in-situ removal of particulate suspended and dissolved inorganic nutrients. The emphasis is on the direct assimilation and recycling of residues/wastes by economically valuable extractive species, which can be harvested as secondary organisms, thus resulting in a net export of nutrients from the system. In flow-through systems with high exchange rates, such as tank-based abalone farming (Robertson-Andersson et al., 2009), integrated cultivation of seaweed species such as Ulva and Gracilaria in effluent waters has been successful in reducing the discharge of NH_4+ (Macchiavello and Bulboa, 2014). The seaweeds can be harvested and fed to the culture species, increasing N recovery and protein production. Microalgae bioreactors can be used as an effective measure to recover dissolved inorganic N from freshwater and marine aquaculture systems with removal rates of ~90% for NH_4-N and 75%-90% for total N under experimental conditions (Tossavainen et al., 2019).

The following text provides a summary of aquaculture systems that enable the conversion of N into living biomass.

Measure	**Impact**						**Reliability**	**Tech. rqmt**
	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
Q8 Periphyton treatment technique	1	1	2	2	1	1	Robust	Intermediate

Periphyton-based aquaculture involves the creation of additional submerged structures (e.g., mesh, stakes, etc.) within ponds or tanks to encourage the proliferation attached biota known as periphyton. Periphyton is a diverse community of bacteria, microalgae, macroalgae, cyanobacteria, protozoa, fungi, zooplankton and other aquatic invertebrates with the ability to assimilation nutrients into biomass, which can be consumed by the culture organism and reduce feed inputs. Periphyton has an assimilation capacity of ~ 0.2 g N m2 day-1, a yield of 4g dry matter m-2 and a protein content of 25% dry matter. Since large surface areas are required for periphyton development, this measure is suited to extensive and semi-intensive aquaculture for pond production of freshwater, brackish and marine finfish and invertebrate species such as Indian major carps, tilapia and prawns.

Measure **Impact** **Reliability** **Tech. rqmt**

Q9 Macroalgal systems

Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
1	1	2	2	1	1	Robust	Intermediate

In land-based marine aquaculture, cultivation of macroalgae can be used as a measure to reduce levels of Nr in discharge waters in a range of land-based aquaculture production systems. In flow-through systems with high exchange rates, such as tank-based abalone farming, integrated cultivation of seaweed species such as Ulva and Gracilaria in effluent waters has been successful in reducing the N concentration in discharge waters. The seaweeds can be harvested and fed to the culture species, increasing N recovery and protein production in a sustainable and circular way. Similarly, IMTA systems that include macroalgae cultivation have also been integrated into RAS systems to assimilate NO_3-produced during biological filtration by diverting nitrate-rich effluent water from daily water exchanges (1%-10%) through seaweed cultivation ponds.

Q10 Microalgal bioreactors

Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
1	1	2	2	1	1	Robust	High

Microalgae bioreactors provide a promising solution for improving N sustainability in freshwater and marine aquaculture. With reported removal rates of around 90% for NH_4-N and 75%-90% for total N under experimental conditions, these bioreactors demonstrate operational efficiency. The harvested microalgal biomass serves as a valuable resource, offering nutrient-rich aquaculture feed and the potential for extracting essential omega-3 fatty acids like eicosapentaenoic acid and docosahexaenoic acid. This utilisation not only supports a closed-loop system in aquaculture but also offers a sustainable alternative to conventional fish oils, addressing concerns related to overfishing and contributing to the overall ecological sustainability of aquaculture operations.

Q11 Aquaponics

Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
1	1	2	2	1	1	Robust	High

Aquaponics, a soilless technology, enhances N sustainability by interconnecting organic vegetable production with the remediation of freshwater aquaculture effluent. In this system, the uneaten feed, faeces and excretion products of fish serve as a valuable N source for plant growth. The symbiotic relationship between aquaculture and agriculture in aquaponics not only promotes efficient N recycling but also minimises the environmental impact of aquaculture effluent. This innovative approach aligns with sustainable N management practices, creating a closed-loop system that harmonises fish farming and plant cultivation, emphasising resource efficiency and ecological balance.

Measure	Impact						Reliability	Tech. rqmt
	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
Q12 Proteinaceous bio-flocs technology	1	1	2	2	1	1	Robust	Hgih

Minimal or zero exchange aquaculture technologies (<1 % water exchange) have shifted towards exploiting heterotrophic pathways for the in-situ treatment of inorganic N. The technique relies on promoting the in-situ proliferation of microorganisms to recycle and transform excess nutrients into biomass, which can be consumed by the culture organism. In biofloc technologies, labile organic C sources are added directly to the culture tanks to induce microbial protein synthesis via the heterotrophic bacterial conversion of NH_4^+ directly to microbial biomass. Substrates, such as wheat bran, are added to promote the development of microbial flocs, while strong aeration is provided to maintain the suspension of dense microbial flocs in the water column.

	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
Q13 Integrated multi-trophic aquaculture	1	1	2	2	1	1	Robust	Intermediate

Typically, IMTA systems combine an aquaculture species that requires external feeding (e.g., finfish) with ‘extractive’ species capable of deriving nutrients from the wastes of the ‘fed’ species. Integrated multi-trophic aquaculture is a measure that can be equally applied to the culture of finfish or crustaceans in coastal lagoons and bays and land-based systems such as ponds and tanks in flow-through or recirculating aquaculture systems.

7.5 Aquaculture sludge management measures

Intensive land-based aquaculture is raising particulate residues (e.g., slowly biodegradable dissolved organic particles) in waterbodies. Next-generation recirculating aquaculture system (RAS) and zero exchange biofloc technologies contribute to this increase with heterotrophic bacterial biomass, necessitating removal and disposal (Martins et al., 2010; Turcios and Papenbrock, 2014). The accumulation of sludge, together with the economic cost of removal and disposal, is a major constraint to the future development of land-based intensive aquaculture systems. Given the limited downstream options for sludge remediation, the majority of sludge recovered from land-based aquaculture is disposed to landfill, municipal sewers or, in the absence of stringent discharge limits, discharged to the marine environment (Cripps and Bergheim, 2000; Summerfelt et al., 1999; Jaap van Rijn et al., 2006).

Five management measures that include N recovery from sludge include: i) constructed wetlands (Zhong et al., 2011), ii) application to land as a fertilizer (van Rijn, 2013), iii) composting (with appropriate storage to avoid N losses) (Koyama et al., 2018), iv) cultivation of deposit feeders including polychaete worms (Bischoff, 2012; Brown et al., 2011) and sea cucumbers (Robinson et al., 2019) in marine aquaculture systems and earthworms in freshwater aquaculture systems and v) anaerobic digestion (Mirzoyan and Gross, 2013).

An overview of aquaculture sludge management measures is provided below.

Measure	**Impact**						**Reliability**	**Tech. rqmt**
	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
Q14 Constructed wetlands to treat aquaculture sludge	1	1	x	2	1	x	Robust	Intermediate

Constructed wetlands represent ecologically-driven systems initially designed for wastewater treatment, now successfully employed in freshwater aquaculture to manage both wastewater and sludge. Capitalizing on the high C content of plants, constructed wetlands facilitate the assimilation of reactive N species, including NH_3 and NO_3^-, into plant-based biomass. This application of constructed wetlands technology serves as a strategic management measure, effectively mitigating discharges of total suspended solids and NH_3 in flow-through freshwater aquaculture systems. By leveraging natural processes, constructed wetlands contribute to the sustainable treatment of aquaculture effluents, aligning with environmentally friendly practices in N management.

Measure	**Impact**						**Reliability**	**Tech. rqmt**
	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
Q15 Application of aquaculture sludge to land as a fertilizer	1	2	2	2	1	1	Robust	Intermediate

In freshwater RAS, sludge can be applied directly to crops, however saline sludge was previously considered to be unsuitable for agricultural applications due to the high salt content leading to scorching. Advances in flocculation and de-watering technologies, are being successfully used to increase the dry matter content so that sludge from marine RAS can be successfully applied to land as a fertilizer. In this context, farmers receive dual economic benefits from payments to collect and transport the sludge in addition to savings in fertilizer costs. This is an effective sustainable N management measure both in terms of N recovery and reducing the use of chemical fertilizers.

	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
Q16 Composting aquaculture sludge (with proper storage)	1	2	2	2	1	1	Promising	Basic

Composting of aquaculture sludge, through windrow composting, is an effective measure to recover of waste N (49%-64%) and convert it into nutrient rich compost that can replace agricultural fertilizers. Composting of organic rich sediments from aquaculture ponds, in conjunction with C sources such as wheat straw, grass and biochar to increase the C to N ratio is also being tested for agricultural application to enhance plant growth. As described for the management of manure, appropriate storage (e.g., covers and drainage controls) is necessary to avoid NH_3 emissions and N leaching.

	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
Q17 Cultivation of deposit feeders to process aquaculture sludge	1	1	2	2	1	1	Robust	Intermediate

Deposit feeders, such as polychaete worms in marine aquaculture and earthworms in freshwater settings, play a pivotal role in efficiently managing aquaculture waste—comprising uneaten feed and faecal material—by transforming it into valuable biomass. Their dual capacity for thriving on and recycling waste highlights their significance for ecological and economic sustainability. A noteworthy strategy involves converting waste nitrogen into alternative protein sources, presenting a novel approach to closing the N cycle loop in aquaculture. This not only addresses environmental concerns related to nutrient discharge but also enhances the sustainability of livestock feeds, marking a crucial step towards a circular and efficient aquaculture system with a specific focus on N management.

Measure	Impact: Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
Q18 Anaerobic digestion of aquaculture sludge	1	1	2	2	1	1	Robust	High

Anaerobic digesters are developed to extract biogas from sludge for sustainable energy and reduced solid waste. While effective for low-salinity waste, their use with saline sludge in marine Recirculating Aquaculture Systems (RASs) is hindered by high salt content. Saline waste discharge poses environmental risks, causing soil and water salinisation. The expanding production of salty waste in brackish and marine aquaculture necessitates managing its impact on water resources. In controlled RASs, 25%-50% of fish feed accumulates as sludge, comparable to a mid-sized town's waste volume. Current disposal methods face limitations due to high sludge salinity, leading to soil and water salinisation. To address this, feasible treatment methods, including anaerobic digestion, are crucial for managing the negative impact of saline effluent release and promoting sustainability in aquaculture waste management.

7.6 Summary table of measures to improve nitrogen management in aquaculture

The following table offers a concise overview of these measures.

Table 7.1 Measures for better N management in aquaculture. The 'impact' on N emissions (i.e., 1 = large reduction, 2 = medium reduction, 3 = small reduction, 4 = potential increase and X = unclear or unknown effect), 'reliability' and 'technological requirement' (i.e., expertise and/or specialized equipment) are indicated for each measure. See Box 1.1 for further details on these indicators. For further guidance on implementation, efficiency and the cost, risks and benefits of implementing measures, see the INMS Nitrogen Measures Database – www.inms.international/measures.

Measure sub-cateogory	Measure reference and name	Net effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Technical Rqmt
Optimising nitrogen inputs to aquaculture systems	Q1 Regular water quality monitoring	1	2	2	2	1	1	Robust	High
	Q2 Nutrient budgeting in aquaculture systems	1	2	2	2	1	1	Robust	High
	Q3 Optimise protein intake of farmed aquatic species	1	2	2	2	1	1	Robust	Intermediate
	Q4 Minimise excess aquaculture feed and feed loss	1	2	2	2	1	1	Robust	Intermediate
Biofiltration of aquaculture discharge waters and other nutrient removal approaches	Q5 Conventional recirculating aquaculture systems (nitrification only)	2	1	x	x	4	4	Robust	High
	Q6 Rotating biological contractors (nitrification only)	2	1	x	x	4	4	Robust	High
	Q7 Recirculating aquaculture systems with integrated denitrifying filters	2	1	4	4	2	4	Robust	High
Aquaculture with recovery of nitrogen into living biomass	Q8 Periphyton treatment technique	1	1	2	2	1	1	Robust	Intermediate
	Q9 Macroalgal systems	1	1	2	2	1	1	Robust	Intermediate
	Q10 Microalgal bioreactors	1	1	2	2	1	1	Robust	High
	Q11 Aquaponics	1	1	2	2	1	1	Robust	High
	Q12 Proteinaceous bio-flocs technology	1	1	2	2	1	1	Robust	High
	Q13 Integrated multi-trophic aquaculture	1	1	2	2	1	1	Robust	Intermediate
Aquaculture sludge management	Q14 Constructed wetlands to treat aquaculture sludge	1	1	x	2	1	x	Robust	Intermediate
	Q15 Application of aquaculture sludge to land as a fertilizer	1	2	2	2	1	1	Robust	Intermediate
	Q16 Composting aquaculture sludge (with proper storage)	1	2	2	2	1	1	Robust	Basic
	Q17 Cultivation of deposit feeders to process aquaculture sludge	1	1	2	2	1	1	Robust	Intermediate
	Q18 Anaerobic digestion of aquaculture sludge	1	1	2	2	1	1	Robust	High

8

Key actions for better nitrogen management by optimizing societal demand

8.1 Overview of nitrogen management by optimizing societal demand

The role that consumers play in the N cycle is often overlooked. Optimizing societal demand to support sustainable N management requires integrated actions across different scales because patterns of food consumption, demand for non-food agricultural products (e.g., cotton, wool, silk, hide and skin) and waste production stem from decisions and actions of policymakers, institutions (e.g., schools, hospitals), businesses (e.g., food processors, supermarkets and restaurants), individuals and households (Figure 8.1). They occur in the context of local to global policies, infrastructure and culture. Agricultural N demand can be optimized by increasing the uptake of healthy diets with low N footprints and reducing food waste and curtailing demand for non-food agricultural products, thereby offering integrated opportunities to reduce all forms of N losses simultaneously (Leip et al., 2023; Oenema et al., 2009; Quemada et al., 2020) (Table 8.1).

While the following sections provide brief summaries, more detailed descriptions including access to relevant literature are provided in the INMS Nitrogen Measures Database.

8.2 Measures to optimize agricultural nitrogen demand

Reducing food loss (after harvest and during processing) and domestic food waste would improve the efficiency of the overall food supply chain. It has been estimated that globally, 23% of the nutrients in fertilizers are used to produce agricultural products that are lost during production, distribution, processing and consumption (Kummu et al., 2012). While large amounts of food waste in Asia can be attributed to the large population, food waste is much higher on a per-capita basis in higher-income countries than in lower-income countries (Kummu et al., 2012). Consumers in Europe and North America waste an estimated 95-115 kg cap^{-1} yr^{-1} of food, in contrast to only 6-11 kg cap^{-1} yr^{-1} in Sub-Saharan Africa and South/Southeast Asia (Gustavsson et al., 2011). The amount of food wasted at each stage, from farm to fork, also differs among regions. Typically, lower-income countries have more food losses before products reach consumers because of food storage issues, while higher-income nations tend to waste more food in retail and home settings (Parfitt et al., 2010). Therefore, interventions to reduce food waste across regions may differ significantly.

In addition to opportunities to reduce food loss/food waste, lowering the global consumption of animal products will significantly reduce N demands. Plant-based foods have relatively low losses and lower N footprints, whilst livestock products have much higher losses, e.g., N losses per unit of food protein from beef are >25 times that of cereals (Westhoek et al., 2015). For meat and dairy products, NUE is between 5%-30%, compared with 45%-75% for plant commodities (Westhoek et al., 2015). In the EU, a 50% reduction in livestock product consumption and production was estimated to reduce current European NH3 emissions by 40%, N_2O emissions by 24% and NO_3^- emissions by 29% (Westhoek et al., 2015).

While many people remain underfed in other world regions, high levels of consumption put undue pressure on N and other forms of pollution. There are major benefits of avoiding excessive consumption of animal products for human health (e.g., within World Health Organization guidelines for saturated fats), climate and the environment. Market, education and policy measures that can address the barriers to change should be further investigated.

The following text presents an overview of measures to optimize agricultural N demand.

Measure	Impact						Reliability	Tech. rqmt
	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
S1 Reduce food loss and food processing waste	1	1	1	1	1	1	Robust	Basic

Reducing post-harvest food loss and food processing waste is vital for optimizing the food supply chain. Unlike domestic food waste, this pertains to losses during food storage and industrial processes. Processing wastes rich in organic matter, can be a source of NH3 emissions which are lost during decomposition. Implementing waste reduction strategies in the food industry can cut N emissions, offering environmental benefits. Challenges include altering industrial practices to minimise waste generation.

Measure	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
S2 Reducing domestic food waste	1	1	1	1	1	1	Robust	Basic

Reducing domestic food waste is pivotal in enhancing the efficiency of the food supply chain, mitigating losses incurred during production, distribution, processing and consumption. This reduction not only conserves resources but also positively impacts N management. Food waste, rich in organic matter, contributes to N loads in landfills as it decomposes, leading to the release of N species like NH3. Implementing food waste reduction measures can reduce N emissions, benefiting the environment. Challenges involve changing consumer behaviour and implementing effective waste reduction strategies.

Measure	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
S3 Reduce consumption of foods with high nitrogen footprints	1	1	1	1	1	1	Robust	Intermediate

Reducing the consumption of food items with high N footprints offer a major opportunity to optimize NUE and mitigate N and phosphorus pollution. This approach, emphasising adherence to recommended dietary guidelines such as those by the World Health Organization, can support reductions in N emissions across the whole food production chain. Benefits include improved NUE, decreased N and phosphorus pollution and positive effects on both human health and the environment.

8.3 Summary table of measures to deliver better nitrogen management by optimizing societal demand

The following table offers a concise overview of these measures.

Table 8.1 Measures to optimize societal N demand. The 'impact' on N emissions (i.e., 1 = large reduction, 2 = medium reduction, 3 = small reduction, 4 = potential increase and X = unclear or unknown effect), 'reliability' and 'technological requirement' (i.e., expertise and/or specialized equipment) are indicated for each measure. See Box 1.1 for further details on these indicators. For further guidance on implementation, efficiency and the cost, risks and benefits of implementing measures, see the INMS Nitrogen Measures Database – www.inms.international/measures.

Measure sub-cateogory	Measure reference and name		Net effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Technical Rqmt
Measures to optimise agricultural nitrogen demand	S1	Reducing domestic food waste	1	1	1	1	1	1	Robust	Basic
	S2	Reduce food processing waste	1	1	1	1	1	1	Robust	Basic
	S3	Reduce consumption of foods with high nitrogen footprints	1	1	1	1	1	1	Robust	Intermediate

9

Key actions for better nitrogen management related to fuel combustion

9.1 Overview nitrogen management related to fuel combustion

Burning fuels produces a significant additional N_r resource that could be captured and used but is currently wasted as emissions of NO_x to air (Figure 9.1). This contributes to particulate matter and ground-level (tropospheric) ozone that adversely affects human health, ecosystems and food production systems. Globally, transportation, electricity and industry are estimated to contribute 81% of NO_x emissions, with the transportation sector alone responsible for over 40% (Shaw and Van Heyst, 2022). Here, we focus on reducing NO_x emissions from combustion. However, we highlight NO_x emissions produced by soil microbes in cropland soils are potentially globally significant (Almaraz et al., 2018).

Measures to reduce NO_x from soils are integrated into the chapters on crops and forestry (Chapter 3). During combustion, NO_x are formed by three key mechanisms (US EPA, 1999).

i) Firstly, thermal NO_x, which results from the reaction of N and oxygen in the air, especially at high temperatures (e.g., combustion of gaseous or liquid fuels at >1300 °C).

ii) Secondly, fuel NO_x, the reaction products of fuel-bound N (usually N-C or N-H compounds). Fuels with higher N content (e.g., coal and peat) typically produce more NO_x during combustion than lower N content fuels (natural gas).

iii) Thirdly, prompt NO_x occurs at the flame front in rich fuel-air ratios where oxidised CH-radicals react with N_2, contributing the smallest share of NO_x emissions.

The flame temperature, the retention time (of fuel at peak temperature) and the fuel-air ratio determine the amount of NO_X generated during combustion. Measures beyond energy efficiency improvements and switching to low N fuels aim to address these factors, reducing NO_X generation, whilst 'end of pipe' measures remove or recover NO_X already formed in the flue gas (e.g., using catalysts etc.). Here, we focus on NO_X control measures applied in the combustion of fossil fuels in power stations and mobile vehicles and processes used in the chemical industry. Measures (see Table 9.1) are grouped into:

i) primary measures to reduce NO_X generation,

ii) end-of-pipe measures to reduce/recover/abate NO_X emissions,

iii) NO_X removal from automobile emissions,

iv) N recovery from industrial gas emissions, and

v) broad (non-technical) measures to reduce the demand for fuel combustion, through behavioural/infrastructural change.

While the following sections provide brief summaries, more detailed descriptions including access to relevant literature are provided in the INMS Nitrogen Measures Database.

9.2 Primary measures to reduce NOx generation

Reducing the available N in combustion will limit NO_X formation and can be achieved by switching from high N content fuels (e.g., oil and coal) to N-poor fuels like natural gas, as well as by using adequate oxygen content in combustion air. However, it should be noted that hydrogen-rich fuels (e.g., natural gas) can lead to high thermal NO_X formation at high combustion temperatures. A range of processes can remove N from fuels, including hydrotreating, liquid–liquid phase partitioning, adsorption, solvent deasphalting and chemical conversion followed by separation and microbial conversion. However, most are not economically feasible for commercial use (Prado et al., 2016).

Reducing peak combustion temperature can reduce thermal NO_X formation, by disrupting the stoichiometric ratio (e.g. the ideal proportion of fuel to air required for complete combustion) (US EPA, 1999). Combustion temperature may be reduced by: i) using fuel-rich mixtures to limit oxygen, ii) using fuel-lean mixtures to limit temperature by diluting energy input, iii) injecting cooled oxygen-depleted flue gas into the combustion air to dilute energy, iv) injecting cooled flue gas with added fuel, or v) injecting water or steam (Anufriev, 2021; Krishnamoorthi et al., 2019; Skalska et al., 2010).

Reducing fuel residence time at high temperatures will also reduce NO_x formation. This can be achieved by injection of fuel, steam, re-circulated flue gas or combustion air immediately after combustion, or by restricting the flame to a short region in which the combustion air becomes flue gas (Elbaz et al., 2019; Sindhu et al., 2018). Nitrogen oxides can also be reduced (to N2) during combustion, using a reducing agent. Examples include reduction aided by catalysts (Irfan et al., 2008), re-burning of the flue gas with fuel added and the generation of fuel-lean and fuel-rich conditions in the combustion zone (US EPA, 1999). Additionally, non-thermal plasma, when used with a reducing agent, can reduce NO_x (Talebizadeh et al., 2014).

Alternatively, NO_x can be oxidised and then absorbed in an aqueous alkaline solution to first form dilute nitric acid and then NO_3^- salts (US EPA, 1999), so turning NO_x into non-air polluting substances. This can be achieved using a range of catalysts, injecting hydrogen peroxide, creating ozone within the airflow, or injecting ozone into the airflow (US EPA, 1999). However, in this case, while NO_x is reduced, ozone (another pollutant regulated under the Gothenburg Protocol) is generated. Non-thermal plasma can be used to oxidise NO_x in engine exhausts (Bröer and Hammer, 2000; Talebizadeh et al., 2014) and air scrubbers used to absorb dinitrogen pentoxide (N_2O_5) emissions, allowing N recovery (US EPA, 1999).

The following primary measures are based on the principles described above. These measures may not apply to all industries and processes and are usually used in combination.

Measure	Impact						Reliability	Tech. rqmt
	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
F1 Switching to low NO_x producing fuels	3	x	x	2	x	x	Promising	High

Fuels with high N content like heavy fuel oil and coal may lead to high fuel NO_x formation and hydrogen-rich fuels like natural gas as a result of high combustion temperatures to high thermal NO_x formation. The choice of the fuel may also have adverse effects on other emissions like sulphur, particulate matter and greenhouse gas emissions, as well as on applicability and need of abatement measures.

Measure **Impact** **Reliability** **Tech. rqmt**

F2 Fuel cleaning to remove nitrogen compounds from fuels

Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
3	x	x	2	x	x	Promising	High

Extracting N-containing compounds from oil and its fractions can minimise N emissions when they undergo combustion. Various denitrogenation methods involve separating N-rich products from oil without altering the N compounds. However, these processes are generally suitable for low-N content oils (<0.1 wt % N). Hydrodenitrogenation is currently the only industrially viable method for oils with high N content. Although fuel cleaning for N removal is not yet commercially feasible, hydroprocessing in refineries effectively reduces the N content in the end products.

F3 Low excess air combustion

Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
1	x	x	1	x	x	Robust	High

Low excess air combustion is a method optimizing the air-to-fuel ratio during combustion processes to enhance fuel efficiency and minimise NO_x emissions. This technique aims to reduce the surplus oxygen in the combustion chamber, thereby limiting the formation of NO_x. By controlling NO_x, low excess air combustion mitigates environmental pollution. Benefits include improved combustion efficiency and lower NO_x emissions. Challenges involve precise control of air-fuel ratios and potential combustion instability. Implementation requires advanced control systems.

F4 Air staging (in combustion systems)

Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
1	x	x	2	x	x	Robsut	High

Air staging in combustion systems involves creating two distinct zones: a fuel-rich zone for initial combustion and a second zone where air is introduced to ensure complete combustion. This strategy minimises thermal NO_x formation by reducing N availability in the first zone and lowering temperatures in the second. Implementation methods include varying air and fuel flow rates in 'Biased Burner Firing', temporarily cutting fuel flow in 'Burners Out of Service', and injecting air above the usual combustion zone in 'Overfire Air' (US EPA, 1999). Staged air combustion, often combined with Low NO_x burners, offers a scientific approach to enhance combustion efficiency, reduce NO_x emissions and optimize N management in combustion processes.

Measure	Impact						Reliability	Tech. rqmt
	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
F5 Fuel staging (in combustion systems)	1	x	x	1	x	x	Robust	High

Fuel staging in combustion systems mirrors air staging but focuses on fuel manipulation. The initial stage involves an extremely fuel-lean environment, lowering the temperature. Subsequent fuel injection acts as a reducing agent for formed NO_X. In a third stage, air is introduced to ensure complete burnout. This method strategically manages fuel combustion to mitigate NO_X formation. Implementing fuel staging involves precise control of fuel injection rates. Benefits include reduced NO_X emissions and improved combustion efficiency.

Measure	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
F6 Fuel re-burning (in combustion systems)	3	x	x	2	x	x	Promising	High

Fuel re-burning in combustion systems is akin to flue gas recirculation, involving the introduction of additional fuel into the flue gas to lower temperatures. When implemented in a second combustion stage, fuel re-burning utilises the added fuel as a reducing agent, resembling the principles of fuel staging. This approach strategically manages combustion by lowering temperatures and employing the added fuel for NO_X reduction.h

Measure	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
F7 Flue gas recirculation (in combustion systems)	3	x	x	2	x	x	Promising	High

Flue gas recirculation in combustion systems involves reintroducing cooled flue gas into a secondary combustion stage, thereby lowering the combustion temperature and oxygen concentration. This reduction in oxygen concentration helps mitigate thermal NO_X formation. Additionally, the heat from the recirculated flue gas can be recovered using a heat exchanger. Implementation of flue gas recirculation requires precise control over the recirculation rate. Benefits include decreased NO_X emissions and improved combustion efficiency.

Measure	Impact						Reliability	Tech. rqmt
	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
F8 Reduced air preheat (in combustion systems)	2	x	x	2	x	x	Robust	High

Reduced air preheat in combustion systems involves minimising the preheating of combustion air by flue gases. Typically, combustion air is preheated to enhance efficiency by cooling flue gases. However, reducing this preheating lowers flame temperature, subsequently decreasing NO_X formation. It is important to recognize that reducing air preheat also affects overall energy efficiency. Therefore, achieving the right balance between NOx reduction and energy efficiency is crucial.

Measure	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
F9 Low NOx burners	2	x	x	2	x	x	Robust	High

Low NO_X burners (LNB) strategically combine fuel and air/flue gas to establish distinct zones akin to staged combustion. This zoning facilitates lower flame temperatures, reduced oxygen concentrations and chemical reduction of NO_X by fuel within specific zones. LNB types include air-staged, flue-gas recirculation and fuel-staged variations, each employing different principles to diminish NO_X emissions. An advanced iteration is the ultra-low NO_X burner, reflecting ongoing developments in combustion technology for even more stringent emission control. Implementation considerations involve choosing the most suitable LNB type based on specific combustion requirements and environmental goals.

Measure	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
F10 Water/steam injection (in combustion systems)	2	x	x	2	x	x	Robust	High

Water/steam injection in combustion systems involves introducing water or steam to cool the flame and diminish thermal NO_X formation. This method strategically lowers flame temperatures, mitigating the conditions conducive to NO_X production during combustion.

Measure	Impact						Reliability	Tech. rqmt
	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
F11 Oxycombustion (to reduce NO_x generation)	2	x	x	2	x	x	Robust	High

Oxycombustion involves substituting combustion air with oxygen to eliminate thermal NO_x formation. Presently, oxycombustion is predominantly utilised in glass production. However, its application may expand in the future, particularly due to its potential to yield high CO_2 concentrations in flue gas—an advantageous feature for CO_2 capture and sequestration.

Measure	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
F12 Catalytic combustion (to reduce NO_x generation)	1	x	x	1	x	x	Robsut	High

Catalytic combustion, employed to curtail NO_x generation, utilises a catalyst to lower combustion temperatures below the threshold for NO_x formation, resulting in significant emission reductions. The catalyst's ability to facilitate efficient combustion at reduced temperatures holds promise for NO_x reduction in specific industrial contexts.

Measure	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
F13 Improving efficiency stoves and fireplaces	1	x	x	1	x	x	Robust	Intermediate

Enhancing the efficiency of stoves and fireplaces in domestic wood heating is crucial for reducing emissions of NO_x, particulate matter, black carbon as well as other organic pollutants. Implementing measures such as proper sizing, installation and usage, optimizing combustion operation, ensuring proper start-up, preventing smouldering and maintaining dry, clean firewood, switching to modern technology devices (i.e automatic controlled pellet stoves), can significantly improve fuel efficiency.

9.3 End-of-pipe measures to reduce/ recover NO_x emissions

End-of-pipe measures reduce the emission of pollutants without modifying the combustion process itself and can be configured to allow N recovery. These include selective catalytic reduction (SCR), typically used for stationary fossil fuel combustion (e.g., industrial boilers and turbines) where 70%-95% NO_x reduction rates can be achieved (ECE EB LRTAP, 2015; Sorrels et al., 2019). In SCR, NO_x is reduced, commonly by reaction with NH_3 or urea in a catalytic bed at 170-510°C. Base metal oxides, zeolites, iron oxides or activated C are used as catalysts (Han et al., 2019). The selection of the catalyst is influenced by the position of the SCR in the flue gas processing path and the presence of other pollutants in the flue gas (Sorrels et al., 2019). In selective non-catalytic reduction (SNCR), a reducing agent (usually NH_3 or urea) is injected into the firebox of the boiler to reduce NO_x, but without catalysts, higher temperatures (e.g., 850-1100°C) are needed. selective non-catalytic reduction can be used for all boilers (not for engines and gas turbines) using all fuels and can achieve 30%-50% NO_x reduction rates (ECE EB LRTAP, 2015).

The sorption and neutralisation of NO_x in emissions from stationary sources can also be achieved. Sorption techniques use an adsorbent (e.g., activated C, zeolites, or metal oxides) to capture NO_x from emissions, whilst neutralization methods utilise a reagent (e.g., NH_3) which is injected into the exhaust gas stream to convert NO_x into harmless compounds like N_2 and water.

The following text presents an overview of end-of-pipe measures to reduce/recover NO_x emissions.

Measure	**Impact**						**Reliability**	**Tech. rqmt**
	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
F14 Selective Catalytic Reduction	1	3	3	1	x	x	Robust	High

Selective Catalytic Reduction (SCR) is employed to reduce NO_x to N_2 by injecting a reducing agent, usually NH_3, directly into the flue gas over a catalyst in the presence of sufficient oxygen. This conversion occurs on the catalyst surface within a temperature range of 170 to 510°C (typically 300 to 400°C). Flue gas temperature, dependent on fuel sulfur content, must be maintained to avoid ammonium bisulfate formation, which could clog SCR elements. SCR is effective for diesel engines, but faces limitations in applications with varying loads, such as frequent start-up and shut down, affecting catalyst temperature.

Measure	Impact: Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
F15 Selective Non-Catalytic Reduction	2	3	3	2	x	x	Robust	High

Selective Non-Catalytic Reduction (SNCR) utilises a reducing agent, commonly NH_3, urea, or caustic NH_3, to reduce NO_x without the presence of a catalyst. Unlike Selective Catalytic Reduction (SCR), SNCR operates at higher temperatures ranging between 850 and 1100°C. This technique involves injecting the reducing agent directly into the flue gas to initiate NO_x reduction reactions. Higher operating temperatures may pose challenges in terms of energy consumption and material compatibility, however SNCR remains a viable option for NO_x reduction in certain industrial processes.

Measure	Impact: Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Tech. rqmt
F16 Sorption/ neutralisation of NO_x	1	x	x	1	x	x	Robust	High

Microalgae bioreactors provide a promising solution for improving N sustainability in freshwater and marine aquaculture. With reported removal rates of around 90% for NH_4-N and 75%-90% for total N under experimental conditions, these bioreactors demonstrate operational efficiency. The harvested microalgal biomass serves as a valuable resource, offering nutrient-rich aquaculture feed and the potential for extracting essential omega-3 fatty acids like eicosapentaenoic acid and docosahexaenoic acid. This utilisation not only supports a closed-loop system in aquaculture but also offers a sustainable alternative to conventional fish oils, addressing concerns related to overfishing and contributing to the overall ecological sustainability of aquaculture operations.

9.4 NOx removal from automobile emissions

Selective catalytic reduction (SCR) is commonly used in modern automobiles to reduce polluting emissions, such as NOx. Although noble-metal converters are technologically superior, zeolite-based catalysts are preferred due to their lower cost (Bhattacharyya and Das, 1999). Plasma-assisted catalytic systems (PACS) are a modified version of SCR that combines a catalyst and non-thermal plasma to reduce NOx emissions. Like SCR, PACS uses a catalyst to promote the reaction between NOx and reducing agents to form N_2 and water, but the addition of non-thermal plasma generates reactive species that further enhance NOx breakdown. Selective adsorber catalysts are another alternative, where NOx is stored on an adsorbing catalyst while the engine runs lean. The adsorbed NOx is released and reduced by precious metal components (e.g., platinum) on the catalytic system upon switching to a short rich biased stoichiometric excursion (Gill et al., 2004). In some cases, selective adsorber catalysts can be used to recover N.

Exhaust gas recirculation and lean burn combustion can also reduce NOx emissions by lowering combustion temperature. However, optimization is required to balance NOx reduction with other factors such as engine efficiency, power output and emissions of other pollutants (e.g., particulate matter and hydrocarbons).

The following text presents an overview of measures for NOx removal from automobile emissions.

Measure	**Impact**						**Reliability**	**Tech. rqmt**
	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
F17 Selective catalytic reduction of automobile exhausts	1	x	x	1	x	x	Robust	High

Selective Catalytic Reduction (SCR) stands as a well-established and widely employed technology for reducing NOx in diesel engines. In this method, a urea-based reducing agent (e.g., AdBlue), is injected into the exhaust stream. This agent reacts with NOx over a catalyst, typically composed of materials like titanium dioxide, tungsten oxide, or vanadium oxide. The catalyst facilitates the conversion of NOx into N_2 and water. Catalytic converters, integral to most modern vehicles, serve as devices to minimise emissions from internal combustion engines. In exhaust systems, catalytic converters enable the oxidation and reduction of harmful by-products (e.g., NOx, carbon monoxide and hydrocarbons), transforming them into less hazardous substances like CO_2, water vapor and N_2.

Measure	Impact						Reliability	Tech. rqmt
	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
F18 Exhaust gas recirculation	2	x	x	2	x	4	Promising	High

Exhaust Gas Recirculation (EGR) is a well-established technique for alleviating NO_X emissions in internal combustion engines. The process involves reintroducing a portion of the exhaust gas into the engine, reducing available oxygen for combustion and subsequently lowering the overall combustion temperature. This reduction in temperature reduces formation of NO_X, hence cutting emissions. EGR is extensively utilised across combustion engine applications, proving to be an efficient strategy for adhering to emission standards.

	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
F19 Lean burn combustion	2	x	x	2	x	4	Unproven	High

In lean burn engines, the air-fuel mixture is intentionally lean, containing less fuel in proportion to the amount of air. This design choice lowers the combustion temperature, effectively mitigating NO_X emissions. By operating with a lean mixture, the reduction in fuel quantity results in decreased combustion temperatures, minimising the conditions conducive to NO_X formation.

	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
F20 Plasma-assisted catalytic system	1	x	x	1	x	x	Promising	High

Plasma-assisted catalytic systems use plasma to activate catalysts, improving their efficiency in reducing NO_X emissions. The high-energy environment generated by the plasma discharge facilitates the oxidation or reduction of pollutants in exhaust gases, converting them into less harmful substances. These systems offer benefits like lower operating temperatures, reducing energy consumption and emissions of pollutants like carbon monoxide. They can also be more selective and efficient in removing specific pollutants, such as NO_X, compared with conventional catalysts. Despite promising results in labs and pilot studies, plasma-assisted catalysts are in early development for automotive use. Further research is needed to optimize their performance and durability for production vehicles.

Measure	Impact						Reliability	Tech. rqmt
	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
F21 Selective adsorber catalysts	1	x	x	1	x	x	Robust	High

Selective adsorber catalysts, a newer NOx reduction technology for car engines, adsorb NOx onto a catalyst surface and convert it into N2 and water during regeneration. This is achieved through thermal or electrical means. These catalysts, crafted from materials like zeolites, oxides or metals, present an evolving alternative to established SCR technology. Unlike the widespread use of SCR in diesel engines for NOx reduction, selective adsorber catalysts are in the research and development phase for car engines and await broader commercialisation. Further advancements are necessary to refine these catalysts and assess their potential for widespread adoption in automotive applications.

9.5 Nitrogen recovery from industrial gas emissions

Several NO_x recovery technologies have shown promising results at the lab-scale. These include NO_x partial oxidation followed by physical or chemical adsorption, which involves catalytic oxidation of NO_x to NO, captured by either physical or chemical adsorption techniques and recovered as nitric acid. Another technology, NOx partial oxidation followed by adsorption in water or aqueous alkali solutions, oxidises NO_x to NO_2, which is then absorbed in water or an aqueous alkali solution and recovered as nitric acid or NO_3- salts (Langhammer et al., 2022). Chemisorption-aided physisorption of NO in microporous adsorbents, specifically zeolite-based materials, has also demonstrated successful N recovery from gaseous emissions (Tao and Liu, 2022).

The following provides a summary of strategies aimed at recovering N_r from emissions in industrial gases.

Measure	Impact						Reliability	Tech. rqmt
	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
F22 Partial NOx oxidation followed by physical or chemical adsorption	2	x	x	2	x	x	Robust	High

Partial oxidation of NO_X followed by physical or chemical adsorption is a N recovery technology designed to capture NO_X emissions from industrial sources. This method involves partially oxidising NOx to NO_2 using a catalyst, followed by capturing the NO_2 through physical or chemical adsorption. In physical adsorption, NO_2 molecules are captured onto a surface (e.g., activated C), while chemical adsorption involves reacting NO_2 with a specific compound (e.g., titanium dioxide) which can chemically react with NO_2 to form a solid product for easy collection . Once captured, the NO_2 can be processed to recover N in the form of nitric acid or other compounds. While this technology has the potential to reduce N emissions and recover valuable resources, further research is required to optimize its efficiency and cost-effectiveness.

	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
F23 Chemisorption aided physisorption of NO in microporous adsorbents	2	x	x	2	x	x	Robust	High

Chemisorption aided physisorption of NO in microporous adsorbents employs zeolite-based materials as effective adsorbents. Zeolites possess a well-defined pore structure and high surface area, making them adept at physically adsorbing NO. Moreover, specific zeolites can be modified with metal ions or chemical groups, enhancing the chemical adsorption of NO. For instance, copper-exchanged zeolites demonstrate both physical and chemical adsorption of NO, exhibiting a higher adsorption capacity compared to unmodified zeolites. This approach utilising zeolite-based adsorbents holds promise for NO capture, with the potential for further optimization and application in mitigating NO_X emissions.

	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
F24 Partial NOx oxidation followed by adsorption in water or aqueous alkali solutions	2	x	x	2	x	x	Robust	High

The partial oxidation of NO_X followed by adsorption in water or aqueous alkali solutions is a method that involves capturing and converting NO_X emissions from industrial sources. In this process, NO_X is partially oxidised to NO_2 and then captured through adsorption in water or aqueous alkali solutions. The captured NO_2 can react with water or alkali compounds to form nitric acid or other N-containing products. This technology shows promise in reducing N emissions from industrial sources while enabling the recovery of valuable N resources. However, further research and development are needed to optimize its efficiency and cost-effectiveness for widespread implementation.

9.6 Broad measures to reduce the demand for fuel combustion

Reducing fuel combustion can be achieved across all sectors and societal groups. Detailed guidance on measures to achieve this are provided in multiple reports (Bruckner et al., 2014; Martínez-Blanco et al., 2013) and publications (Ameyaw et al., 2019; Coram and Katzner, 2018; Stern et al., 2016) and whilst focused on mitigation of CO_2, will also achieve a reduction in NOx emissions.

As detailed guidance on decarbonisation measures already exists, here we identify broad goals where efforts can be targeted. These include improving energy efficiency in buildings, industries and transportation; promoting transportation electrification through electric vehicle investment and infrastructure; shifting to renewable energy sources to diminish reliance on fuels; and advocating sustainable urban planning for compact, well-designed areas encouraging eco-friendly commuting. A detailed discussion of specific measures to achieve these goals exceeds the scope of the document.

The following provides a summary of broad strategies to reduce the demand for fuel combustion.

Measure	**Impact**						**Reliability**	**Tech. rqmt**
	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
F25 Energy efficiency improvements	1	x	1	1	x	1	Robust	Intermediate

Selective Catalytic Reduction (SCR) is employed to reduce NO_X to N_2 by injecting a reducing agent, usually NH_3, directly into the flue gas over a catalyst in the presence of sufficient oxygen. This conversion occurs on the catalyst surface within a temperature range of 170 to 510°C (typically 300 to 400°C). Flue gas temperature, dependent on fuel sulfur content, must be maintained to avoid ammonium bisulfate formation, which could clog SCR elements. SCR is effective for diesel engines, but faces limitations in applications with varying loads, such as frequent start-up and shut down, affecting catalyst temperature.

Measure	**Impact**						**Reliability**	**Tech. rqmt**
	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2		
F26 Electrification of transportation	1	x	1	1	x	1	Robust	Intermediate

Electrification of Transportation, a pivotal aspect of environmental sustainability, centres on promoting electric vehicles (EVs), investing in infrastructure and encouraging public transportation. This shift away from conventional internal combustion engines reduces fossil fuel combustion, a primary source of NOx, contributing to cleaner air and lower greenhouse gas emissions. However, careful considerations must be given to mitigating potential NOx emissions, particularly in electricity generation for EVs (i.e. from renewable sources). Challenges encompass establishing a robust charging infrastructure, mitigating the N-related environmental impact of battery production and ensuring equitable access to EV technologies.

Measure	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	**Reliability**	**Tech. rqmt**
F27 Sustainable urban planning	1	x	1	1	x	1	Robust	Intermediate

Sustainable urban planning focuses on designing cities to promote sustainable modes of transportation such as walking, cycling and public transit, aiming to reduce dependence on personal vehicles. By creating compact, well-planned urban areas, the necessity for lengthy commutes diminishes, leading to a decreased overall demand for fossil fuels in transportation. By reducing fossil fuel combustion, a primary source of NOx, this transition contributes to improved air quality and a reduction in C emissions. Challenges involve balancing urban development with environmental conservation and ensuring equitable access to amenities.

Measure	Net Effect	NH_3	N_2O	NO_x	Nr to water	N_2	**Reliability**	**Tech. rqmt**
F28 Transition to renewable energy	1	x	1	1	x	1	Robust	Intermediate

The transition to renewable energy involves amplifying the share of sources like solar, wind, hydro and geothermal, markedly reducing dependence on fossil fuels for electricity generation. This deliberate shift not only aligns with environmental conservation goals, climate change mitigation and enhanced energy security, but also actively contributes to the mitigation of N emissions. Unlike fossil fuel combustion, renewable energy processes produce lower or negligible NOx. Challenges include intermittency in renewables and the need for advanced energy storage solutions are being addressed. Government policies, technological innovations and heightened public awareness are pivotal in facilitating this transition towards a more sustainable, resilient energy future with a concurrent positive impact on N emissions, promoting environmental well-being.

9.7 Summary table of measures to deliver better nitrogen management related to fuel combustion

The following table offers a concise overview of these measures.

Table 9.1 Measures for better N management related to fuel combustion. The 'impact' on N emissions (i.e., 1 = large reduction, 2 = medium reduction, 3 = small reduction, 4 = potential increase and X = unclear or unknown effect), 'reliability' and 'technological requirement' (i.e., expertise and/or specialized equipment) are indicated for each measure. See Box 1.1 for further details on these indicators. For further guidance on implementation, efficiency and the cost, risks and benefits of implementing measures, see the INMS Nitrogen Measures Database – www.inms.international/measures.

Measure sub-category	Measure reference and name		Net effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Technical Rqmt
Primary measures to reduce NO_X generation	F1	Switching to low NO_X producing fuels	3	x	x	2	x	x	Promising	High
	F2	Fuel cleaning to remove nitrogen compounds from fuels	3	x	x	2	x	x	Promising	High
	F3	Low excess air combustion	1	x	x	x	x	x	Robust	High
	F4	Air staging (in combustion systems)	1	x	x	2	x	x	Robust	High
	F5	Fuel staging (in combustion systems)	1	x	x	1	x	x	Robust	High
	F6	Fuel re-burning (in combustion systems)	3	x	x	2	x	x	Promising	High
	F7	Flue gas recirculation (in combustion systems)	3	x	x	2	x	x	Promising	High
	F8	Reduced air preheat (in combustion systems)	2	x	x	2	x	x	Robust	High
	F9	Low NO_X burners	2	x	x	2	x	x	Robust	High
Primary measures to reduce NO_X generation(cont)	F10	Water/steam injection (in combustion systems)	2	x	x	2	x	x	Robust	High
	F11	Oxycombustion (to reduce NO_X generation)	2	x	x	2	x	x	Robust	High
	F12	Catalytic combustion (to reduce NO_X generation)	1	x	x	x	x	x	Robust	High
	F13	Improving efficiency stoves and fireplaces	1	x	x	x	x	x	Robust	Intermediate
End of pipe measures to reduce/recover NO_X emissions	F14	Selective Catalytic Reduction	1	3	3	1	x	x	Robust	High
	F15	Selective Non-Catalytic Reduction	2	3	3	2	x	x	Robust	High
	F16	Sorption/neutralisation of NO_X	1	x	x	x	x	x	Robust	High
	F17	Selective catalytic reduction of automobile exhausts	1	x	x	1	x	x	Robust	High

Measure sub-cateogory	Measure reference and name		Net effect	NH_3	N_2O	NO_x	Nr to water	N_2	Reliability	Technical Rqmt
End of pipe measures to reduce/recover NOx emissions (cont.)	F18	Exhaust gas recirculation	2	x	x	2	x	4	Promising	High
	F19	Lean burn combustion	2	x	x	2	x	4	Unproven	High
	F20	Plasma-assisted catalytic system	1	x	x	1	x	x	Promising	High
	F21	Selective adsorber catalysts	1	x	x	1	x	x	Robust	High
Nitrogen recovery from industrial gas emissions	F22	NOx partial oxidation followed by physical or chemical adsorption	2	x	x	2	x	x	Robust	High
	F23	Chemisorption aided physisorption of NO in microporous adsorbents	2	x	x	2	x	x	Robust	High
	F24	NOx partial oxidation followed by adsorption in water or aqueous alkali solutions	2	x	x	2	x	x	Robust	High
Broad measures to reduce the demand for fuel combustion	F25	Energy efficiency improvements	1	x	1	1	x	1	Robust	Intermediate
	F26	Electrification of transportation	1	x	1	1	x	1	Robust	Intermediate
	F27	Sustainable urban planning	1	x	1	1	x	1	Robust	Intermediate
	F28	Transition to renewable energy	1	x	1	1	x	1	Robust	Intermediate

10

Integrating nitrogen measures for sustainable nitrogen management

10.1 The need for integration in nitrogen management

At present, guidance and governance on sustainable N management tend to be fragmented between different forms of N and different sectors (Morseletto, 2019; Sutton et al., 2021, 2019). To fully exploit the synergies that operate through the N cycle, and to avoid trade-offs that can also result from biogeochemical linkages, there is a pressing need to develop consolidated guidance on sustainable N practices (Houlton et al., 2019; UNEP, 2019c). The scientific community is working with the UN to coordinate and accelerate the necessary action (Sutton et al., 2021). It is evident that an integrated approach to N management across sectors/scales, underpinned by the principles of the circular economy, is essential to deliver much-needed improvements towards N sustainability (Kanter et al., 2020; Morseletto, 2019; Reis et al., 2016b; Sutton et al., 2021, 2019).

10.2 Designing ‘measure packages’

By applying the principles of integrated sustainable N management (see Chapter 2) and leveraging the array of measures discussed in Chapters 3-9, a cohesive, holistic strategy to enhance N sustainability can be designed for any system. Such strategies can benefit from the concept of 'measure packages,' as introduced in (Sutton et al., 2022).

When selecting packages of measures for any system, measures should be selected to:

i) optimize N_r inputs and outputs,

ii) maximize desired flows of N (e.g., those that favour biological assimilation) and reduce N losses, and

iii) circularise N flows (highlighted in Principles 1-4 in Chapter 2).

Efforts to reduce N losses at one stage of the cycle may increase the risk of losses at a later stage (Principle 2) and of other nutrient cycles (Principle 5). For example, covering manure will reduce NH_3 losses and produce a more N-rich manure, therefore, corresponding reductions for manure applied to soils should be made if N application in excess of plant needs is to be avoided (unless yields can be increased). Indeed, according to mass balance, all measures that reduce total N_r inputs, while maintaining productivity, will increase system-wide NUE and lead to a reduction in all N_r losses (Principle 3). A reverse-engineered example of this would be reducing food waste, which will improve NUE across the whole food supply chain because fewer nutrients would be needed to produce the same amount of food consumed. In addition, when designing measures packages to address local goals for N_r emission reductions, it is important to consider local physico-chemical conditions and socioeconomics and to share responsibility across relevant stakeholders (Principles 6-8).

In the following hypothetical case studies, we show how this thinking may be applied to design coherent packages of measures. Nitrogen sustainability concerns and example measure packages for these case studies are summarised in Boxes 10.1 and 10.2, respectively.

Case Study 1: Wheat production in temperate climates:

Wheat production in temperate agriculture is typically achieved by large-scale industrial agriculture systems which are prolific in production outputs. The farming system in this case study is in a region dominated by arable agriculture but is reasonably close to a large city. The farming system is characterised by sophisticated agronomic practices, intense mechanisation and the use of inputs like irrigation sourced from groundwater, chemical fertilizers, pesticides and (in some instances) genetically modified organisms (GMOs). Currently, the fertilizer formulations used in the case study are based on urea composite fertilizers, augmented by other nutrients. Characteristics that distinguish temperate from tropical agricultural systems include: i) seasonality, leading to well-defined operations and growing periods, ii) less weathered soils, with different fertility characteristics and slower soil organic matter dynamics, iii) substantial inputs of fertilizers, agrochemicals, or mechanisation in different combinations, and iv) substantial investment by the private sector. A measures package to address key N sustainability concerns for this case study system is provided in Box 10.1.

Box 10.1 shows how a range of measures is available that can be combined according to the agreed level of ambition for any context. It should be noted that some measures are incompatible. For example, the use of legumes in rotation is obviously not possible for a continuous wheat cropping system.

Case Study 2: Intensive dairy farming:

Milk and dairy products account for about 14% of the global agricultural trade. Dairy farming has become more intensive to increase the amount of milk produced by each cow (Kristensen et al., 2005). Intensive dairy farming typically includes both housed animals and animals grazing for part of the year. Grassland production increasingly relies on N inputs from fertilizers, as well as perennial N fixing crops and livestock excretion. Irrespective of whether livestock are grazing, or confinement-based, dairy systems are recognised as significant contributors of excess N in the environment (Gourley et al., 2012; Stenfield et al., 2006; VandeHaar and St-Pierre, 2006). Reported NUE in animal production systems ranges between 15-35% (De Klein et al., 2016). Whilst the relationship between N inputs and losses differs little between temperate and tropical croplands, recent analysis suggests total nitric oxide (NO) losses in the tropics are higher than in temperate climates (Huddell et al., 2020). The farming system in this case study is a medium-large dairy farm (>1000 cows), with pastures maintained through N inputs from synthetic fertilizers and manures. The livestock are mainly confined, however, measures to address N losses from both confined and grazing systems are considered. As such, measures must target the efficient husbandry of both plants and animals. An example measures package to address key N sustainability concerns for this system is provided in Box 10.2.

As shown, there is a wide range of options available to optimize N inputs/outputs, reduce N losses and promote circularity. It should be noted that soil testing is required to inform on soil nutrient needs – not only N. If N inputs are in excess of needs, then reducing inputs (e.g., via reduction in fertilizer application) can save money without significant yield penalty. A critical point is that actions to reduce N losses (the fraction wasted to the environment) leave more N in the dairy system, giving further opportunity to save money through reduced N inputs.

The case study also lists increasing productivity as a mean to reduce emissions per product. Here, the package of measures must be tuned to the specific situation and local ecosystem sensitivity. In a particularly sensitive location such a strategy may not be sufficient. Instead, the package of measures would need to focus on N losses to an appropriately ambitious target according to relevant local requirements and other agreed actions plans. Further INMS guidance for dairy systems is provided by Gourley et al., (2024) .

Box 10.1 Nitrogen sustainability concerns and an example measures package aimed to address them for case study 1 ‘Wheat production in temperate climates’.

Concerns	Measures package
Excess nitrogen inputs Nutrient testing is not carried out regularly, and insufficient economic barriers allow synthetic N fertilizers to be applied in excess, leading to increased risk of losses. Measures to minimize energy use are not implemented.	**To optimize nitrogen inputs and outputs** • Regular soil nutrient testing and plant tissue analysis to support appropriate fertilizer application rates. • Fertilizer application appropriately timed (e.g., multiple or split applications) during the growing season to meet crop growth needs, taking account of climatic difference to reduce the risk of large leaching events (e.g., storm events). • Lower NO_X emissions by reducing fossil fuel combustion throughout the whole farming system (e.g., by using high fuel-efficient or electric machinery, lowering automobile mileage and switching to sources of renewable energy).
Nitrogen losses Long-term monoculture crop farming has had negative effects on soil structure and fertility. The soil types and vegetation type are conducive to NO_3 – leaching to groundwater and surface runoff in areas with high seasonal.	**To maximize desired flows of nitrogen and reduce nitrogen losses apply a selection of the following according to the target ambition** • Precision placement of fertilizers close to the rooting zone of the crop to enhance nutrient uptake and reduce NH_3 volatilisation. • Switching from urea to ammonium nitrate fertilizers to reduce NH_3 emissions. • Use nitrification inhibitors to slow conversion of ammonium to NO_3^- and increase N plant uptake, reducing the risk of losses. • Controlled release fertilizer technologies can be used to slow the release of nutrients to the soil over several months (depending on thickness and composition of coating), allowing pre-plant N application. • Use of fertigation technologies for more precise delivery of nutrients as per crop demands. • The inclusion of leguminous N fixing crops and inoculation of soils with plant-growth-promoting rhizobacteria to promote biological N fixation to support reduction synthetic fertilizer requirements (in rotation or intercropping). • Reduce or limit nutrient applications in areas that have a higher risk of N losses. • Planting of cover crops to reduce available soil N levels during high-risk periods for N leaching by taking up N originating from post-harvest decomposition and mineralisation. • Introduce agroforestry to help remove surplus Nr from neighbouring arable fields, minimizes erosion, provide wind shelter, and support biodiversity. • Introduce flow control structures such as vegetated open channels to slow runoff and subsurface water flow increase retention and promote plant-mediated denitrification.
Minimal nitrogen recycling Little to no recycling of N from manures or other organic residues is carried out because farms landscape dominated by arable agriculture where manures are not easily available.	**To circularize nitrogen flows** • Reduce the distance between existing livestock and crop farming to increase nutrient recycling potential. • Recover nutrient from urban and industrial wastewaters using low-energy innovations to produce recycled fertilizers/biofertilizers, which can be used to lower the demand for synthetic N fertilizers. • Recycle biochars (resulting from the pyrolysis of waste biomass) to increases soil C storage, water holding capacity and decrease NH_3 emissions.

Box 10.1 Nitrogen sustainability concerns and an example measures package aimed to address them for case study 1 'Wheat production in temperate climates'.

Concerns	Measures package
Excess nitrogen inputs Animals are fed protein in excess of their growth requirements. Manures and fertilizer are applied to pastures in excess to requirements. Measures to minimize energy use are not implemented.	**To optimize nitrogen inputs and outputs** • Adjust crude protein content in animal diets to match growth needs. • Maximize feed grain surface area (e.g., pelleting feed) to enhance digestibility and nutrient gut absorption. • Optimize animal productivity (e.g., increasing milk yield and production cycles per cow) and longevity of animals (e.g., through better diet and housing conditions), to reduce N losses per product. • Regular soil nutrient testing to support appropriate manure application rates to pastures, taking account of reduced losses to reduce N inputs to match. • Lower NO_X emissions by reducing fossil fuel combustion throughout the whole farming system (e.g., by using high fuel-efficient or electric machinery, lowering automobile mileage and switching to sources of renewable energy).
Nitrogen losses Manure N management is rudimentary (e.g., manures are collected from housing floors once daily, and are stored uncovered in pits). Pastures adjacent to rivers and streams with little management to limit animal access.	**To maximize desired flows of nitrogen and reduce nitrogen losses apply a selection of the following according to the target ambition** • Extend cattle grazing time, both daily and seasonally, to reduce NH_3 emissions by increasing the proportion of excreted N that is returned to the soil, in comparison with housed animals. • Implement treatment of exhaust air from large-scale intensive livestock housing by acid scrubbers. • Regularly remove slurry and manures from flooring and under the slats in animal housing, to a 'covered' outside store to reduce NH_3 emissions, by reducing the emitting surface and the slurry storage temperature. • Foster innovations in flooring systems that reduce the emitting surface area of slurry and aid collection e.g., convex floors, slurry channels with slanted walls, use of 'toothed' scrapers on grooved floors. • Store manures and slurries to minimize NH_3 losses and N leaching; options include metal or concrete tanks with solid lids, floating covers on lagoons, slurry bags, dispersed coverings of peat, clay, zeolite or phosphogypsum, and an impermeable base to avoid N leaching. • Reduce the pH of stored slurry, (e.g., through the addition of strong acids) to reduce NH_3 emissions and potentially reduce CH_4, N_2O and N_2 emissions. • Avoid grazing in areas with a high risk of N losses, which include those with high connectivity to the streams and/or groundwaters
Inefficient nitrogen recycling Manures and fertilizer are applied to pasture in excess of plant needs using the surface broadcast method, leading to extensive NH_3 losses, N leaching and runoff.	**To circularize nitrogen flows** • Optimize application methods of manures and fertilizer to pastures that reduce N losses and enhance plant nutrient uptake (e.g., slurry injection, band spreading, rapid manure incorporation, and precision fertilizer placement). • Dilute slurries to allow more rapid infiltration into the soil, hence reducing NH_3 losses. • Correctly calibrate manure spreaders to ensure nutrients are applied at the desired rate, which can reduce NH_3 and NO_3^- losses associated with the excess application of manures. • Recycle manures (in excess to crops/pasture requirements) via biological assimilation into economically valuable extractive species which can be harvested as secondary organisms, thus resulting in a net export of nutrients from the system, this may include black soldier fly larvae and certain aquatic species in land-based aquaculture

10.4 Grasping the future challenge

The measures and measures packages described in this INMS guidance document offer a varied set of approaches to improve N sustainability across the N cycle. The challenge lies in achieving coordinated implementation on a scale substantial enough to fulfil N sustainability objectives (UNEP, 2019a). Socioeconomic barriers and missing and/or fragmented policies slow progress (Sutton et al., 2021). For some stakeholders (e.g., smallholder farmers), a barrier may be accessing accurate guidance on actions to take and how to implement them. The rapid spread of GPS-enabled smartphones presents a 'low-cost' opportunity to engage directly with 2 billion smallholder farmers, providing them with scientifically sound and actionable advice on nutrient management – a prospect previously unattainable (Fabregas et al., 2019). A practical example could be the translation of geospatial and satellite monitoring data via artificial intelligence (AI) decision-making software, to provide accurate up to date farm-scale crop nutrient management advice to farmers via smart phone apps (Cassman and Dobermann, 2022).

Looking to the future, machine learning and other AI approaches may play an increasingly important role in guiding site-specific management (Saikai et al., 2020), especially as it becomes increasingly possible to move from 'big' data sets to automated decision making and prescriptive analytics (Smith, 2020). Advances in satellite imagery, remote sensing and computing hard/software allow large-scale monitoring and spatial characterisation of landscapes (Huang et al., 2018; Shanmugapriya et al., 2019). The development and refinement of automated data analysis systems allow faster responses to potential threats (e.g., flood and drought risk) (Huang et al., 2018; Shanmugapriya et al., 2019). Artificial intelligence techniques are already being developed to simulate human expertise within problem-solving software and may be an effective way to apply agricultural science to user-friendly applications for non-specialists (Ben Ayed and Hanana, 2021; Jung et al., 2021; Zhang et al., 2021).

Innovations in Nr recovery and gene manipulation of crops have the potential to become disruptive, offering opportunities to reconfigure the N cycle by significantly reducing global reliance on synthetic N fertilizer. Over the past decade, sustainability concerns have boosted the development of Nr recovery technologies for concentrated and refined products (Spiller et al., 2022). Rising fertilizer prices due to the energy crisis and Russia's invasion of Ukraine have increased concerns and potential support for innovation (Alexander et al., 2022). Several NH_3 and NOx recovery technologies are overcoming earlier system issues (e.g., low N concentrated products, operational energy requirements), using novel catalysts or plasma technologies. As a result, the production of 'white nitrogen' (e.g., Nr recovered from existing residues and brought back into the system as a circular N source) becomes increasingly viable at the industrial scale. Decarbonisation goals and breakthroughs in NH_3 fuelled solid oxide fuel cells are driving innovations towards NH_3 as a hydrogen carrier and as a fuel (Wan et al., 2021). However, NH_3 combustion currently produces high rates of NOx emissions representing a significant environmental challenge if NH_3 fuels are to be increasingly used.

Gene modification of crops to enhance biological nitrification inhibition (Subbarao et al., 2017), or N fixation (Curatti and Rubio, 2014) also continues to progress. However, this work is highly complex and further research is still required to deliver genetic improvements in N-use efficiency that are applicable for widespread use (Cassman and Dobermann, 2022).

10.5 Conclusion

Nitrogen plays a vital role in global food security and bioenergy production, but increasing N emissions pose significant threats to soil, air and water quality, exacerbating biodiversity loss and climate change impacts. Sustainable N management is crucial for achieving various United Nations Sustainable Development Goals, addressing hunger, climate action and biodiversity. The 'nitrogen challenge' as described in Sutton et al. (2021), underscores the intricate link between N and these global challenges. Human activities have drastically altered the biogeochemical N cycle, surpassing the planetary boundary set by Steffen et al. (2015) and risking irreversible changes to the Earth System. To meet the challenge, a goal to halve N waste by 2030 has been set, looking to save at least saving $100 billion annually and aiding post-COVID-19 economic recovery (Sutton et al., 2021). Sustainable N management is essential for supporting food, fibre and energy production while mitigating environmental impacts. However, current N policies are fragmented, hindering cohesive efforts across the N cycle. To address this, consolidated guidance on sustainable N practices is needed. The Task Force on Reactive Nitrogen has published documents focusing on agriculture (Bittman et al., 2014; Sutton et al., 2022), but broader, integrated N management is crucial for achieving sustainability goals. The present guidance document aims to extend beyond agriculture, providing a comprehensive overview of opportunities for improved N management across all sectors involved in the N cycle, emphasising the importance of an integrated approach for a sustainable N future.

Opportunities to reduce N inputs, maximize N outputs and optimize N circularity exist across sectors. Agriculture, being the foremost consumer and emitter of N_r, stands out as a pivotal sector demanding focused efforts for achieving N sustainability. Nevertheless, implementing such actions in this sector continues to pose a challenge. The management of organic residues presents opportunities for N recovery and recycling, which are not yet fully utilised. Innovations in N_r recovery may have the potential to significantly reduce reliance on synthetic N fertilizer. Landscapes and waterbodies can be better managed to mitigate the impacts of N losses and to buffer N pollution through biological assimilation, which in some cases can produce useful secondary products (e.g., feeds and fertilizers). Consumers, with the support of the broader regulatory and marketing system, can also contribute by lowering their demand for animal products with high N footprints and by reducing food waste. Fossil fuel combustion is a major source of NOx pollution in the atmosphere and continues to be the dominant energy source for all sectors. In this way decarbonisation efforts can align with N sustainability targets for N.

Advances in satellite imagery, remote sensing, 'big data' handling and AI, combined with the rapid rise in GPS-enabled smartphones offer opportunities to disseminate accurate, farm-scale nutrient management advice to support measure uptake. Without an integrated approach to N management across sectors/scales (including aquaculture, residue and land use management), underpinned by the principles of the circular economy, goals to improve N sustainability will not be possible. These ambitions include 'halving nitrogen waste by 2030', as agreed in the Colombo Declaration in launching the United Nations (UN) Global Campaign on Sustainable N Management in 2019 (UNEP, 2019a) and latterly endorsed in other regional and international initiatives (Sutton et al., 2021). Such a reduction could save $100-300 billion worth of N resources a year (UNEP, 2022). In a post-COVID-19 economic recovery landscape, urgent and integrated action to improve N management is an environmental and economic necessity.

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Nitrogen mitigation

Integrating measures to improve nitrogen mitigation throughout the nitrogen cycle

At present, guidance and governance on sustainable nitrogen management tend to be fragmented between different forms of nitrogen and different sectors. To fully exploit the synergies that operate through the nitrogen cycle there is a pressing need to develop consolidated guidance on sustainable nitrogen practices. In this INMS guidance document the principles that underpin integrated sustainable nitrogen management are discussed. An overview of >150 measures to reduce nitrogen losses and improve nitrogen use efficiency throughout the anthropogenic nitrogen cycle are provided. The synergies and trade-offs of applying multiple measures are considered alongside case studies to demonstrate how a ‘package of measures’ can be selected to achieve integrated nitrogen management for a given system.

This guidance document is intended to be used alongside the INMS Nitrogen Measures Database; an online resource that provides further details on nitrogen measures (see www.inms.international/measures). Both were prepared as outputs of the GEF-UNEP project ‘Towards an International Nitrogen Management System project' (Towards-INMS).

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