Nonpoint Source Nitrogen Pollution

Challenges, Solutions, and Sustainable Approaches

Edited by
Tonni Agustiono Kurniawan
Abdelkader Anouzla

ELSEVIER

Nonpoint Source Nitrogen Pollution

Nonpoint Source Nitrogen Pollution

Challenges, Solutions, and Sustainable Approaches

Edited by

TONNI AGUSTIONO KURNIAWAN
College of Environment and Ecology, Xiamen University,
Xiamen, P.R. China

ABDELKADER ANOUZLA
Laboratory of Process Engineering and Environment, Faculty of
Science and Technology, Hassan II University, Mohammedia,
Morocco

ELSEVIER

Elsevier
Radarweg 29, PO Box 211, 1000 AE Amsterdam, Netherlands
125 London Wall, London EC2Y 5AS, United Kingdom
50 Hampshire Street, 5th Floor, Cambridge, MA 02139, United States

Copyright © 2026 Elsevier Inc. All rights are reserved, including those for text and data mining, AI training, and similar technologies.

For accessibility purposes, images in electronic versions of this book are accompanied by alt text descriptions provided by Elsevier. For more information, see https://www.elsevier.com/about/accessibility.

Books and Journals published by Elsevier comply with applicable product safety requirements. For any product safety concerns or queries, please contact our authorised representative, Elsevier B.V., at productsafety@elsevier.com.

Publisher's note: Elsevier takes a neutral position with respect to territorial disputes or jurisdictional claims in its published content, including in maps and institutional affiliations.

No part of this publication may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or any information storage and retrieval system, without permission in writing from the publisher. Details on how to seek permission, further information about the Publisher's permissions policies and our arrangements with organizations such as the Copyright Clearance Center and the Copyright Licensing Agency, can be found at our website: www.elsevier.com/permissions.

This book and the individual contributions contained in it are protected under copyright by the Publisher (other than as may be noted herein).

Notices

Knowledge and best practice in this field are constantly changing. As new research and experience broaden our understanding, changes in research methods, professional practices, or medical treatment may become necessary.

Practitioners and researchers must always rely on their own experience and knowledge in evaluating and using any information, methods, compounds, or experiments described herein. In using such information or methods they should be mindful of their own safety and the safety of others, including parties for whom they have a professional responsibility.

To the fullest extent of the law, neither the Publisher nor the authors, contributors, or editors, assume any liability for any injury and/or damage to persons or property as a matter of products liability, negligence or otherwise, or from any use or operation of any methods, products, instructions, or ideas contained in the material herein.

ISBN: 978-0-443-29070-1

For Information on all Elsevier publications
visit our website at https://www.elsevier.com/books-and-journals

Publisher: Peter Llewellyn
Acquisitions Editor: Pamela Sadhukhan
Editorial Project Manager: Vasowati Shome
Production Project Manager: Prem Kumar Kaliamoorthi
Cover Designer: Mark Rogers

Typeset by MPS Limited, Chennai, India

ELSEVIER Book Aid International
Working together
to grow libraries in
developing countries
www.elsevier.com • www.bookaid.org

Contents

Section I Emission sources of nitrogen pollution

Section II How does nitrogen pollution decrease soil quality?

Section III Toward a sustainable nitrogen management

List of contributors

Manzoor Ahmad Ahanger
Department of Civil Engineering, National Institute of Technology, Srinagar, Jammu and Kashmir, India

Mukhtar Ahmed
India Meteorological Department Rambagh, Meteorological Centre Srinagar, Srinagar, Jammu and Kashmir, India

Rashid Ali
Department of Life Sciences, Faculty of Natural and Applied Sciences, Khwaja Fareed University of Engineering and Information Technology, Rahim Yar Khan, Punjab, Pakistan

Abdullah Altunışık
Department of Biology, Faculty of Arts and Sciences, Recep Tayyip Erdoğan University, Rize, Türkiye

Areeba Ameen
Department of Zoology, Faculty of Life Sciences, Government College University Faisalabad, Faisalabad, Punjab, Pakistan

Ugbenyen Anthony Moses
Department of Biochemistry, Edo State University Uzairue, Auchi, Edo State, Nigeria

Sarah Aphirta
Environmental Engineering Department, Faculty of Landscape Architecture and Environmental Technology, Universitas Trisakti, Jakarta, Indonesia

Tasrif Nur Ariyan
Department of Environmental Science, Bangladesh University of Professionals (BUP), Dhaka, Bangladesh

Muhammad Asrar
Department of Zoology, Faculty of Life Sciences, Government College University Faisalabad, Faisalabad, Punjab, Pakistan

Letícia Barbosa Alves
Inorganic Processes Department, Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brazil

Rafael Novaes Barros
Department of Bioprocess Engineering and Biotechnology, Polytechnic Center, Federal University of Parana, Curitiba, PR, Brazil

Vladimir N. Bashkin
Institute of Physical-Chemical and Biological Problems of Soil Science, RAS, Pushchino, Russia

Juacyara Carbonelli Campos
Inorganic Processes Department, Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brazil

Dimpal Chauhan
Department of Chemistry, Career Point University, Hamirpur, Himachal Pradesh, India; Centre for Nano-Science and Technology, Career Point University, Hamirpur, Himachal Pradesh, India

Francisco Corona
CARTIF Technology Centre, Circular Economy Area, Boecillo, Spain

Alida Cosenza
Engineering Department, University of Palermo, Palermo, Italy

Ronei de Almeida
Department of Sanitary and Environmental Engineering, Faculty of Engineering, Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

Daniele Di Trapani
Engineering Department, University of Palermo, Palermo, Italy

Doaa A. El-Emam
Environmental Sciences Department, Faculty of Science, Damietta University, New Damietta, Egypt

Melati Ferianita Fachrul
Environmental Engineering Department, Faculty of Landscape Architecture and Environmental Technology, Universitas Trisakti, Jakarta, Indonesia

Farzana Ferdous Faria
Department of Environmental Science, Bangladesh University of Professionals (BUP), Dhaka, Bangladesh

Asif Farooq
Department of Civil Engineering, National Institute of Technology, Srinagar, Jammu and Kashmir, India

Fernando Burgoa Francisco
CARTIF Technology Centre, Circular Economy Area, Boecillo, Spain

Avijit Ghosh
ICAR-Indian Grassland and Fodder Research Institute, Jhansi, Uttar Pradesh, India

Zakia Gueboudji
Department of Microbiology and Biochemistry, Faculty of Natural and Life Sciences, University of Batna 2, Batna, Algeria

Sadaf Gul
Department of Botany, University of Karachi, Karachi, Sindh, Pakistan

Imtiyaz Ahmad Gull
Department of Commerce, Government Degree College Tral, Higher Education Department, Govt. of Jammu and Kashmir, Srinagar, Jammu and Kashmir, India

Maryam Hamid
Department of Zoology, Faculty of Life Sciences, Government College University Faisalabad, Faisalabad, Punjab, Pakistan

Abdennaceur Hassen
Water Research and Technology Center (C.E.R.T. E), Borj-Cédria Techno-Park, Soliman, Tunisia

Bilel Hassen
Group of Aquatic Bacteriology and Biotechnology (GAB2), LR16INSTM05, The National Institute of Science and Technology of the Sea, University of Carthage, Salammbô, Tunisia

Wafa Hassen
Water Research and Technology Center (C.E.R.T. E), Borj-Cédria Techno-Park, Soliman, Tunisia

Diana Irvindiaty Hendrawan
Environmental Engineering Department, Faculty of Landscape Architecture and Environmental Technology, Universitas Trisakti, Jakarta, Indonesia

Sadia Ilyas
Department of Zoology, Faculty of Life Sciences, Government College University Faisalabad, Faisalabad, Punjab, Pakistan

Zeeshan Javed
Department of Zoology, Faculty of Life Sciences, Government College University Faisalabad, Faisalabad, Punjab, Pakistan

Neerja Kharwal
Division of Agrotechnology, Council of Scientific and Industrial Research-Institute of Himalayan Bioresource Technology (CSIR-IHBT), Palampur, Himachal Pradesh, India

Kuldeep Kumar
Department of Chemistry, Career Point University, Hamirpur, Himachal Pradesh, India; Centre for Nano-Science and Technology, Career Point University, Hamirpur, Himachal Pradesh, India

Ravi Kumar
Department of Chemistry, School of Sciences, Baddi University of Emerging Sciences and Technology, Baddi, Himachal Pradesh, India

Afaan A. Malla
Department of Environmental Science, Government Degree College Baramulla, Indira Gandhi National Open University, Baramulla, Jammu and Kashmir, India

Fayaz A. Malla
Department of Environmental Science, Government Degree College Tral, Higher Education Department, Govt. of Jammu and Kashmir, Srinagar, Jammu and Kashmir, India

Maria Clara Manzoki
Department of Bioprocess Engineering and Biotechnology, Polytechnic Center, Federal University of Parana, Curitiba, PR, Brazil

Sheilla Megagupita Putri Marendra
Environmental Engineering Department, Faculty of Landscape Architecture and Environmental Technology, Universitas Trisakti, Jakarta, Indonesia

Walter J. Martínez-Burgos
Department of Bioprocess Engineering and Biotechnology, Polytechnic Center, Federal University of Parana, Curitiba, PR, Brazil

Astari Minarti
Environmental Engineering Department, Faculty of Landscape Architecture and Environmental Technology, Universitas Trisakti, Jakarta, Indonesia

Sukanya Misra
Rani Lakshmi Bai Central Agricultural University, Jhansi, Uttar Pradesh, India

Kingshuk Modak
Forest Ecology and Climate Change Division, Rain Forest Research Institute, Jorhat, Assam, India

Ersan Muslih
Environmental Engineering Department, Faculty of Landscape Architecture and Environmental Technology, Universitas Trisakti, Jakarta, Indonesia

Muhammad Farrakh Nawaz
Institute of Environmental Studies, University of Karachi, Karachi, Sindh, Pakistan

Hong Nam Nguyen
Department of General Education, Vietnam Academy of Science and Technology, University of Science and Technology of Hanoi, Hanoi, Vietnam

Diego Ocán
Department of Bioprocess Engineering and Biotechnology, Polytechnic Center, Federal University of Parana, Curitiba, PR, Brazil

Olulope Olufemi Ajayi
Department of Biochemistry, Edo State University Uzairue, Auchi, Edo State, Nigeria

Probir Kumar Pal
Division of Agrotechnology, Council of Scientific and Industrial Research-Institute of Himalayan Bioresource Technology (CSIR-IHBT), Palampur, Himachal Pradesh, India; Academy of Scientific and Innovative Research (AcSIR), Ghaziabad, Uttar Pradesh, India

Anshuman Patel
Forest Ecology and Climate Change Division, Rain Forest Research Institute, Jorhat, Assam, India

Roberta Pozzan
Department of Cell Biology, Laboratory of Cell Toxicology, Polytechnic Center, Federal University of Paraná, Curitiba, PR, Brazil

Prachiprava Pradhan
Department of Chemical Engineering, Visvesvaraya National Institute of Technology, Nagpur, Maharashtra, India

Reno Pratiwi
Petroleum Engineering Department, Faculty of Earth and Energy Technology, Universitas Trisakti, Jakarta, Indonesia

Muhammad Sohail Qadir
Entomological Research Institute, Ayub Agricultural Research Institute, Faisalabad, Punjab, Pakistan

Md. Mostafizur Rahman
Department of Environmental Science, Bangladesh University of Professionals (BUP), Dhaka, Bangladesh; Laboratory of Environmental Health and Ecotoxicology, Department of Environmental Sciences, Jahangirnagar University, Savar, Dhaka, Bangladesh

R-Rafiul Rahman
Department of Environmental Science, Bangladesh University of Professionals (BUP), Dhaka, Bangladesh

Showkat Rashid
Department of Economics, Government Degree College Tral, Higher Education Department, Govt. of Jammu and Kashmir, Srinagar, Jammu and Kashmir, India

Ajit P. Rathod
Department of Chemical Engineering, Visvesvaraya National Institute of Technology, Nagpur, Maharashtra, India

Guilherme Anacleto dos Reis
Department of Bioprocess Engineering and Biotechnology, Polytechnic Center, Federal University of Parana, Curitiba, PR, Brazil

Ammara Riaz
Department of Life Sciences, Faculty of Natural and Applied Sciences, Khwaja Fareed University of Engineering and Information Technology, Rahim Yar Khan, Punjab, Pakistan

Sana Riaz
Department of Botany, University of Karachi, Karachi, Sindh, Pakistan

Astri Rinanti
Environmental Engineering Department, Faculty of Landscape Architecture and Environmental Technology, Universitas Trisakti, Jakarta, Indonesia

Cristine Rodrigues
Department of Bioprocess Engineering and Biotechnology, Polytechnic Center, Federal University of Parana, Curitiba, PR, Brazil

Mubshar Saleem
Department of Plant Pathology, PMAS Arid Agriculture University, Rawalpindi, Punjab, Pakistan

Usama Saleem
Department of Zoology, Faculty of Life Sciences, Government College University Faisalabad, Faisalabad, Punjab, Pakistan

Hafza Asma Shafique
Department of Botany, University of Karachi, Karachi, Sindh, Pakistan

Sheeza Shahid
Department of Life Sciences, Faculty of Natural and Applied Sciences, Khwaja Fareed University of Engineering and Information Technology, Rahim Yar Khan, Punjab, Pakistan

Sadia Sikder
Department of Environmental Science, Bangladesh University of Professionals (BUP), Dhaka, Bangladesh; Laboratory of Environmental Health and Ecotoxicology, Department of Environmental Sciences, Jahangirnagar University, Savar, Dhaka, Bangladesh

Carlos Ricardo Soccol
Department of Bioprocess Engineering and Biotechnology, Polytechnic Center, Federal University of Parana, Curitiba, PR, Brazil

Nazir A. Sofi
Department of Agriculture Research Information System, Sher-e-Kashmir University of Agricultural Sciences and Technology, Shalimar Campus, Srinagar, Jammu and Kashmir, India

Thalia Sunaryo
Environmental Engineering Department, Faculty of Landscape Architecture and Environmental Technology, Universitas Trisakti, Jakarta, Indonesia

Tahsin Tabassum
Department of Environmental Science, Bangladesh University of Professionals (BUP), Dhaka, Bangladesh

Javaid A. Tali
Department of Geography, Government Degree College Tral, Higher Education Department, Govt. of Jammu and Kashmir, Srinagar, Jammu and Kashmir, India

Babit Kumar Thakur
Division of Agrotechnology, Council of Scientific and Industrial Research-Institute of Himalayan Bioresource Technology (CSIR-IHBT), Palampur, Himachal Pradesh, India; Academy of Scientific and Innovative Research (AcSIR), Ghaziabad, Uttar Pradesh, India

Isha Thakur
Division of Agrotechnology, Council of Scientific and Industrial Research-Institute of Himalayan Bioresource Technology (CSIR-IHBT), Palampur, Himachal Pradesh, India

Manuela Russo Tiesi
Engineering Department, University of Palermo, Palermo, Italy

Mohammad Toha
Department of Environmental Science, Bangladesh University of Professionals (BUP), Dhaka, Bangladesh; Laboratory of Environmental Health and Ecotoxicology, Department of Environmental Sciences, Jahangirnagar University, Savar, Dhaka, Bangladesh

Hassan Usman
Department of Zoology, Faculty of Life Sciences, Government College University Faisalabad, Faisalabad, Punjab, Pakistan

Giovanni Vinti
Engineering Department, University of Palermo, Palermo, Italy

Gaspare Viviani
Engineering Department, University of Palermo, Palermo, Italy

About the editors

Dr. Tonni Agustiono Kurniawan is a recognized global leader in tackling complex environmental problems that have significant societal relevance and positive impact in the world. His research interests are in the areas of wastewater treatment and solid waste management. His degrees include a BSc in chemistry from the Bogor Agricultural University (Indonesia), an MSc in environmental technology from the Thammasat University (Thailand), and a PhD in applied chemical technology from the Hong Kong Polytechnic University (China). He is the author of over 350 peer-reviewed publications in ISI-rated journals and 30 conference proceedings, including 20 book chapters and 6 monographs in waste to energy and wastewater treatment.

Dr. Abdelkader Anouzla received his PhD in science and technology from Hassan II University—Faculty of Science and Technology Mohammedia, specializing in water treatment. Dr. Abdelkader Anouzla has published almost 100 peer-reviewed articles and 17 books. As well as being a guest speaker at several conferences, he has also published numerous proceedings. He has experience in water and wastewater, solid waste management, environmental chemistry, pollutants in soil, study and characterization of waste, recycling and reuse of waste to produce new materials, and air pollution.

Anouzla conducts research in the areas of water and waste treatment, wastewater treatment plant operation, leachate discharge treatment, solid waste sorting, technical landfill management, composting of solid waste and sludge from wastewater treatment plants, algae as a natural solution for water-food-energy nexus and microplastic pollution in the environment, digitalization in the water sector, saving water in business and irrigation, and nitrogen pollution.

Preface

Nitrogen, a vital nutrient for plant and microbial growth, plays an essential role in supporting agricultural productivity, ecosystem function, and the global food supply. Yet, its unchecked mobilization in the form of reactive nitrogen species (NO_3^-, NH_4^+, NOx, and organic nitrogen) has created one of the most pressing environmental challenges of our time: nonpoint source (NPS) nitrogen pollution. Unlike emissions from identifiable and discrete origins (point sources), NPS pollution arises diffusely from myriad land surfaces and water runoff, making it far more complex to quantify, trace, regulate, and mitigate.

This book addresses the science, policy, and management frameworks necessary to confront the growing threat of diffuse nitrogen pollution. It offers a multidisciplinary, evidence-based, and forward-looking perspective—bringing together insights from environmental chemistry, agronomy, hydrology, ecology, remote sensing, and socio-economics. This volume is aimed at a diverse audience: academic researchers, environmental engineers, policy practitioners, planners, students, and anyone engaged in water resource management and sustainable land-use planning.

The idea for this book was born from the mounting realization that achieving clean water, healthy ecosystems, and climate-resilient agriculture will remain elusive unless the challenge of NPS nitrogen pollution is addressed head-on. Globally, the release of nitrogen from fertilizers, animal husbandry, urban runoff, and atmospheric deposition continues to increase. As a result, eutrophication of freshwater and marine environments, groundwater contamination, and emissions of nitrous oxide—a potent greenhouse gas—are intensifying.

The insidious nature of NPS pollution lies in its invisibility. It does not originate from a single pipe or factory outlet, but rather from thousands of hectares of fertilized farmland, stormwater drains, leaky septic systems, and atmospheric deposition—often acting synergistically. This diffuseness makes detection difficult and regulatory enforcement even more so. At the same time, the complexity of nitrogen pathways—spanning surface runoff, subsurface leaching, plant uptake, microbial transformation, and atmospheric transport—necessitates integrated scientific tools and holistic management responses.

The urgency of addressing NPS nitrogen pollution cannot be overstated. According to UNEP's 2022 Global Nitrogen Assessment, over 80% of nitrogen fertilizers applied globally are not taken up by plants and instead escape into air, water, and soil. NPS nitrogen is a key driver of hypoxic dead zones, including in the Gulf of Mexico, Baltic Sea, and East China Sea. In rural and peri-urban areas, nitrate-contaminated drinking water is associated with elevated risks of methemoglobinemia and potential carcinogenic effects. In developing countries, poor regulatory oversight combined with rapidly intensifying agriculture and urbanization exacerbates these risks, especially where wastewater infrastructure is inadequate or nonexistent.

This book was written in recognition of a paradox: while the sources and consequences of NPS nitrogen pollution are well-documented, the solutions remain underimplemented, underfunded, and often undervalued in policy agendas. One of the key contributions of this volume is its attempt to bridge the science-policy-practice divide, showing how advanced knowledge and modeling can translate into scalable, context-sensitive action.

As authors and editors, our collective hope is that this book will serve as both a scientific reference and a catalyst for real-world change. It seeks to empower professionals and students alike with the conceptual clarity and technical tools needed to confront NPS nitrogen pollution as a climate, agriculture, public health, and water security issue.

We acknowledge the contributions of numerous colleagues, institutions, and datasets that have informed this work. In particular, we express gratitude to the research teams advancing integrative watershed science, to field practitioners testing solutions in real-world environments, and to the global scientific networks that have fostered interdisciplinary collaboration on nitrogen issues. We are also deeply grateful to Elsevier for supporting the publication of this book and for their commitment to advancing sustainable environmental science.

Let this book be a contribution to a broader movement: toward a nitrogen-smart planet—where food systems, ecosystems, and human health thrive together, guided by the principles of science, stewardship, and sustainability.

Tonni Agustiono Kurniawan
Abdelkader Anouzla

SECTION III

Toward a sustainable nitrogen management

CHAPTER 23

Sustainable solutions investigated for nitrogen pollution

Astri Rinanti[1], Melati Ferianita Fachrul[1], Diana Irvindiaty Hendrawan[1], Sarah Aphirta[1], Sheilla Megagupita Putri Marendra[1], Astari Minarti[1], Thalia Sunaryo[1], and Reno Pratiwi[2]
[1]Environmental Engineering Department, Faculty of Landscape Architecture and Environmental Technology, Universitas Trisakti, Jakarta, Indonesia,
[2]Petroleum Engineering Department, Faculty of Earth and Energy Technology, Universitas Trisakti, Jakarta, Indonesia

23.1 Introduction

Nitrogen pollution is a serious and complex environmental issue, and addressing it sustainably is essential for multiple interrelated reasons. It negatively impacts human health, disrupts aquatic and terrestrial ecosystems, contributes to climate change, and poses significant economic challenges. Nitrate (NO_3^-), a common form of nitrogen pollution, can contaminate groundwater and drinking water sources, leading to methemoglobinemia, or "blue baby syndrome," which affects oxygen transport in infants (Das et al., 2023). Ammonia (NH_3) and nitrogen dioxide (NO_2) emissions from industrial activities, agriculture, and motor vehicles can trigger respiratory issues, exacerbate asthma, and increase the risk of cardiovascular diseases. Additionally, nitrogen oxides (NO_x) contribute to the formation of fine particulate matter (PM2.5), which can penetrate deep into the lungs, potentially causing severe respiratory and cardiovascular diseases, including cancer (Afifa et al., 2024; Al-Hemoud et al., 2019).

Beyond its direct health effects, nitrogen emissions have significant environmental consequences. The release of NH_3, NO_x, and N_2O into the atmosphere contributes to aerosol formation, acid rain, and nitrogen deposition (both dry and wet), altering soil and water chemistry and harming ecosystems (Ti et al., 2022). Additionally, N_2O is a potent greenhouse gas that accelerates global warming, while NO_x contributes to stratospheric ozone depletion, exacerbating climate-related challenges (Houlton et al., 2019).

23.1.1 Human health

Exposure to NO_x and fine particulate matter from secondary aerosols is linked to respiratory and cardiovascular diseases (Sutton, 2011). Additionally, elevated nitrate

Nonpoint Source Nitrogen Pollution
DOI: https://doi.org/10.1016/B978-0-443-29070-1.00025-2

levels in drinking water and the consumption of contaminated seafood may increase the risk of colorectal cancer (Brender, 2020). Tropospheric ozone, driven in part by nitrogen emissions, negatively affects crop yields, ecosystems, and human health by contributing to global warming.

23.1.2 Ecosystems

Nitrogen deposition disrupts biodiversity, freshwater, and marine ecosystems. While policies like the US Clean Air Act have reduced NO_x emissions by 36%, NH_3 emissions remain largely unregulated and have increased. Excessive fertilizer use has also led to the proliferation of harmful algal blooms (HABs), causing severe ecological and economic consequences (Pardo et al., 2015).

23.1.3 Climate change

Nitrogen-driven N_2O emissions accelerate global warming and reduce carbon sequestration (Butterbach-Bahl et al., 2011). The use of nitrification inhibitors like DCD can lower N_2O emissions by up to 70% (Misselbrook et al., 2014), but their implementation remains limited. Without mitigation, global N_2O emissions could double by 2050, necessitating comprehensive reductions in emissions and lower per capita meat consumption in developed nations (Davidson & Kanter, 2014; Sunaryo et al., 2023).

Nitrogen (N) plays a crucial role in boosting food and fuel production; however, its excessive use has been identified as a significant threat to both the environment and human health due to an imbalance between nitrogen creation and its removal through denitrification. Researchers have categorized nitrogen-related threats into five key areas, collectively referred to as WAGES: water quality, air quality, greenhouse gas balances, ecosystem and biodiversity, and soil quality (Fig. 23.1) (Howard et al., 2011; Ti et al., 2022).

Surface water pollution is primarily driven by nitrogen (N), with approximately 18% to 21% of the total nitrogen (TN) input being transported to water bodies (Ti et al., 2022). As a result, many lakes and rivers in China suffer from eutrophication due to excessive nitrogen. For instance, Taihu Lake, the third-largest freshwater lake in southeastern China, has been undergoing eutrophication and frequent algal blooms since 1987. In May 2007 a severe algal bloom in Taihu Lake led to a drinking water crisis, impacting the water supply for approximately 2 million people in Wuxi, China. Over the past 30 years the annual average TN concentration has remained above $1.50\ mg \cdot L^{-1}$(Houlton et al., 2019; Qin et al., 2010). Excess nitrogen in freshwater and marine ecosystems can lead to eutrophication, a process that promotes excessive algal growth. As the algae die and decompose, they can reduce the oxygen levels in the water

Figure 23.1 The five key threats of excess reactive N. *Modified from Howard, C.M., Erisman, J.W., Beasley, W.J., Billen, G., Bleeker, A., Bouwman, A., Grennfelt, P., Grinsven, H., & Grizzetti, B. (2011).* The European nitrogen assessment approach: The challenge to integrate nitrogen science and policies. *Cambridge University Press, 82–96. Available fromhttp://www.nine-esf.org/files/ena_doc/ENA_pdfs/ENA_c5.pdf; Ti, C., Yan, X., Xia, L., & Huang, J. (2022). Improving nitrogen safety in China: Nitrogen flows, pollution and control.* Frontiers of Agricultural Science and Engineering*, 9(3), 465–474. https://doi.org/10.15302/J-FASE-2022454.*

(known as hypoxia or anoxia), causing the mass mortality of fish, invertebrates, and aquatic life. It also triggers HABs that produce toxins dangerous to humans and animals. In coral reefs, nitrogen imbalance increases disease susceptibility and bleaching. Changes in nitrogen levels can alter species composition and abundance in aquatic ecosystems, reducing biodiversity and favoring nitrogen-tolerant organisms (Akinnawo, 2023; Ngatia et al., 2019).

In terrestrial ecosystems, excess nitrogen disrupts plant species composition by favoring fast-growing and nitrogen-loving species, often outcompeting native or rare plants. Some nitrogen compounds contribute to soil acidification, which can mobilize heavy metals and affect nutrient availability to plants (Botez & Postolache, 2013; Pardo et al., 2015). Nitrous oxide (N_2O), a very potent greenhouse gas released through nitrification and denitrification processes, significantly contributes to climate change. As mentioned earlier, nitrous oxide (N_2O) is a powerful greenhouse gas. N_2O emissions from agriculture, industry, and waste management contribute to global warming and climate change. Nitrogen pollution also disrupts the natural carbon cycle in both terrestrial and aquatic ecosystems, affecting their capacity to absorb and store carbon (Aryal et al., 2022; Yao et al., 2022).

Nitrogen pollution incurs economic losses. The cost of treating nitrogen-related health conditions is enormous. Eutrophication-driven declines in fish populations harm the fishing industry while environmental degradation reduces tourist attraction and negatively affecting the local economy. Moreover, nitrogen-contaminated water requires extensive treatment costs to meet safe consumption standards (De Laporte et al., 2021). Addressing nitrogen pollution requires a sustainable approach. It is not a temporary issue; its impacts can persist and even amplify over time. Given that nitrogen pollution originates from multiple sources, including agriculture, industry, transportation, and sewage treatment, sustainable solution must comprehensively target all contributing sectors. Since ecosystems are highly complex, disruption to the nitrogen cycle can create unpredictable and interrelated consequences (de Vries, 2021). Sustainable strategies must consider this complexity by promoting systemic changes in food production, energy use, and waste management. Moreover, nitrogen pollution often disproportionately affects vulnerable communities. Sustainable approaches to address nitrogen pollution include the following:

- Optimizing fertilizer use in agriculture to minimize excess nitrogen.
- Developing effective sewage treatment systems to remove nitrogen before it enters the environment.
- Reducing nitrogen oxide emissions from industrial activities and motor vehicles.
- Restoring wetlands and other ecosystems that can absorb nitrogen naturally.
- Raising public awareness about the impacts of nitrogen pollution and ways to reduce individual nitrogen footprints.
- Implementing strict policies and regulations to control nitrogen pollution.

Addressing nitrogen pollution sustainably is important to protecting health, ecosystems, and the climate. Effective solutions should not only mitigate symptoms but also target the root causes. A holistic, integrated, and long-term approach is crucial, balancing environmental, economic, and social consideration (Ayuwaningsih et al., 2018). By applying a cross-sectoral strategy involving agriculture, industry, urban planning, and strong policy support, we can significantly minimize the negative impacts of nitrogen pollution while creating a healthier and more sustainable environment for future generations.

Improved wastewater treatment technologies and ecosystem restoration approaches are essential to address nitrogen pollution

Conventional wastewater treatment technologies are often ineffective in removing nitrogen. Therefore advanced technologies are needed to enhance the efficiency of nitrogen removal processes. These technologies address the limitations of conventional methods by optimizing biological processes such as nitrification and denitrification, thereby reducing the impact of nitrogen pollution on aquatic environments (Habibah et al., 2020; Hendrawan et al., 2022; Karima et al., 2018; Rohmah et al., 2018).

Modified biological treatment processes, such as the anaerobic/anoxic/oxidation (A^2/O) process and the oxidation ditch activated sludge treatment, are designed to enhance nitrification (conversion of ammonia to nitrate) and denitrification (conversion of nitrate to nitrogen gas) (Rahimi et al., 2020; Paul et al., 2022). There are two main processes to remove nitrogen (Fig. 23.2):

1. Nitrification, a gradual biological process where ammonia is converted into nitrate with the help of bacteria, which is the key in the nitrogen cycle and wastewater treatment.
2. Denitrification, a biological process where nitrate (NO_3^-) is converted into nitrogen gas (N_2) by bacteria, which is then released into the atmosphere. This process requires anoxic conditions (no oxygen, but nitrate is available).

Nitrogen removal from wastewater is essential to prevent environmental pollution and eutrophication. Fig. 23.3 illustrates four advanced nitrogen removal technologies:

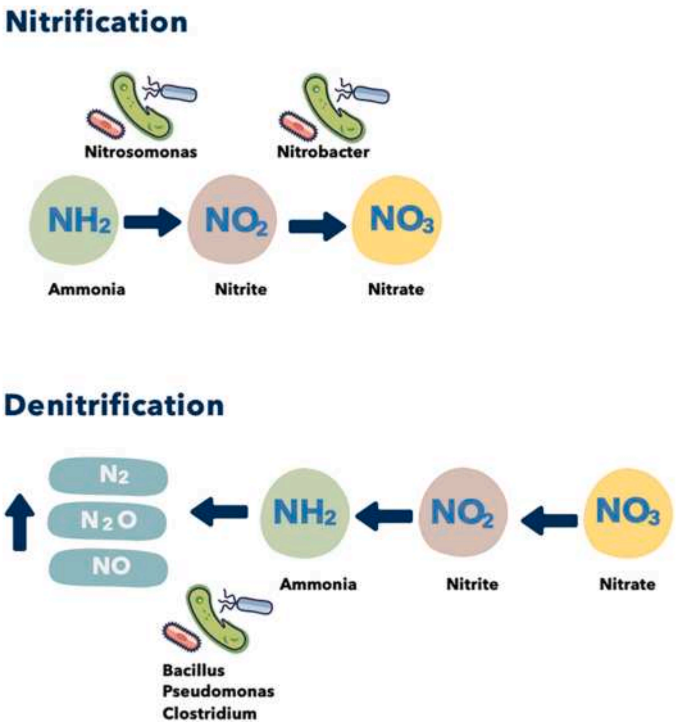
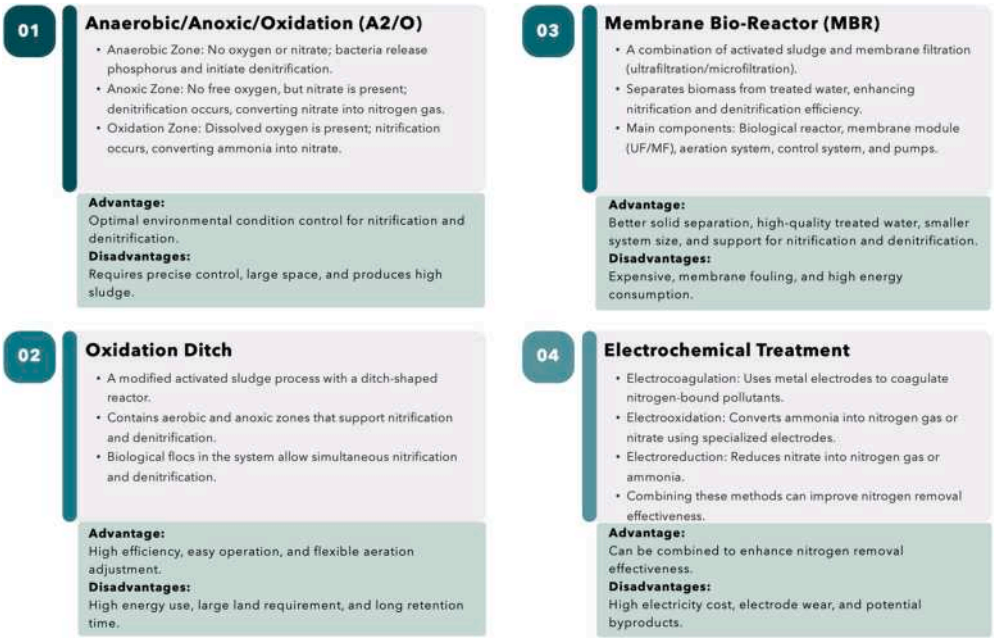


Figure 23.2 Nitrification and denitrification process.



01 **Anaerobic/Anoxic/Oxidation (A2/O)**

- Anaerobic Zone: No oxygen or nitrate; bacteria release phosphorus and initiate denitrification.
- Anoxic Zone: No free oxygen, but nitrate is present; denitrification occurs, converting nitrate into nitrogen gas.
- Oxidation Zone: Dissolved oxygen is present; nitrification occurs, converting ammonia into nitrate.

Advantage:
Optimal environmental condition control for nitrification and denitrification.
Disadvantages:
Requires precise control, large space, and produces high sludge.

02 **Oxidation Ditch**

- A modified activated sludge process with a ditch-shaped reactor.
- Contains aerobic and anoxic zones that support nitrification and denitrification.
- Biological flocs in the system allow simultaneous nitrification and denitrification.

Advantage:
High efficiency, easy operation, and flexible aeration adjustment.
Disadvantages:
High energy use, large land requirement, and long retention time.

03 **Membrane Bio-Reactor (MBR)**

- A combination of activated sludge and membrane filtration (ultrafiltration/microfiltration).
- Separates biomass from treated water, enhancing nitrification and denitrification efficiency.
- Main components: Biological reactor, membrane module (UF/MF), aeration system, control system, and pumps.

Advantage:
Better solid separation, high-quality treated water, smaller system size, and support for nitrification and denitrification.
Disadvantages:
Expensive, membrane fouling, and high energy consumption.

04 **Electrochemical Treatment**

- Electrocoagulation: Uses metal electrodes to coagulate nitrogen-bound pollutants.
- Electrooxidation: Converts ammonia into nitrogen gas or nitrate using specialized electrodes.
- Electroreduction: Reduces nitrate into nitrogen gas or ammonia.
- Combining these methods can improve nitrogen removal effectiveness.

Advantage:
Can be combined to enhance nitrogen removal effectiveness.
Disadvantages:
High electricity cost, electrode wear, and potential byproducts.

Figure 23.3 Advanced nitrogen removal technologies for wastewater treatment.

A^2/O, oxidation ditch, membrane bioreactor (MBR), and electrochemical treatment, each with its advantages and disadvantages. The choice between these systems depends on various factors, including wastewater characteristics, land availability, and cost.

23.1.4 The anaerobic/anoxic/oxidation process

The A^2/O process is a widely used biological wastewater treatment system designed to improve nitrogen and phosphorus removal. This process is an enhancement of the conventional activated sludge system, incorporating three sequential treatment zones: anaerobic, anoxic, and aerobic (oxic). Each zone plays a crucial role in removing nitrogen compounds from wastewater, ensuring compliance with environmental discharge standards and minimizing the risk of water pollution, particularly eutrophication caused by excessive nitrogen and phosphorus in aquatic ecosystems (Chen et al., 2021; Wang et al., 2021). This is a common modification consisting of three main zones:

1. Anaerobic zone, where oxygen and nitrate are absent. The aim is to release phosphorus and initiate denitrification by breaking down organic compounds into simpler ones.

2 Anoxic zone contains nitrate (NO_3^-) but no free oxygen where denitrifying bacteria convert nitrate into nitrogen gas (N_2).
3 Oxidation zone (aerobic) contains dissolved oxygen where nitrifying bacteria convert ammonia (NH_3) into nitrate (NO_3^-) while oxidizing organic matter.

This process enhances nitrogen removal by optimizing microbial activity under controlled conditions (dissolved oxygen, temperature, pH). By separating the aerobic and anoxic zones the system efficiently converts ammonia into nitrogen gas, making it a widely used method for reducing nitrogen pollution in wastewater management.

23.1.5 Oxidation ditch—modification of the conventional activated sludge

Conventional activated sludge processes typically have one aeration tank, effective for carbon removal but less so for nitrogen removal. To improve this, oxidation ditches—using a ditch-shaped reactor or closed ring—are used in activated sludge systems. These provide long residence times. Long winding ditch moves wastewater at low velocities. Mechanical aerators placed along the ditch create aerobic zones, while anoxic zones may develop in areas far from the aerators due to bacterial oxygen consumption (Agbewornu et al., 2021).

Oxidation ditches enhance nitrification and denitrification by optimizing both processes. Continuous circulation of wastewater ensures even distribution of microorganisms to grow and perform effectively. Aerators maintain aerobic zones for nitrification on a scheduled basis, while anoxic zones in deeper sections or within biological floc allow denitrification (Mantziaras et al., 2010). Some ditches use aeration and nonaeration cycles to promote anoxic zone formation. Microorganisms in the oxidation ditch form a biological floc, a mass of microbial cells and organic matter. These flocs have an aerobic outer layer and an anoxic inner layer, enabling simultaneous nitrification and denitrification. Oxidation ditches have longer hydraulic retention times (HRTs) than other wastewater systems, making this system a reliable wastewater treatment solution (Gogina et al., 2021; Wang et al., 2011).

23.1.6 Membrane bioreactor

This is a wastewater treatment technology combining activated sludge process with membrane filtration. Biological processes (activated sludge) decompose pollutants from wastewater, while membrane filtration separates suspended solids (biomass) from treated water. Key components include (Mao et al., 2020):

1 Biological reactor (activated sludge), a tank where microorganisms (activated sludge) break down organic matter. Aeration supplies oxygen for aerobic bacteria.

2. Membrane module houses ultrafiltration (UF) or microfiltration (MF) membranes acting as a physical barrier to separate suspended solids (biomass) from treated water.
3. Aeration system provides oxygen for biological processes and helps clean membranes using fine bubble diffusers.
4. Control system monitors and regulates dissolved oxygen level, temperature, pH, and transmembrane pressure.
5. Pumps, transport wastewater, circulate water, and draw treated water through the membrane.

In conventional activated sludge systems, solid separation is done using sedimentation tanks. However, this process is often inefficient and can result in treated water of varying quality. Therefore MBR overcomes this problem by using filtration membranes. The filtration membrane within a membrane bioreactor (MBR) has an extremely small pore size, effectively retaining suspended solids, bacteria, viruses, and colloidal particles. This ensures high-quality treated water that is virtually free of solids. Since the membrane acts as a physical barrier, water quality remains stable despite fluctuations in wastewater composition or operating conditions. MBRs also maintain a higher concentration of biomass, improving pollutant decomposition efficiency while eliminating the need for sedimentation tanks, saving space and construction costs (Mao et al., 2020; Choi et al., 2021).

With higher biomass concentrations, MBRs enhance solids separation and nitrogen removal by supporting more nitrifying bacteria, which convert ammonia to nitrate. Some configurations include an anoxic zone for denitrification, further improving nitrogen removal. MBRs operate with shorter HRT, reducing reactor size and construction costs while maintaining high water quality. Their longer solid retention time supports the growth of sensitive bacteria essential for effective wastewater treatment. MBRs produce high-quality treated water suitable for reuse in irrigation, industrial cooling, or even drinking water with further treatment. Their compact design makes them ideal for areas with limited space, and automation reduces labor needs. However, they require higher investment and operational costs, and membrane may experience fouling, necessitating regular cleaning or replacement (Liu & Wang, 2014)

Despite these challenges, MBR technology is increasingly adopted due to its superior water quality and compliance with strict environmental regulations. By combining activated sludge with membrane filtration, MBRs efficiently remove pollutants using oxidation–reduction processes, making them a promising solution for modern wastewater treatment (Jijingi et al., 2024).

23.1.7 Electrochemical treatment process

This method involves the use of electrodes to oxidize or reduce nitrogen pollutants in wastewater. Techniques such as electrocoagulation, electrooxidation, and electroreduction are examples of electrochemical processes that can effectively remove nitrogen. Utilizing electrified electrodes, electrochemical treatment triggers chemical reactions that facilitate the removal of pollutants from wastewater. The process utilizes oxidation and reduction (redox) principles to convert pollutants into less harmful or more easily separated forms (Galoppo et al., 2024; Lee et al., 2024; Iovino et al., 2023).

23.1.8 Electrocoagulation

Electrocoagulation employs a metal electrode, typically aluminum or iron, that dissolves (anode) when an electric current is applied. These dissolved metal ions act as coagulant agents. When these ions interact with pollutants, including nitrogen in particulate form or bound to organic matter, they form larger flocs which are easily precipitated or filtered out. The process starts when an electric current is applied; the anode (e.g., aluminum) oxidizes and releases metal ions (Al^{3+}).

$Al \rightarrow Al^{3+} + 3e-$

Metal ions (e.g., Al^{3+}) react with water and hydroxide (OH^{-}) in solution to form complex metal hydroxide polymers.

$Al^{3+} + xH_2O \Leftrightarrow Al(OH)_x^{(3-X)} + xH^{+}$

These metal hydroxide polymers attract and agglomerate pollutants, including organic nitrogen compounds or nitrogen-containing particulates, forming larger flocs. These flocs can be precipitated, filtered, or separated through other methods. Electrocoagulation effectively removes nitrogen bound to particulate or organic matter but not dissolved nitrogen like ammonia, nitrite, or nitrate directly. It works if these nitrogen forms are attached to coagulated particles or organic matter. The method is simple, cost-effective, efficient, and needs minimal chemical additives. However, it may produce sludge requiring further treatment, and its efficiency depends on the type of wastewater.

23.1.9 Electrooxidation

Electrooxidation (EO) employs electrodes that act as catalysts to oxidize nitrogen pollutants directly or through the formation of strong oxidative species on the electrode surface. Certain electrodes, such as boron-doped diamond electrodes, can directly oxidize nitrogen pollutants, such as ammonia, into simpler products like nitrogen gas (N_2) or nitrate (NO_3-). For example:

Additionally, electrodes can generate strong oxidative species, including hydroxyl radicals (-OH), ozone (O_3), or hydrogen peroxide (H_2O_2), capable of oxidizing nitrogen pollutants. An example reaction is as follows:

These oxidation reactions can convert various forms of nitrogen into nitrogen gas or other forms that are easier to remove. Electrooxidation is effective in eliminating ammonia, nitrite, and certain organic nitrogen compounds. However, the efficiency of this process varies depending on the type of electrode, operating conditions, and the form of nitrogen present. While electrooxidation can efficiently oxidize pollutants, produce fewer hazardous end products, and eliminate the need for additional chemicals, it requires significant electrical energy. Moreover, its efficiency can be influenced by the type of electrode and the formation of by-products (e.g., nitrate).

Electroreduction (ER) uses electrodes to reduce nitrogen pollutants like nitrate (NO_3-) into less harmful products such as nitrogen gas (N_2) or ammonia (NH_3). At the cathode, NO_3- can be reduced through several electrochemical reactions: Each method has its own advantages and limitations, and the selection of the appropriate method depends on the dominant nitrogen species, wastewater conditions, and treatment objectives. A combination of several electrochemical methods may result in a more effective and efficient solution in removing nitrogen from wastewater.

Under certain conditions, nitrate can also be reduced to ammonia. Electroreduction effectively removes nitrates, which are hard to eliminate by other methods. However, it can produce ammonia as a by-product. This method can produce a less harmful product (nitrogen gas) without needing additional chemicals but requires electrical energy and careful optimization of operating conditions to avoid excessive ammonia production.

Three electrochemical methods—electrocoagulation, electrooxidation, and electroreduction—can be used alone or combined for better nitrogen removal efficiency (Asfaha et al., 2021), such as:

- Electrocoagulation + electrooxidation: removing particulate-bound nitrogen and then dissolved nitrogen.
- Electrooxidation + electroreduction: converting ammonia to nitrate and then reducing nitrate to nitrogen gas.

These processes offer promising solutions for addressing nitrogen pollution in wastewater. Each method has specific benefits and limitations, and choosing the suitable method relies on the dominant nitrogen species, wastewater conditions, and treatment goals. Combining multiple electrochemical methods can provide a more effective and efficient solution for removing nitrogen from wastewater.

23.2 Exploitation of natural ecosystem capabilities

Natural ecosystems have inherent abilities to regulate and purify environmental components, making them valuable tools for mitigating nitrogen pollution. By leveraging these natural processes, we can enhance water quality and promote ecosystem balance in a sustainable manner.

23.2.1 Restoration of degraded natural wetlands

Restoration of degraded natural wetlands supports higher biodiversity and complex nitrogen cycling, offering stable and efficient nitrogen removal if successful. They provide additional benefits like wildlife habitat, flood control, and carbon storage. However, severe degradation such as topsoil loss, drastic hydrological changes, or invasive plant dominance may require significant time and cost, with unpredictable results. Controlling parameters such as water depth and vegetation type is challenging, and unresolved pollution sources may lead to redegradation (Land et al., 2016).

23.2.2 Constructed wetlands

Constructed wetlands can be tailored to specific needs such as the type of pollutants to be removed, treatment capacity, and local environmental conditions. They can be constructed in optimal locations to address specific pollution problems, even if there are no natural wetlands in the area. The operating parameters of artificial wetlands, such as water depth, flow rate, and plant type, can be set to optimize nitrogen removal. Constructed wetlands can be implemented at different scales, ranging from small-scale systems for domestic wastewater treatment to large-scale systems for urban and industrial wastewater treatment. Constructed wetlands generally have more quantifiable and predictable nitrogen removal efficiencies than restored natural wetlands due to the ability to control their operational parameters. Despite these advantages, constructed wetlands may not exhibit the same biodiversity and complex ecosystem functions as natural wetlands. The construction of artificial wetlands typically incurs higher costs compared to natural wetlands restoration, especially when soil excavation, construction, and planting are required. Constructed wetlands require regular maintenance activities, such as plant pruning, sediment removal, and water quality monitoring, to ensure proper functioning (Liu, Zhang, et al., 2024; Liu, Li, et al., 2024).

To address nitrogen pollution in the environment, constructed wetlands often prove to be more efficient and reliable than restoring degraded natural wetlands (Ruiz et al., 2025), particularly:

- When the primary focus is efficient nitrogen removal, constructed wetlands can be specifically designed and optimized for this purpose.
- In locations where no degraded natural wetlands exist or where natural wetlands are too deteriorated to restore effectively, constructed wetlands may serve as a superior alternative.
- Where greater control over operational parameters and nitrogen removal efficiency is required, constructed wetlands provide advantages through more precise regulation.

- Constructed wetlands can be engineered to accommodate various scales of wastewater treatment, ranging from small-scale to large-scale applications.

However, it is important to consider that natural wetland restoration remains important for broader ecological purposes, such as biodiversity, carbon storage, and flood control. Where possible, it is best to prioritize restoration of degraded natural wetlands as part of a more comprehensive solution. To efficiently address nitrogen pollution, constructed wetlands are often a better choice due to their controlled design, site flexibility, and ability to optimize operational parameters (Tazkiaturrizki, 2016). However, natural wetland restoration remains important for broader ecological purposes and can be part of a comprehensive solution. The final decision should be based on project-specific objectives, local conditions, available resources, and required scale. Always consider combining both approaches to achieve the most optimal results (Liu et al., 2020).

23.2.3 Riparian zone

Riparian zones are areas of vegetation located on the banks of rivers, lakes, or other water bodies, serving as the transition between aquatic and terrestrial ecosystems. The vegetation in these zones typically includes trees, bushes, grasses, and aquatic plants, offering an effective, natural, and sustainable solution to nitrogen pollution by leveraging biological and physical processes. These zones play a significant role in maintaining water quality and supporting healthy ecosystems. Understanding the nitrogen cycle and its related factors in riparian zones is necessary for assessing feasible and effective nitrogen reduction measures. Additionally, riparian zones act as "sinks" for inorganic nitrogen (especially NO_3^-), where microbial processes, particularly denitrification, play a crucial role in converting inorganic nitrogen into N_2 gas, reducing nitrogen pollution through atmospheric emissions (Kim et al., 2016; Lyu et al., 2021).

Riparian zones play a significant role in reducing nitrogen pollution by filtering and removing nitrogen from water flowing into water bodies. This occurs through several main mechanisms:

- Riparian vegetation absorbs nitrogen (nitrate and ammonia) from the water through its roots, using it as nutrients for growth. This reduces the amount of nitrogen entering the water bodies.
- The soil in riparian zones often has anoxic (low oxygen) conditions, particularly in areas close to water. These conditions are ideal for denitrification, a process wherein bacteria convert nitrate (NO_3-) into nitrogen gas (N_2), which is then released into the atmosphere. Organic carbon from decaying plant matter further accelerates this process, effectively removing nitrogen from the water system (Rinanti et al., 2014).

- Riparian vegetation slows the flow of surface water, allowing sediment and nitrogen-containing particles to settle. Plant roots also filter these particles from the water, preventing dissolved and bound nitrogen in sediments from directly entering water bodies.
- Plant roots enhance the infiltration of water into the soil, reducing surface runoff that can carry nitrogen to water bodies. Infiltrated water undergoes filtration and denitrification processes in the soil before reaching groundwater or water bodies.

Riparian zones represent a natural solution that utilizes ecosystem processes to address nitrogen pollution, making them a sustainable option in the long term. In addition to reducing nitrogen pollution, riparian zones also provide a range of other benefits, such as:

- Habitat for wildlife and biodiversity.
- Bank stability and erosion prevention.
- Clean water provision and water quality protection.
- Regulation of water temperature and microclimate.

Establishing and maintaining riparian zones can be more cost-effective than engineering solutions over time. These zones can adapt to various environmental conditions and local vegetation types. The implementation of riparian zones often starts with the restoration of damaged or lost areas to improve water quality and biodiversity. In new development projects, riparian zones can be included as part of the water management system to mitigate nitrogen pollution. In agricultural areas, riparian zones serve as a buffer between farmland and water bodies to reduce nitrogen runoff from fertilizers.

The effectiveness of buffer zones depends on various factors, including topography, size, width, vegetation, soil type, management mode, climatic conditions, nutrient load extent, and the kind, intensity, and transformation of pollutants. Effective riparian zone design requires careful planning that considers these aspects to maximize benefits such as pollution reduction, biodiversity enhancement, and other ecosystem services. By optimizing these factors, riparian buffers can function more efficiently in filtering contaminants, stabilizing ecosystems, and supporting long-term environmental sustainability (Jin et al., 2022; Lind et al., 2019; Wu et al., 2023).

The key steps and considerations in designing an effective riparian zone are (Jiang et al., 2020):

1. Assessing location and environmental conditions
   a. Consider slope, elevation, and other topographic features that may affect water and sediment flow. Analyze soil type, texture, and water infiltration capacity. Improve sandy soils if needed. Also, consider surface water and groundwater flow patterns, including frequency and duration.

  - **b** Analyze water quality (including nitrogen, phosphorus, and other pollutants) and discharge, especially in the rainy season.
  - **c** Identify native vegetation growing in the area for resilience and biodiversity. Assess vegetation health, density, and diversity.
- **2** Define riparian zone design objective
  - **a** Set targets for pollutant reduction, especially nitrogen.
  - **b** Enhance biodiversity by selecting wildlife-attracting plants.
  - **c** Prevent erosion, maintain bank stability, and regulate water temperature
  - **d** Incorporate recreational and esthetic value.
- **3** Establish vegetation zones before selecting vegetation types, which are as follows:
  - **a** Riparian zone (wet vegetation), planted with aquatic plants, wet grasses, and shrubs that are tolerant of flooding and water-saturated soil conditions.
  - **b** Middle zone, planted with trees and shrubs with high water and nutrient absorption, damp-tolerant.
  - **c** Terrestrial zone (dry vegetation), planted drought-tolerant plants for soil stabilization.

Various types of vegetation were planted to enhance the biodiversity and resilience of the riparian zone against disturbances. Trees with robust root systems capable of absorbing substantial amounts of water and nutrients, such as willow, maple, and alnus, were selected. Shrubs were densely planted to combat soil erosion, including species like dogwood and elderberry. Grasses and herbaceous plants with effective root systems and tolerance to wet conditions, such as sedge and rush grasses, were also chosen. Additionally, fast-growing vegetation was selected to expedite the establishment of the riparian zone (Prosser et al., 2020; Yi et al., 2021).

The proper selection of plants is critical to ensure the riparian zone functions effectively in reducing pollution, preventing erosion, and supporting biodiversity. The chosen plants must be resilient to the typical environmental conditions of riparian zones, such as moist or flooded soils and fluctuations in water levels. Table 23.1 presents recommended plant species for wetland and riparian areas, highlighting their key characteristics. These plants are selected based on their ability to tolerate wet conditions, absorb excess water and nutrients, stabilize banks, reduce nitrogen levels, and support wildlife habitats.

While riparian zones offer numerous benefits, several challenges must be addressed for successful implementation. Technical and environmental challenges include soil infertility, erosion, fluctuating water levels, invasive species, and wildlife damage. Social and economic challenges involve landowner resistance, conflicts of interest, lack of awareness, funding, expertise, and opposition from industries and farmers due to land use restrictions. Institutional and policy challenges stem from unclear regulations, weak law enforcement, lack of coordination between agencies, and insufficient research on

Table 23.1 Recommended plants for wetland and riparian areas.

Plant type	Plant names	Characteristics
Trees	Willow (*Salix* spp.), including Salix nigra (Black Willow), Salix alba (White Willow)	Tolerant to wet conditions, absorbs nitrogen, stabilizes riverbanks
	Red Maple (*Acer rubrum*)	Absorbs large amounts of water, provides wildlife habitat
	River Birch (*Betula nigra*)	Absorbs nitrogen, suitable for wet areas
	Green Ash (*Fraxinus pennsylvanica*)	Resistant to high humidity, fast-growing
	Sycamore (*Platanus occidentalis*)	Absorbs large amounts of water, strong trunk
	Alder (*Alnus* spp.), including Alnus glutinosa (Black Alder)	Stabilizes soil, improves nitrogen levels in the soil
Shrubs	Dogwood (*Cornus* spp.)	Thrives in wet conditions, dense growth, attractive stems and flowers. Examples: *Cornus sericea* (Red Osier Dogwood), *Cornus amomum* (Silky Dogwood)
	Elderberry (*Sambucus* spp.)	Tolerates wet conditions, fast growth, produces bird-attracting fruits. Example: *Sambucus canadensis* (American Elderberry)
	Buttonbush (*Cephalanthus occidentalis*)	Thrives in wet or flooded areas, unique growth, spherical flowers
	Spicebush (*Lindera benzoin*)	Tolerates moist conditions, fragrant leaves, shade-tolerant
	Winterberry (*Ilexverticillata*)	Thrives in wet areas, produces attractive red berries in winter
Grasses and herbs	Sedges (*Carex* spp.)	Resistant to wet and flooded conditions, strong root system. Examples: *Carex stricta* (Tussock Sedge), *Carex lurida* (Lurid Sedge)
	Rushes (*Juncus* spp.)	Resistant to wet conditions, upright growth, strong root system
	Switchgrass (*Panicum virgatum*)	Tolerant to both wet and dry conditions, deep root system
		Blue Flag Iris (Iris versicolor): Tolerant to wet conditions, beautiful blue flowers
	Joe-Pye Weed (*Eutrochium* spp.)	Thrives in moist areas, produces attractive pink or purple flowers
Aquatic plants	Cattails (*Typha* spp.)	Grows in shallow water or wet soil, dense tall growth

(*Continued*)

Table 23.1 (Continued)

Plant type	Plant names	Characteristics
	Water Lily (*Nymphaea* spp.)	Thrives in still water, broad floating leaves, beautiful flowers
	Pickerelweed (*Pontederiacordata*)	Grows in shallow water, heart-shaped leaves, purple flowers

effective restoration methods. Implementation and maintenance challenges include high costs, long maturation periods, and the need for continuous monitoring, maintenance, and adaptive management to ensure effectiveness (Jiang et al., 2020; Kim et al., 2016; Liu et al., 2024).

23.3 Sustainable solutions for nitrogen pollution

Fig. 23.4 illustrates various sustainable strategies to reduce nitrogen pollution across agriculture, industry, and urban areas. These solutions focus on improving nitrogen fertilizer efficiency, sustainable farming, waste management, industrial emission control, and eco-friendly transportation to mitigate environmental impacts.

23.3.1 Sustainable solutions in agriculture

Agriculture is a major contributor to nitrogen pollution, but several sustainable solutions can help mitigate its impact:

1. More efficient utilization of nitrogen fertilizers (Ren, Xu, et al., 2022; Rütting et al., 2018; Waqas et al., 2023).
    - **a** Precision fertilization techniques use technology (such as soil sensors and GPS systems) to apply fertilizer only where it is needed and at the right time, reducing excess fertilizer released into the environment.
    - **b** Slow-release fertilizers, fertilizers that release nitrogen gradually that reducing leaching into the water.
    - **c** Replacing chemical fertilizers with organic alternatives, such as compost and manure that release nitrogen slowly and enhance soil health.
2. Sustainable agriculture practices (Bednarek et al., 2014; Spiertz, 2010).
    - **a** Rotating high nitrogen-requiring crops with legume crops which fix atmospheric nitrogen and decrease the need for nitrogen fertilizers.
    - **b** Reducing excessive tillage to maintain soil structure and reduce nitrogen release into the atmosphere.

Figure 23.4 Comprehensive sustainable solutions for nitrogen pollution.

   c Integrating trees with crops, as trees can help absorb nitrogen and improve soil quality.

3 Livestock waste reduction (Bai et al., 2022; Zhang et al., 2024).

   a Processing livestock waste into biogas or organic fertilizer, reducing ammonia and nitrate emissions.

   b Providing proper feed to reduce nitrogen excretion in livestock manure.

23.3.2 Sustainable solutions in industry and cities

Beyond agriculture, routine industrial and urban activities also contribute to nitrogen pollution. Several solutions can mitigate this impact (Han et al., 2022; Petrovic et al., 2016; Seddon et al., 2021; Raghuram et al., 2021):

1. Reducing industrial emissions through catalytic converters and scrubbers minimizes nitrogen oxide (NO_x) emissions from industrial chimneys. Improving energy efficiency in the factories further cuts fossil combustion.
2. Advanced wastewater management using bioreactors and membrane filtration removes nitrogen from sewage before it is discharged. Reclaimed wastewater can be reused for irrigation or other industrial processes (Wikaningrum et al., 2022).
3. Reduce reliance on NO_x-emitting fossil fuel vehicles by expanding public transportation and bicycle lanes to reduce the number of private vehicles on the road.
4. Urban waste management improvements, such as enhanced organic waste composting systems to reduce landfill waste while generating compost for agriculture.

23.3.3 Government strategies for nitrogen management

Government policies addressing nitrogen pollution span multiple sectors, including agriculture, industry, and transportation, aim to reduce nitrogen emissions and mitigate their negative impacts on the environment and public health. While nitrogen is essential for agricultural productivity and ecosystem balance, its excessive use and poor management contribute to severe environmental problems such as water contamination, greenhouse gas emissions, and soil degradation. To address these challenges, many countries have implemented sustainable nitrogen management policies (Sitawati et al., 2022). These policies take various forms, from strict regulatory measures to economic incentives and research-driven initiatives, ensuring a more balanced and environmentally responsible approach to nitrogen use. Policies by adapting frameworks from the International Energy Agency's policy database and the NewClimate Institute's policy database to the nitrogen context illustrate each category with a relevant as follows (Kanter et al., 2020; IEA Energy Policy Inventory, 2019; Yang et al., 2022):

1. These policies set clear and enforceable limits on nitrogen consumption, production, or loss to control environmental impact. One example is the environmental protection regulations in Australia, which establish nitrogen oxide (NO_x) emission standards for vehicles and impose financial penalties for noncompliance. Such regulations help reduce air pollution and its harmful effects on human health and ecosystems.
2. Financial incentives are used to encourage industries and individuals to adopt nitrogen management practices that align with environmental goals. For instance, wastewater regulations in Mauritius require businesses to obtain licenses for effluent discharge, ensuring compliance with nitrogen concentration limits. Economic policies like tax incentives, subsidies, or market-based instruments can promote efficient nitrogen use while reducing environmental degradation.
3. These policies establish broad objectives for managing nitrogen pollution without imposing strict quantitative limits. An example is Egypt's biodiversity strategy, which includes guidelines for fertilizer and pesticide use. Such frameworks provide a long-term vision and strategic direction for sustainable nitrogen management while allowing flexibility in implementation at different levels of governance.
4. Accurate data collection and standardized reporting protocols are essential for monitoring nitrogen pollution and assessing its environmental impact. Policies in this category focus on setting measurement parameters for nitrogen compounds in air, soil, and water. For example, air quality monitoring regulations in Bosnia and Herzegovina specify methods for tracking nitrogen dioxide and ammonia levels, ensuring better pollution control and informed decision-making.
5. Investment in scientific research is crucial for developing innovative solutions to mitigate nitrogen pollution. Governments fund research programs aimed at

improving nitrogen use efficiency and minimizing environmental harm. In Vietnam a national initiative supports high-tech agricultural research, fostering advancements in precision farming and enhanced-efficiency fertilizers.

6 Regulations governing nitrogen-related commercial activities ensure the safe production, distribution, and use of fertilizers and other nitrogen-based products. Policies in this category often set requirements for packaging, labeling, transport, and registration of nitrogen-containing materials. For example, fertilizer use laws in Albania establish clear rules to prevent misuse and ensure proper handling within the agricultural sector.

7 These policies provide incentives to increase nitrogen use, often targeting agricultural productivity. Governments may introduce subsidy programs or reduce costs through private-sector involvement in fertilizer importation and manufacturing. A relevant example is Kenya's Crops Act, which encourages more affordable access to fertilizers by supporting local production and distribution networks.

The effectiveness of government policies in addressing nitrogen pollution can be measured through various environmental, economic, health, and social indicators. Environmentally, this involves monitoring the reduction of nitrate ($NO3-$), ammonia ($NH4+$), and TN levels in water, air, and soil, as well as improvements in water quality and ecosystems. Economically, effectiveness can be assessed through changes in agricultural and industrial production costs, increased nitrogen fertilizer efficiency, and higher incomes for farmers adopting sustainable practices. From a health perspective, indicators include reductions in respiratory diseases and methemoglobinemia caused by nitrogen pollution. Social indicators encompass public acceptance and participation in nitrogen pollution control programs, behavioral changes among farmers and consumers, and increased public awareness of nitrogen pollution's impacts and mitigation efforts. To ensure accurate assessment, data from monitoring stations, surveys, and health records are regularly analyzed, while mathematical models predict outcomes and identify areas needing further attention. Periodic evaluations help measure policy effectiveness and guide necessary improvements (Ngatia et al., 2019; Srivastava et al., 2024).

The limited data available make it challenging to measure policy effectiveness and isolate its impact from other factors affecting nitrogen pollution. Environmental policies often show long-term effects, requiring continuous monitoring. Climate change and other conditions can influence measurement results. However, a comprehensive and integrated approach using various indicators and methods is essential. Collected data should be carefully analyzed to evaluate policy impact and make necessary improvements. Regular evaluations help the government and other stakeholders determine if policies are effectively protecting the environment and public health (EPA United States Environmental Protection Agency, 2015).

23.3.4 Key challenges in managing nitrogen pollution

This include technical, social, political, global, administrative, and economic barriers. To overcome these issues, various strategic solutions are proposed, such as institutional strengthening, cross-sector collaboration, economic incentives, and continuous research and innovation

23.3.4.1 Technical and scientific challenges

The nitrogen cycle is highly complex, involving various biochemical and physical processes. Fully understanding nitrogen movement and transformation requires continuous research and sophisticated modeling. Some nitrogen reduction technologies, such as catalytic converters for industry or advanced wastewater treatment systems, require significant investments, which can be a constraint for small and medium industries or developing countries. Technologies that are successfully implemented in one location may not be immediately applicable elsewhere due to differences in environmental, social, and economic conditions. Adapting these technologies often requires additional research and development. Accurately and continuously monitoring nitrogen pollution levels demands adequate infrastructure and resources. Additionally, standardized measurement methods are essential to ensure comparable and reliable data (Akinnawo, 2023; Awewomom et al., 2024).

23.3.4.2 Economic challenges

Strict nitrogen pollution reduction policies can be costly for governments, industries, and farmers. These costs may include investments in new technologies, changes in farming practices, or adjustments to production processes. Industries required to meet strict emission standards may face higher production costs, potentially reducing their competitiveness in the global market, especially if competitors in other countries under less restrictive regulations. Strict policies may disproportionately burden on lower-economic groups, such as small-scale farmers or home industries, which may lack of resources to comply with the new requirements. In developing countries, limited financial and technical resources often pose a significant challenge to implementing effective environmental policies (Gazzani, 2017Ren, Zhang, et al., 2022).

23.3.4.3 Social and political challenges

Stakeholders, such as industries or farmers, may oppose policies that are perceive as restrictive or reduce their profits. Public support may be weak if citizens are unaware of nitrogen pollution's negative impacts and the importance of control measures. Policies developed without community involvement are often less effective due to lack of support and active participation. Political decisions are often influenced by specific group interests or short-term considerations, which can hinder long-term sustainability efforts. Corruption and weak law enforcement can lead to ineffective environmental policies, as violations go unpunished or even ignored (Awewomom et al., 2024; Morseletto, 2019).

23.3.4.4 Administrative and institutional challenges

Nitrogen pollution control requires coordination among multiple sectors and institutions, including central and local governments, as well as nongovernmental organizations. Implementing agencies may lack sufficient human resources or expertise to enforce policy effectively. Unclear or even conflicting regulations can create confusion and obstruct policy implementation. The lack of accurate data and relevant information can impede to make informed and effective decisions. The absence of robust evaluation and monitoring system can lead ineffective policies to continue without improvements (Awewomom et al., 2024; Stuart et al., 2014; Yang et al., 2022).

23.3.4.5 Global challenges

International trade can shift the pollution burden from one country to another, making strong international cooperation essential for nitrogen pollution control. Climate change affects the nitrogen cycle and exacerbates the impacts of nitrogen pollution, requiring climate-adaptive policies. Population growth and urbanization increase environmental pressure and exacerbating nitrogen pollution if not addressed with appropriate policies (Liu et al., 2020; Basu et al., 2025).

Overcoming the above challenges requires a comprehensive and integrated approach, which includes:

1. Improving the human resources and expertise of institutions responsible for policy implementation. Strengthening the capacity of government agencies and research institutions through training programs, knowledge-sharing initiatives, and recruitment of skilled professionals ensures more effective implementation and enforcement of nitrogen-related policies (David, 2024).
2. Engaging the community in both the formulation and implementation of policies. Public participation in environmental decision-making fosters awareness, accountability, and social acceptance of regulations. Community-led initiatives, educational programs, and stakeholder consultations can improve policy effectiveness and encourage sustainable practices (UNEP Working Group, 2023).
3. Providing economic incentives to encourage the adoption of eco-friendly technologies and practices. Subsidies, tax reductions, and financial support for sustainable farming, clean industrial processes, and pollution control technologies can encourage businesses and individuals to adopt environmentally friendly solutions (Zhang et al., 2015).
4. Enforcing strict penalties for rule violations. Robust monitoring, reporting, and enforcement mechanisms are essential to ensure compliance with nitrogen

regulations. Imposing substantial fines, legal actions, and operational restrictions on violators can deter practices that contribute to nitrogen pollution (Srivastava et al., 2024).

5. Continuously conducting research and development to find more effective and efficient solutions. Investment in scientific research, technological advancements, and policy innovations is essential to developing better nitrogen management strategies. Research on fertilizer efficiency, emission reduction, and pollution mitigation can lead to more sustainable solutions (Herrera et al., 2016; Udvardi et al., 2021).

Artificial intelligence disclosure

During the preparation of this work the author(s) used Kakak.ai. In the preparation of this manuscript, AI is used solely to broaden perspectives and generate a framework or outline. The content will then be rewritten based on the authors' insights and supported by valid references. After using this tool/service the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

References

Afifa, Arshad, K., Hussain, N., Ashraf, M. H., & Saleem, M. Z. (2024). Air pollution and climate change as grand challenges to sustainability. *Science of the Total Environment, 928*. https://doi.org/10.1016/J.SCITOTENV.2024.172370, 172370.

Agbewornu, K. C. D., Adyel, T. M., & Zhai, J. (2021). Optimizing nitrogen removal in a hybrid oxidation ditch. *Journal of Environmental Chemical Engineering, 9*(4), 1. https://doi.org/10.1016/J.JECE.2021.105443, 05443.

Akinnawo, S. O. (2023). Eutrophication: Causes, consequences, physical, chemical and biological techniques for mitigation strategies. *Environmental Challenges, 12*. https://doi.org/10.1016/J.ENVC.2023.100733, 100733.

Al-Hemoud, A., Gasana, J., Al-Dabbous, A., Alajeel, A., Al-Shatti, A., Behbehani, W., & Malak, M. (2019). Exposure levels of air pollution (PM2.5) and associated health risk in Kuwait. *Environmental Research, 179*. https://doi.org/10.1016/J.ENVRES.2019.108730, 108730.

Aryal, B., Gurung, R., Camargo, A. F., Fongaro, G., Treichel, H., Mainali, B., Angove, M. J., Ngo, H. H., Guo, W., & Puadel, S. R. (2022). Nitrous oxide emission in altered nitrogen cycle and implications for climate change. *Environmental Pollution, 314*. https://doi.org/10.1016/J.ENVPOL.2022.120272, 120272.

Asfaha, Y. G., Tekile, A. K., & Zewge, F. (2021). Hybrid process of electrocoagulation and electrooxidation system for wastewater treatment: A review. *Cleaner Engineering and Technology, 4*. https://doi.org/10.1016/J.CLET.2021.100261, 100261.

Awewomom, J., Dzeble, F., Takyi, Y. D., Ashie, W. B., Ettey, E. N. Y. O., Afua, P. E., Sackey, L. N. A., Opoku, F., & Akoto, O. (2024). Addressing global environmental pollution using environmental control techniques: A focus on environmental policy and preventive environmental management. *Discover Environment 2024 2:1, 2*(1), 1–20. https://doi.org/10.1007/S44274-024-00033-5, https://link.springer.com/article/10.1007/s44274-024-00033-5.

Ayuwaningsih, I. P., Fachrul, M. F., & Rinanti, A. (2018). Increasing lipid content from biomass of microalgae to produce biofuels with optimization of nitrogen source. *MATEC Web of Conferences, 197*. https://doi.org/10.1051/matecconf/201819713011, http://creativecommons.org/licenses/by/4.0/.

Bai, Z., Fan, X., Jin, X., Zhao, Z., Wu, Y., Oenema, O., Velthof, G., Hu, C., & Ma, L. (2022). Relocate 10 billion livestock to reduce harmful nitrogen pollution exposure for 90% of China's population. *Nature Food, 3*(2), 152–160. https://doi.org/10.1038/s43016-021-00453-z, https://www.nature.com/articles/s43016-021-00453-z.

Basu, N. B., Van Meter, K. J., Byrnes, D. K., Cappellen, V. P., Brouwer, R., Jacobsen, B. H., Jarsjo, J., Rudolph, D. L., Cunha, M. C., Nelson, N., Bhattacharya, B., Destouni, F., & Olsen, S. B. (2025). Managing nitrogen legacies to accelerate water quality improvement. *Nature Geoscience, 15*, 97–105. https://research.vu.nl/ws/portalfiles/portal/216945373/Managing_nitrogen_legacies_to_accelerate_water_quality_improvement.pdf.

Bednarek, A., Szklarek, S., & Zalewski, M. (2014). Nitrogen pollution removal from areas of intensive farming—comparison of various denitrification biotechnologies. *Ecohydrology & Hydrobiology, 14*(2), 132–141. https://doi.org/10.1016/J.ECOHYD.2014.01.005.

Botez F. & Postolache C. (2013). Bucharest Printed in Romania. All rights reserved REVIEW Abstract Biodiversity loss, as a result of human activities, affects ecosystem productivity and sustainability. Along with climate change and habitat reduction, enhanced nitrogen inputs via atmospheric deposition represent the major drivers of biodiversity reduction. Nitrogen is a limiting factor for ecosystems. Increased bioavailable nitrogen due to increased nitrogen emissions is detrimental for biodiversity compartments. This review summarizes the general soil nitrogen biogeochemical cycle, macro regional nitrogen deposition studies and trends as well as the effects of increased nitrogen deposition, whether site specific or experimental addition. Present review also describes types of impact that elevated nitrogen induce on different ecosystem types and managerial propositions to mitigate the negative impacts of nitrogen depositions. Romanian Biotechnological Letters 6 biodiversity grasslands microorganisms terrestrial nitrogen cycle 8723 8723 Nitrogen deposition impact on terrestrial ecosystems 18.

Brender, J. D. (2020). Human health effects of exposure to nitrate, nitrite, and nitrogen dioxide. *Just Enough Nitrogen,* 283–294. https://doi.org/10.1007/978-3-030-58065-0_18.

Butterbach-Bahl, K., Nemitz, E., Zaehle, S., Billen, G., Boeckx, P., Erisman, J. W., Garnier, J., Upstill-Goddard, R., Kreuzer, M., Oenema, O., Reis, S., Schaap, M., Simpson, D., de Vries, W., Winiwarter, W., & Sutton, M. A. (2011). Nitrogen as a threat to the European greenhouse balance. *The European Nitrogen Assessment,* 434–462. https://doi.org/10.1017/CBO9780511976988.022, https://www.cambridge.org/core/books/european-nitrogen-assessment/nitrogen-as-a-threat-to-the-european-greenhouse-balance/FC325D3683723456BEC0F27E17A54C56.

Chen, X., Wei, X., Yang, Y., Wang, S., Lu, Q., Wang, Y., Li, Q., & Wang, S. (2021). Comparison of nitrogen removal efficiency and microbial characteristics of modified two-stage A/O, A2/O and SBR processes. *Environmental Geochemistry and Health, 43*(11), 4687–4699. https://doi.org/10.1007/S10653-021-00855-9/METRICS, https://link.springer.com/article/10.1007/s10653-021-00855-9.

Choi, M. S., Hwang, Y. H., & Lee, T. J. (2021). Nitrogen removal using a membrane bioreactor with rubber particles as the fouling reducer. *Applied Sciences, 11*(8), 3578. https://doi.org/10.3390/APP11083578, https://www.mdpi.com/2076-3417/11/8/3578.

Das, R., Rao, N. S., Sahoo, H. K., & Sakram, G. (2023). Nitrate contamination in groundwater and its health implications in a semi-urban region of Titrol block, Jagatsinghpur district, Odisha, India. *Physics and Chemistry of the Earth, Parts A/B/C, 132*. https://doi.org/10.1016/J.PCE.2023.103424, 103424.

David, K. (2024). *Good practices in capacity building and awareness creation on sustainable nitrogen management.* https://chatgpt.com/c/67c0a3fa-cb7c-800e-93ad-aa9eef41b60f.

Davidson, E. A., & Kanter, D. (2014). Inventories and scenarios of nitrous oxide emissions. *Environmental Research Letters, 9*(10). https://doi.org/10.1088/1748-9326/9/10/105012, https://iopscience.iop.org/article/10.1088/1748-9326/9/10/105012/meta.

De Laporte, A., Banger, K., Weersink, A., Wagner-Riddle, C., Grant, B., & Smith, W. (2021). Economic and environmental consequences of nitrogen application rates, timing and methods on corn in Ontario. *Agricultural Systems, 188*. https://doi.org/10.1016/J.AGSY.2020.103018, 103018.

EPA United States Environmental Protection Agency. (2015). *A compilation of cost data associated with the impacts and control of nutrient pollution.*

Galoppo, S., Fenti, A., Falco, G., Huang, Q., Chianese, S., Musmarra, D., & Iovino, P. (2024). Efficient electrochemical removal of ammoniacal nitrogen from livestock wastewater: The role of the electrode material. *Heliyon, 10*(17). https://doi.org/10.1016/J.HELIYON.2024.E36803, e36803.

Gazzani, F. (2017). Economic and environmental evaluation of nitrogen fertilizer taxation: A review. *International Journal of Environment, Agriculture and Biotechnology (IJEAB), 2*(4), 1829–2834. https://doi.org/10.22161/ijeab/2.4.47, http://doi.org/10.22161/ijeab/2.4.47.

Gogina, E., & Gulshin, I. (2021). Characteristics of low-oxygen oxidation ditch with improved nitrogen removal. *Water, 13*(24), 3603. https://doi.org/10.3390/W13243603, https://www.mdpi.com/2073–4441/13/24/3603.

Habibah, R., Iswanto, B., & Rinanti, A. (2020). The significance of tropical microalgae *Chlorella sorokiniana* as a remediate of polluted water caused by chlorpyrifos. International Journal of Scientific & Technology Research. *9*, 1. https://doi.org/10.1016/j.etap.2016.05.032, http://www.ijstr.org.

Han, C. Y., Gu, Z. L., & Yang, H. (2022). Effects of industrial agglomeration on nitrogen dioxide pollution using spatial panel durbin and panel threshold models. *Frontiers in Environmental Science, 10*. https://doi.org/10.3389/fenvs.2022.844479.

Hendrawan, D. I., Fachrul, M. F., & Rinanti, A. (2022). Water quality status and pollution load capacity analysis of lakes in Depok City, West Java, Indonesia. *Indian Journal of Environmental Protection, 42*(14). https://www.e-ijep.co.in/42-14-1737-1741/.

Herrera, J. M., Rubio, G., Häner, L. L., Delgado, J. A., Lucho-Constantino, C. A., Islas-Valdez, S., & Pellet, D. (2016). Emerging and established technologies to increase nitrogen use efficiency of cereals. *Agronomy, 6*(2), 25. https://doi.org/10.3390/AGRONOMY6020025, https://www.mdpi.com/2073-4395/6/2/25.

Houlton B.Z., Almaraz M., Aneja V., Austin A.T., Bai E., Cassman K.G., Compton J.E., Davidson E.A., Erisman J.W., Galloway J.N., Gu B., Yao G., Martinelli L.A., Scow K., Schlesinger W.H., Tomich T. P., Wang C., & Zhang X. (2019). Nitrogen is a critical component of the economy, food security, and planetary health. Many of the world's sustainability targets hinge on global nitrogen solutions, which, in turn, contribute lasting benefits for (i) world hunger; (ii) soil, air, and water quality; (iii) climate change mitigation; and (iv) biodiversity conservation. Balancing the projected rise in agricultural nitrogen demands while achieving these 21st century ideals will require policies to coordinate solutions among technologies, consumer choice, and socioeconomic transformation. Earth's Future doi: 10.1029/2019EF001222 8 biogeoscience climate change nitrogen planetary health policy technology 865 872 John Wiley and Sons Inc A world of co-benefits: Solving the global nitrogen challenge 7.

Howard, C. M., Erisman, J. W., Beasley, W. J., Billen, G., Bleeker, A., Bouwman, A., Grennfelt, P., Grinsven, H., & Grizzetti, B. (2011). *The European nitrogen assessment approach: The challenge to integrate nitrogen science and policies*. Cambridge University Press, 82–96. http://www.nine-esf.org/files/ena_doc/ENA_pdfs/ENA_c5.pdf.

IEA Energy Policy Inventory. (2019). Global energy and climate model—Policies https://www.iea.org/reports/global-energy-and-climate-model/policies.

Iovino, P., Fenti, A., Galoppo, S., Najafinejad, M. S., Chianese, S., & Musmarra, D. (2023). Electrochemical removal of nitrogen compounds from a simulated saline wastewater. *Molecules, 28*(3), 1306. https://doi.org/10.3390/MOLECULES28031306, https://www.mdpi.com/1420-3049/28/3/1306.

Jiang, F., Preisendanz, H. E., Veith, T. L., Cibin, R., & Drohan, P. J. (2020). Riparian buffer effectiveness as a function of buffer design and input loads. *Journal of Environmental Quality, 49*(6), 1599–1611. https://doi.org/10.1002/JEQ2.20149, https://pubmed.ncbi.nlm.nih.gov/33043471/.

Jijingi, H. E., Yazdi, S. K., Abakar, Y. A., & Etim, E. (2024). Evaluation of membrane bioreactor (MBR) technology for industrial wastewater treatment and its application in developing countries: A review. *Case Studies in Chemical and Environmental Engineering, 10*. https://doi.org/10.1016/J.CSCEE.2024.100886, 100886.

Jin, B., Liu, X., Tan, J., Shao, X., & Cheng, J. (2022). Effect of plant buffer zone–antifouling curtain wall on reducing non-point source pollution in paddy fields, China. *Sustainability, 14*(10), 6044. https://doi.org/10.3390/SU14106044, https://www.mdpi.com/2071-1050/14/10/6044.

Kanter, D. R., Chodos, O., Nordland, O., Rutigliano, M., & Winiwarter, W. (2020). Gaps and opportunities in nitrogen pollution policies around the world. *Nature Sustainability*. https://doi.org/10.1038/s41893-020-0577-7, https://doi.org/10.1038/s41893-020-0577-7.

Karima, A., Silalahi, M.D.S., & Rinanti, A. (2018). *The 3rd Annual Applied Science and Engineering Conference Water Quality Status and Pollution Load Capacity Analysis of Lakes in Depok City, West Java, Indonesia* https://www.e-ijep.co.in/42−14−1737−1741/.

Kim, H., Bae, H. S., Reddy, K. R., & Ogram, A. (2016). Distributions, abundances and activities of microbes associated with the nitrogen cycle in riparian and stream sediments of a river tributary. *Water Research, 106*, 51–61. https://doi.org/10.1016/J.WATRES.2016.09.048.

Land M., Granéli W., Grimvall A., Hoffmann C., Christian M.W.J., Karin S.T., & Verhoeven J.T.A. (2016). Background: Eutrophication of aquatic environments is a major environmental problem in large parts of the world. In Europe, EU legislation (the Water Framework Directive and the Marine Strategy Framework Directive), international conventions (OSPAR, HELCOM) and national environmental objectives emphasize the need to reduce the input of nutrients to freshwater and marine environments. A widely used method to achieve this is to allow water to pass through a created or restored wetland. However, the large variation in measured nutrient removal rates in such wetlands calls for a systematic review. Methods: Searches for primary studies were performed in electronic databases and on the internet. One author performed the screening of all retrieved articles at the title and abstract level. To check that the screening was consistent and complied with the agreed inclusion/exclusion criteria, subsets of 100 articles were screened by the other authors. When screening at full-text level the articles were evenly distributed among the authors. Kappa tests were used to evaluate screening consistency. Relevant articles remaining after screening were critically appraised and assigned to three quality categories, from two of which data were extracted. Quantitative synthesis consists of meta-analyses and response surface analyses. Regressions were performed using generalized additive models that can handle nonlinear relationships and interaction effects. Results: Searches generated 5853 unique records. After screening on relevance and critical appraisal, 93 articles including 203 wetlands were used for data extraction. Most of the wetlands were situated in Europe and North America. The removal rate of both total nitrogen (TN) and total phosphorus (TP) is highly dependent on the loading rate. Significant relationships were also found for annual average air temperature (T) and wetland area (A). Median removal rates of TN and TP were 93 and 1.2 g m-2 year-1, respectively. Removal efficiency for TN was significantly correlated with hydrologic loading rate (HLR) and T, and the median was 37 %, with a 95 % confidence interval of 29-44 %. Removal efficiency for TP was significantly correlated with inlet TP concentration, HLR, T, and A. Median TP removal efficiency was 46 % with a 95 % confidence interval of 37-55 %. Although there are small differences in average values between the two quality categories, the variation is considerably smaller among high quality studies compared to studies with lower quality. This suggests that part of the large variation between studies may be explained by less rigorous study designs. Conclusions: On average, created and restored wetlands significantly reduce the transport of TN and TP in treated wastewater and urban and agricultural runoff, and may thus be effective in efforts to counteract eutrophication. However, restored wetlands on former farmland were significantly less efficient than other wetlands at TP removal. In addition, wetlands with precipitation-driven HLRs and/or hydrologic pulsing show significantly lower TP removal efficiencies compared to wetlands with controlled HLRs. Loading rate (inlet concentrations × hydraulic loading rates) needs to be carefully estimated as part of the wetland design. More research is needed on the effects of hydrologic pulsing on wetlands. There is also a lack of evidence for long-term (>20 years) performance of wetlands. Environmental Evidence 10.1186/s13750–016−0060−0 1 Constructed wetland Eutrophication Nitrogen Nutrient Phosphorus Pond Removal efficiency Removal rate Restored wetland Wetland creation BioMed Central Ltd. How effective are created or restored freshwater wetlands for nitrogen and phosphorus removal? A systematic review 5.

Lee, J., Antonini, G., Al-Omari, A., Muller, C., Mathew, J., Bell, K., Pearce, J. M., & Santoro, D. (2024). Electrochemical methods for nutrient removal in wastewater: A review of advanced electrode materials, processes, and applications. *Sustainability, 16*(22), 9764. https://doi.org/10.3390/SU16229764, https://www.mdpi.com/2071-1050/16/22/9764.

Lind, L., Hasselquist, E. M., & Laudon, H. (2019). Towards ecologically functional riparian zones: A meta-analysis to develop guidelines for protecting ecosystem functions and biodiversity in agricultural landscapes. *Journal of Environmental Management, 249*. https://doi.org/10.1016/J.JENVMAN.2019.109391, https://pubmed.ncbi.nlm.nih.gov/31445372/.

Liu, D., Chen, Q., Zhang, J., Zhang, W., Wang, Z., Jiang, Q., & Lee, J. Y. (2024). Regulating flow to maximize riverine nitrogen removal by riparian zones downstream of reservoirs. *Journal of Hydrology, 638*. https://doi.org/10.1016/J.JHYDROL.2024.131526, 131526–131526.

Liu, L., Zhang, X., Xu, W., Liu, X., Li, Y., Wei, J., Gao, M., Bi, J., Lu, X., Wang, Z., & Wu, X. (2020). Challenges for global sustainable nitrogen management in agricultural systems. *Journal of Agricultural and Food Chemistry, 68*(11), 3354–3361. https://doi.org/10.1021/ACS.JAFC.0C00273/ASSET/IMAGES/MEDIUM/JF0C00273_0005.GIF, https://pubs.acs.org/doi/abs/10.1021/acs.jafc.0c00273.

Liu, Q., Wang, X. C. (2014). Mechanism of nitrogen removal by a hybrid membrane bioreactor in municipal wastewater treatment. In Conference on water resources and urbanization development desalination and water treatment. Tianjin, China Liu Q., & Wang X.C. (2014) 2014 Conference on Water Resources and Urbanization Development Desalination and Water Treatment Tianjin, China Mechanism of nitrogen removal by a hybrid membrane bioreactor in municipal wastewater treatment.

Liu, S., Zhang, Y., Feng, X., & Pyo, S. H. (2024). Current problems and countermeasures of constructed wetland for wastewater treatment: A review. *Journal of Water Process Engineering, 57*. https://doi.org/10.1016/J.JWPE.2023.104569, 104569.

Liu, T., Li, D., Tian, Y., Zhou, J., Qiu, Y., Li, D., Liu, G., & Feng, Y. (2024). Enhancing nitrogen removal in constructed wetlands: The role of influent substrate concentrations in integrated vertical-flow systems. *Environmental Science and Ecotechnology, 21*. https://doi.org/10.1016/J.ESE.2024.100411, 100411.

Lyu, C., Li, X., Yuan, P., Song, Y., Gao, H., Liu, X., Liu, R., & Yu, H. (2021). Nitrogen retention effect of riparian zones in agricultural areas: A meta-analysis. *Journal of Cleaner Production, 315*. https://doi.org/10.1016/j.jclepro.2021.128143, https://doi.org/10.1016/j.jclepro.2021.128143, 128143.

Mantziaras, I. D., Stamou, A., & Katsiri, A. (2010). Performance optimization of an alternating oxidation ditch system by cycle timelength variation. *3rd International Conference on Small and Decentralized Water and Wastewater Treatment Plants (SWAT-III,* 1–6.

Mao, X., Myavagh, P. H., Lotfikatouli, S. M. A. S., Benjamin, S. H., & M Asce, H. W. W. (2020). Membrane bioreactors for nitrogen removal from wastewater: A review. *Journal of Environmental Engineering, 145*(5). https://doi.org/10.1061/(ASCE)EE.1943-7870.0001682.

Misselbrook, T. H., Cardenas, L. M., Camp, V., Thorman, R. E., Williams, J. R., Rollet, A. J., & Chambers, B. J. (2014). An assessment of nitrification inhibitors to reduce nitrous oxide emissions from UK agriculture. *Environmental Research Letters, 9*, 1–11. https://iopscience.iop.org/article/10.1088/1748-9326/9/11/115006/pdf.

Morseletto, P. (2019). Confronting the nitrogen challenge: Options for governance and target setting. *Global Environmental Change, 54*, 40–49. https://doi.org/10.1016/J.GLOENVCHA.2018.10.010, https://www.researchgate.net/publication/329755204_Confronting_the_nitrogen_challenge_Options_for_governance_and_target_setting.

Ngatia, L., Grace, J. M., III, Moriasi, D., Taylor, R., Ngatia, L., Moriasi, D., & Taylor, R. (2019). Nitrogen and phosphorus eutrophication in marine ecosystems. In *Monitoring of Marine Pollution*. IntechOpen. http://chapters/64674.10.5772/INTECHOPEN.81869.

Pardo, L. H., Blett, T., Clark, C. M., Geiser, L. H., Peak, E., Metcalf, W. L. (2015). Impacts of nitrogen pollution on terrestrial ecosystem in the United States. Pardo by, L. H., Blett, T., Clark, C. M., Geiser, L. H., Peak, E., Metcalf, W.L. 2015 Impacts of nitrogen pollution on terrestrial ecosystem in the United States.

Paul, D., Banerjee, A., Macko, S., Paul, D., & Banerjee, A. (2022). Technologies for biological and bioelectrochemical removal of inorganic nitrogen from wastewater: A review. *Nitrogen, 3*(2), 298–313. https://doi.org/10.3390/NITROGEN3020020, https://www.mdpi.com/2504-3129/3/2/20.

Petrovic, J., Lecic, D., & Pavlovic, D. (2016). Sustainable urban development and industrial pollution. *Industrija, 44*(1), 167–185. https://doi.org/10.5937/INDUSTRIJA1-10466, https://www.researchgate.net/publication/303504440_Sustainable_urban_development_and_industrial_pollution.

Prosser, R. S., Hoekstra, P. F., Gene, S., Truman, C., White, M., & Hanson, M. L. (2020). A review of the effectiveness of vegetated buffers to mitigate pesticide and nutrient transport into surface waters from agricultural areas. *Journal of Environmental Management, 261*. https://doi.org/10.1016/J.JENVMAN.2020.110210, https://pubmed.ncbi.nlm.nih.gov/32148280/.

Qin, B., Zhu, G., Gao, G., Zhang, Y., Li, W., Paerl, H. W., & Carmichael, W. W. (2010). A drinking water crisis in Lake Taihu, China: Linkage to climatic variability and lake management. *Environmental Management, 45*(1), 105–112. https://doi.org/10.1007/S00267-009-9393-6/METRICS, https://link.springer.com/article/10.1007/s00267-009-9393-6.

Raghuram, N., Sutton, M. A., Jeffery, R., Ramachandran, R., & Adhya, T. K. (2021). From South Asia to the world: Embracing the challenge of global sustainable nitrogen management. *One Earth, 4*(1), 22–27. https://doi.org/10.1016/J.ONEEAR.2020.12.017.

Rahimi, S., Modin, O., & Mijakovic, I. (2020). Technologies for biological removal and recovery of nitrogen from wastewater. *Biotechnology advances, 43*. https://doi.org/10.1016/J.BIOTECHADV.2020.107570, 107570–107570.

Ren, C., Zhang, X., Reis, S., & Gu, B. (2022). Socioeconomic barriers of nitrogen management for agricultural and environmental sustainability. *Agriculture, ecosystems & environment, 333*. https://doi.org/10.1016/J.AGEE.2022.107950, 107950.

Ren, K., Xu, M., Li, R., Zheng, L., Liu, S., Reis, S., Wang, H., Lu, C., Zhang, W., Gao, H., Duan, Y., & Gu, B. (2022). Optimizing nitrogen fertilizer use for more grain and less pollution. *Journal of Cleaner Production, 360*. https://doi.org/10.1016/J.JCLEPRO.2022.132180, 132180.

Rinanti, A., Kardena, E., Astuti, D. I., & Dewi, K. (2014). Improvement of carbon dioxide removal through artificial light intensity and temperature by constructed green microalgae consortium in a vertical bubble column photobioreactor. *Malaysian Journal of Microbiology, 10*. https://doaj.org/article/51cc6305bdce4a76859b57c00159c446.

Rohmah, Y., Rinanti, A., & Hendrawan, D. I. (2018). The determination of ground water quality based on the presence of Escherichia coli on populated area (a case study: Pasar Minggu, South Jakarta). *IOP Conference Series: Earth and Environmental Science, 106*(1), 012079. https://doi.org/10.1088/1755-1315/106/1/012079, https://iopscience.iop.org/article/10.1088/1755-1315/106/1/012079/meta.

Ruiz, D., Gamboa, S. A., Paniagua-Solar, L. A., Téllez, N., & Zayas, T. (2025). Design of an efficient constructed wetland prototype for sustainable wastewater treatment in developing countries: A community case study in Mexico. *Journal of Water Process Engineering, 69*. https://doi.org/10.1016/J.JWPE.2024.106822, 1068222.

Rütting, T., Aronsson, H., & Delin, S. (2018). Efficient use of nitrogen in agriculture. *Nutrient Cycling in Agroecosystems, 110*(1), 1–5. https://doi.org/10.1007/S10705-017-9900-8/METRICS, https://link.springer.com/article/10.1007/s10705-017-9900-8.

Seddon J., Smit W., Kheirbek I., & Gu B. (2021). Elsevier https://doi.org/10.1016/j.oneear.2020.12.019 8 9 The urban nitrogen challenge 4.

Sitawati, A., Taki, H. M., & Andajani, R. D. (2022). The influence of environmental policies on selecting investment locations. *Indonesian Journal of Urban And Environmental Technology, 5*(3), 266–280. https://doi.org/10.25105/URBANENVIROTECH.V5I3.14448, https://e-journal.trisakti.ac.id/index.php/urbanenvirotech/article/view/14448.

Spiertz, J. H. J. (2010). Nitrogen, sustainable agriculture and food security. A review. *Agronomy for Sustainable Development, 30*(1), 43–55. https://doi.org/10.1051/AGRO:2008064, https://www.researchgate.net/publication/41706463_Nitrogen_Sustainable_Agriculture_and_Food_Security_A_Review.

Srivastava, R. P., Kumar, S., & Tiwari, A. (2024). Continuous emission monitoring systems (CEMS) in India: Performance evaluation, policy gaps and financial implications for effective air pollution control. *Journal of Environmental Management, 359*. https://doi.org/10.1016/J.JENVMAN.2024.120584, 120584.

Stuart, D., Schewe, R. L., & McDermott, M. (2014). Reducing nitrogen fertilizer application as a climate change mitigation strategy: Understanding farmer decision-making and potential barriers to change in the US. *Land Use Policy, 36*, 210–218. https://doi.org/10.1016/J.LANDUSEPOL.2013.08.011.

Sunaryo, T., Radyati, M. R. N., Utha, M. A., Rinanti, A., & Minarti, A. (2023). Research development on carbon capture, utilization and storage as a climate change mitigation technology. *Environmental Research, Engineering and Management, 79*(1), 37–55. https://doi.org/10.5755/J01.EREM.79.1.32424, https://erem.ktu.lt/index.php/erem/article/view/32424.

Sutton, M. A. (2011). The European nitrogen assessment: Sources, effects and policy perspectives. *The European Nitrogen Assessment*. https://doi.org/10.1017/CBO9780511976988, https://www.cambridge.org/core/books/european-nitrogen-assessment/7156D2A2F03CD36FFA0B6EC60BF9A497.

Tazkiaturrizki (2016). Pengaruh penambahan glycine max pada penyisihan nitrogen dalam constructed wetland tipe subsurface horizontal flow. *Indonesian Journal of Urban And Environmental Technology, 8*(1), 117–124. https://doi.org/10.25105/URBANENVIROTECH.V8I1.724, https://e-journal.trisakti.ac.id/index.php/urbanenvirotech/article/view/724.

Ti, C., Yan, X., Xia, L., & Huang, J. (2022). Improving nitrogen safety in China: Nitrogen flows, pollution and control. *Frontiers of Agricultural Science and Engineering, 9*(3), 465–474. https://doi.org/10.15302/J-FASE-2022454.

Udvardi, M., Below, F. E., Castellano, M. J., Eagle, A. J., Giller, K. E., Ladha, J. K., Liu, X., Maaz, T. M. C., Nova-Franco, B., Raghuram, N., Robertson, G. P., Roy, S., Saha, M., Schmidt, S., Tegeder, M., York, L. M., & Peters, J. W. (2021). A research road map for responsible use of agricultural nitrogen. *Frontiers in Sustainable Food Systems, 5*. https://doi.org/10.3389/FSUFS.2021.660155/PDF, http://www.frontiersin.org.

UNEP Working Group. (2023). *Improved coordination of policies across the global nitrogen cycle: Potential options and modalities*.

de Vries, W. (2021). Impacts of nitrogen emissions on ecosystems and human health: A mini review. *Current Opinion in Environmental Science & Health, 21*. https://doi.org/10.1016/J.COESH.2021.100249, 100249.

Wang, J., Peng, Y., & Chen, Y. (2011). Advanced nitrogen and phosphorus removal in A2O-BAF system treating low carbon-to-nitrogen ratio domestic wastewater. *Frontiers of Environmental Science and Engineering in China, 5*(3), 474–480. https://doi.org/10.1007/S11783-011-0360-0/METRICS, https://link.springer.com/article/10.1007/s11783-011-0360-0.

Wang, X., Gao, C., Jin, P., Zhang, Y., Xie, Y., Chen, T., & Zhang, A. (2021). Nitrogen removal performance and bacterial community in a full-scale modified Orbal oxidation ditch with internal nitrate recycle and biocarriers. *Journal of Water Process Engineering, 40*. https://doi.org/10.1016/J.JWPE.2020.101791, 101791.

Waqas, M., Hawkesford, M. J., & Geilfus, C. M. (2023). Feeding the world sustainably: Efficient nitrogen use. *Trends in Plant Science, 28*(5), 505–508. https://doi.org/10.1016/J.TPLANTS.2023.02.010.

Wikaningrum, T., Hakiki, R., Astuti, M. P., Ismail, Y., & Sidjabat, F. M. (2022). The characterisation and pollutant load of greywater containing personal care cosmetic products (PCCPS) for body care. *Indonesian Journal of Urban and Environmental Technology, 5*(2), 115–133. https://doi.org/10.25105/URBANENVIROTECH.V5I2.13535, https://e-journal.trisakti.ac.id/index.php/urbanenvirotech/article/view/13535.

Wu, S., Muhammad, A., Bashir, Q., Ul Ain Raza, A., Rehim, Y., & Geng, L. (2023). Cao, Application of riparian buffer zone in agricultural non-point source pollution control—A review. *Frontiers in Sustainable Food Systems, 7*. https://doi.org/10.3389/FSUFS.2023.985870/BIBTEX, 985870.

Yang, A. L., Raghuram, N., Adhya, T. K., Porter, S. D., Panda, A. N., Kaushik, H., Jayaweera, A., Nissanka, S. P., Anik, A. R., Shifa, S., Sharna, S. C., Joshi, R., Arif Watto, M., Pokharel, A., Shazly, A., Hassan, R., Bansal, S., Kanter, D., Das, S., & Jeffery, R. (2022). Policies to combat nitrogen pollution in South Asia: Gaps and opportunities. *Environmental Research Letters, 17*(2). https://doi.org/10.1088/1748-9326/AC48B2.

Yao, H., Gao, X., Guo, J., Wang, H., Zhang, L., Fan, L., Jia, F., Guo, J., & Peng, Y. (2022). Contribution of nitrous oxide to the carbon footprint of full-scale wastewater treatment plants and mitigation strategies – A critical review. *Environmental Pollution, 314*. https://doi.org/10.1016/J.ENVPOL.2022.120295, 120295.

Yi, X., Lin, D., Li, J., Zeng, J., Wang, D., & Yang, F. (2021). Ecological treatment technology for agricultural non-point source pollution in remote rural areas of China. *Environmental Science and Pollution Research International, 28*(30), 40075–40087. https://doi.org/10.1007/S11356-020-08587-6, https://pubmed.ncbi.nlm.nih.gov/32337672/.

Zhang, C., Gu, B., Liang, X., Lam, S. K., Zhou, Y., & Chen, D. (2024). The role of nitrogen management in achieving global sustainable development goals. *Resources, Conservation and Recycling, 201*. https://doi.org/10.1016/J.RESCONREC.2023.107304, 107304.

Zhang, X., Mauzerall, D. L., Davidson, E. A., Kanter, D. R., & Cai, R. (2015). The economic and environmental consequences of implementing nitrogen-efficient technologies and management practices in agriculture. *Journal of Environmental Quality, 44*(2), 312–324. https://doi.org/10.2134/JEQ2014.03.0129.