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Nitrogen Footprint accounting and food sustainability: Insights from the Italian wine industry

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ABSTRACT

Anthropogenic perturbation of the nitrogen cycle poses significant environmental and social challenges, highlighting the need for effective nitrogen management in sustainable food systems. The Nitrogen Footprint (N-Footprint) offers an innovative metric to quantify reactive nitrogen (Nr) emissions and trace their environmental pathways.

This study refines a previous N-Footprint accounting framework to include both direct and indirect Nr emissions throughout the life cycle, providing a comprehensive perspective on Nr dynamics. The methodology is applied to a case study of Italian wine production, covering vineyard cultivation, winemaking, and bottling processes. Results indicate total emissions of 7.67 g Nr per 0.75 L wine bottle, with the vineyard phase accounting for 64.4 % of the overall impact, largely due to intensive fertilizer use. Water is identified as the most affected environmental compartment (55.7 % of emissions), primarily as a result of nitrate leaching.

Additionally, the study quantifies the Virtual Nitrogen Factor (VNF) to evaluate nitrogen use efficiency. Italian wine production demonstrates relatively high efficiency (2.28 g Nr per gram of nitrogen intake) compared to other fruit-based products. However, the lack of a standardized N-Footprint methodology hinders cross-sectoral comparability. This research calls for the development of nitrogen-specific Life Cycle Assessment (LCA) standards to promote sustainable agricultural practices.

1. Introduction

Nitrogen (N) is essential for the growth of plants, animals, and humans, serving as a key component of amino acids and proteins. The nitrogen biogeochemical cycle is complex and involves intricate interactions. Biological nitrogen fixation converts atmospheric nitrogen (N_2) into ammonia (NH_3), the primary reactive nitrogen (Nr) form. Certain microorganisms use ammonia to synthesize amino acids and oxidized compounds, which plants absorb and integrate into the food chain (Leach et al., 2012; Fowler et al., 2013). Nitrogen can return to the atmosphere as N_2 through denitrification by soil and water microorganisms (Galloway et al., 2004). Nr exists in limited quantities in the biosphere, necessitating ecosystem adaptations to optimize its availability (Pelletier and Leip, 2013).

However, human activities have significantly perturbed this natural cycle. Industrial processes, transportation, biomass combustion, and especially agriculture have greatly increased Nr inputs (Fowler et al., 2013).

From 1860 to 2005, Nr in the environment increased tenfold, from 15 Tg to 187 Tg per year (Galloway et al., 2008; Vitousek et al., 2013). In 2010, 189 Tg Nr were emitted worldwide, and 85 % of these come from industries and agriculture activities, with diffuse losses due to leaching, runoff and atmospheric emissions (Leip and Uwizeye, 2019). In 2020, global nitrogen creation was estimated at 226 Tg Nr per year (Galloway and Cowling, 2021; Galloway et al., 2021), of which 106 Tg from human-driven biological fixation, 43 Tg from industrial fixation, 34 Tg from fossil fuel combustion, and 43 Tg from crop-based biological fixation. The contributors to Nr creation increased, although the human-driven biological fixation remains the largest source (Galloway and Cowling, 2021).

Agriculture is the primary cause of rising Nr concentrations, significantly altering the nitrogen cycle (Erisman et al., 2011). Synthetic fertilizer currently generates approximately 120 Tg of Nr per year, complementing the 60 Tg of Nr per year produced through agricultural biological nitrogen fixation, to support the growing global population (Leip and Uwizeye, 2019). Including about 30 Tg Nr per year from

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combustion activities, anthropogenic N fixation is of the same order of magnitude of natural N fixation (~200 Tg Nr per year) (Leip and Uwizeye, 2019).

The most common Nr forms from fertilizers are nitrous oxide (N_2O) and ammonia (NH_3), released into the atmosphere, while ammonium ion (NH_4^+) and nitrate (NO_3^-) accumulate in soils. Nitrate can leach into groundwater, causing eutrophication (Galloway et al., 2008). Agricultural NH_3 emissions and nitrogen oxides (NO_x) from fossil fuels contribute about 100 Tg of Nr to the atmosphere annually, forming secondary pollutants like ozone (O_3) and ammonium nitrate (NH_4NO_3) (Fowler et al., 2013).

Nr accumulation in the different environmental matrices has gone beyond safe ecological limits (Rockström et al., 2009; Steffen et al., 2015; Richardson et al., 2023). The planetary boundary for nitrogen, defined as the maximum safe introduction of new reactive nitrogen, is estimated at 57 Tg per year, with current anthropogenic contributions exceeding this threshold by 119 Tg (Schulte-Uebbing et al., 2022).

Nr contributes to the increasing greenhouse effect, depletion of stratospheric ozone, loss of biodiversity, smog, and acid rain (IPCC, 2007, 2021), indirectly influencing other planetary boundaries, e.g. climate change, land-system change, biosphere integrity, freshwater quality (Hungate et al., 2003; Gruber and Galloway, 2008; Martinez et al., 2023; Wang et al., 2023). Therefore, achieving effective nitrogen management is crucial for ensuring sustainable development (Zhai et al., 2023; Peng et al., 2024).

To address this, nitrogen research must shift to policy-relevant questions, such as the influence of food system power dynamics and factors affecting farmer decisions (Kanter et al., 2020). Achieving this requires stronger collaboration between natural and social sciences, overcoming ideological, institutional, and knowledge barriers (Galloway et al., 2024).

The Nitrogen Footprint (N-Footprint) is an emerging metric within the footprint framework, specifically addressing reactive nitrogen (Nr) and its pathways across environmental systems throughout the production chain (Leip et al., 2011a, 2011b, 2011c; Leach et al., 2013; Liang et al., 2021). This metric utilizes a life cycle approach, assessing impacts from "cradle to grave"— from the extraction of raw materials to waste disposal following product consumption. The N-Footprint provides insights into how reactive nitrogen is introduced, transformed, incorporated and emitted throughout various stages of production and/or consumption of a product (Leach et al., 2016; Wowra et al., 2022; Galloway et al., 2024).

To date, unlike other footprint-based indicators such as Carbon (ISO 14044, 2021; ISO 14067, 2018) and Water (ISO 14046, 2014), there is currently no international standard or guideline for N-Footprint accounting.

Methodological approaches may vary: some studies calculate nitrogen balances based on national- and subnational- scale average data (Leip et al., 2013; Dukes et al., 2020; Xian et al., 2021), while others use frameworks proposed by the Intergovernmental Panel on Climate Change (IPCC, 2006, 2019). Leach et al. (2012) developed an N-Footprint calculator to assess Nr losses in food production, which was applied to various case studies at both territorial and food product levels (Xian et al., 2021, 2022; Wu et al., 2023). In particular, Cattell Noll et al. (2020) provided a comparison between organic and conventional food production, focusing on new and recycled nitrogen sources.

Additional methods employ complex impact models, such as CAPRI and MITERRA, which are used to estimate nitrogen flows and impacts at the regional or sectoral level (Velthof et al., 2009).

The CAPRI model is an agricultural sector tool that relies on EUROSTAT data and includes a global market calculator for agricultural products (Lesschen et al., 2013). Meanwhile, the MITERRA model is an environmental assessment tool that annually estimates nitrogen emissions and greenhouse gases, based on average European emission rates and leaching fractions. (Lesschen et al., 2013).

Models like CAPRI and MITERRA reveal certain theoretical gaps. The approach used is top-down, which treats an entire country as an "average" or aggregated farm. Furthermore, data is not site specific, but derives from national averages like EUROSTAT, FAOSTAT, and OECD (Leip et al., 2011a; Leip et al., 2011b; Leip et al., 2013).

More recent research has focused on calculating the N-Footprint at the product level using a systemic approach that combines Life Cycle Assessment (LCA) methodology with IPCC-based nitrogen emissions frameworks (Niccolucci et al., 2021). This integration allows for a detailed analysis of nitrogen emissions associated with specific products, improving the accuracy of N-Footprint calculations. However, it is limited to accounting for the contribution of direct emissions only.

Zuliani et al. (2023) proposed a method to quantify the Nr emissions from different food production chains. This approach is LCA compliant but considers only the indirect contribution to the total emissions of nitrogen-containing substances to obtain a food product. Most studies on ammonia synthesis emphasize its role in contributing to the greenhouse effect, while often neglecting its influence on the nitrogen cycle. This gap arises from incomplete N-Footprint frameworks, which fail to comprehensively assess the interconnections between nitrogen, water, and carbon (Li et al., 2023; Deng et al., 2024; He et al., 2024).

In agriculture, the N-Footprint concept has been applied to evaluate nitrogen flows across crop production systems. Although research in this area has grown (Leip et al., 2013; Wang et al., 2020; Zuliani et al., 2023), the number of studies remains limited, and only a small range of crops has been analyzed. This limited application highlights the need for expanding the research to better understand nitrogen impacts across diverse agricultural practices and crop types.

This study addresses the research question of developing a comprehensive accounting methodology for nitrogen footprint calculation, aligned with LCA procedure and specifically tailored for agri-food products.

Building upon the N-Footprint method initially proposed by Niccolucci et al. (2021), which primarily focused on evaluating direct emissions – those released directly from production, usage, and disposal processes, this study expands said approach by incorporating indirect emissions - those that are not released directly from the product's life cycle activities themselves but occur as a consequence of these activities. By including these emissions, this enhanced methodology provides a more complete profile of the environmental dynamics of reactive nitrogen (Nr) compounds throughout the entire life cycle of agri-food products. The paper also provides a detailed, step-by-step guide, which improves both the transparency and replicability of this refined methodology.

Using an Italian wine production case study, this research demonstrates the applicability and effectiveness of the expanded N-Footprint methodology within a vital segment of Italy's agri-food industry. The Italian wine sector is not only a major economic and cultural asset but also holds a central role in global markets (OECD, 2022), underscoring the importance of advancing sustainable practices in this area.

2. Material and methods

According to our previous study (Niccolucci et al., 2021), N-Footprint accounting procedure for products, includes four iterative steps LCA-based:

1) *System description*: define the scope of the analysis by specifying the spatial and temporal boundaries of the system, the functional unit (FU), data quality, assumptions, and allocation procedures;
2) *Data collection and processing*: gather and process all relevant raw materials and energy data (i.e., inventory) supporting the food production process, expressed per FU;
3) *N-Footprint accounting*: quantify all Nr emissions – both direct and indirect - associated with each collected input. Direct emissions, i.e. released directly from production, usage, and disposal processes, are calculated using the framework and default parameters, provided by

IPCC Guidelines (IPCC, 2006, 2019), as well as other standard variables from the Product Environmental Footprint (PEF) reports (JRC, 2019) and the Air Pollutant Emission Inventory Guidebook (EMEP/EEA, 2016). Indirect emissions, i.e. not released directly but occurring as a consequence of the specific production activity, are now included with respect to the previous version (Niccolucci et al., 2021). These estimates are derived using data processes from international databases, which adopt a comprehensive and standardized approach to capturing upstream and downstream environmental impacts. In particular, Ecoinvent 3.8 (Ecoinvent, 2020) was selected for this case study, as it is the most comprehensive and up-to-date database, encompassing a diverse range of sectors and including over 20,000 datasets modeling human activities and processes, as highlighted by Zuliani et al. (2023). All data is then processed and implemented into software (i.e., SimaPro), generating a Life Cycle Inventory (LCI) that identifies the molecules emitted into different environmental compartments. Then, a specific Nitrogen Coefficient (NC) per molecule is defined to aggregate the LCI results into a single indicator, representing the total Nr emitted (see Fig. 1). For each identified nitrogen-containing substances (SN_i), the Nitrogen Coefficient (NC_i) is calculated as the ratio of N Molar Mass (MM-N) to the total Molecular Mass (MM-total) (Eq. (1)):

$$NC_{SN_i} = \frac{(MM-N)_i}{(MM-total)_i} \quad (1)$$

It is assumed that all NO_x is released as NO_2, as proposed by Leach et al. (2012), given that it is estimated to be the most prevalent form among the various forms of nitrogen oxides.

Different types of particulate matter emissions (e.g., particulates, <2.5 μm; from 2.5 to 10 μm; >10 μm) may contain nitrogen compounds that can be chemically traced to ammonium ion (NH_4^+) and nitrate ion (NO_3^-) (Zuliani et al., 2023). To estimate the nitrogen content of particulate matter, results reported by Sillanpää et al. (2006) are used as reference. Their study indicates that nitrate ion (NO_3^-) makes a substantial contribution to particulate matter in the 2.5–10 μm size range (9 %), while ammonium ion (NH_4^+) has a more moderate contribution (3 %).

The "Nitrogen" elementary flow was considered an emission of molecular nitrogen (N_2), for instance, because of denitrification processes, a coefficient of 0 was assigned to this flow, according to Pelletier and Leip (2013), who state that "denitrification, through a series of intermediate gaseous nitrogen oxide products, returns reactive nitrogen to its most thermodynamically stable form, nitrogen gas (N_2). Therefore, N_2 must be assigned a characterization factor of 0 in impact assessments that quantify contributions to perturbation of the nitrogen cycle".

These coefficients are multiplied by the total quantity of the substance (that contains nitrogen atoms), to obtain the amount of reactive nitrogen (g Nr) released into environmental compartments. The Nr per nitrogen-containing substance ($Nr_{(SN_i)}$) is evaluated according to Eq. (2):

$$Nr_{(SN_i)} = NC_i \cdot SN_i \quad (2)$$

Finally, the Nr amounts, are added together to obtain the total Nr emissions released into different environmental compartments (i.e., air, water and soil), defining the total N-Footprint (expressed in g Nr/FU) applying Eq. (3):

$$N\text{-}Footprint = \sum_{i=1}^{n} Nr_{SN_i} \quad (3)$$

4) *Evaluation and interpretation*: several supplementary indices can be derived to provide insights into the system under study and facilitate comparative analysis. One such index is the Virtual Nitrogen Factor (VNF), which quantifies the nitrogen that is utilized in the production process but is not present in the final product (Leach et al., 2012). The VNF is calculated by dividing the total Nr losses to the environment by the total N intake of the product. It is important to note that nitrogen intake refers to the total nitrogen used throughout the entire production process, rather than the nitrogen effectively incorporated into the final product.

The VNF serves as a proxy for the environmental cost associated with products (Zhang et al., 2018).

This refined method offers several key advantages. First, capturing both direct and indirect nitrogen emissions enhances the method's robustness and reliability, providing a comprehensive assessment of nitrogen dynamics throughout the entire life cycle of agri-food products. This approach is adaptable to diverse case studies within the agri-food supply chain, making it a valuable tool for assessing nitrogen impacts across various products and production processes.Second, the method creates a detailed inventory of nitrogen emissions, encompassing a variety of nitrogen-containing molecules.

Finally, the method further supports the establishment of a nitrogen-specific impact category within the LCA framework, as it happens for carbon and water, establishing a standardized approach for evaluating nitrogen footprints. This advancement allows for more accurate identification of hotspots, alternative comparisons, and improved performance evaluation. These developments are crucial for fostering sustainable practices and policies aimed at reducing nitrogen-related environmental impacts and promoting overall sustainability within the agri-food system.

2.1. System description and data collection

The refined N-Footprint accounting methodology has been tested through an Italian winemaking case study, providing valuable insights into nitrogen emissions within the context of one of Italy's most emblematic agricultural products. The anonymous farm is in the south of Tuscany and occupies a surface of 2830 ha, most of which is cultivated with specialized vineyards (1027 ha) while the rest is covered with forestland, olive trees, plums, cereals, and fallow land. This wine is regulated by the respective disciplinary (Protected Designation of Origin (PDO) and Protected Geographical Indication (PGI)), which defines, at European level, that the wines must be produced in compliance with strict regulations that guarantee high quality and specify geographical origin. In fact, the grape used for production comes from vineyards composed exclusively of Sangiovese and Moscadello varieties. The vineyard is managed by applying different agronomic practices (i.e., sapling, spurred cordon and Guyot); moreover, vineyard plots of different ages coexist, characterized by various soil compositions that therefore required specific agricultural procedures.

For the year 2021, the company declared production of 5375 tons of grapes, 43,652 hectoliters of wine, and 7,263,386 bottles.

The system boundaries include three production phases:

1) Vineyard (i.e. agricultural phase that includes all activities performed in the field for the cultivation of vines and the harvesting of the produced grapes);

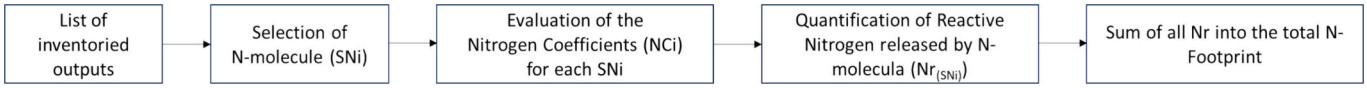

Fig. 1. Workflow for N-Footprint accounting.

2) Winery (referred to those actions related to "grape to wine" transformation, like alcoholic fermentation and aging in oak barrels);
3) Wine bottling using dark and transparent glass carefully packaged for sale.

The phases of distribution to the customers, use and end of life of the bottles are excluded from the analysis because the responsibility is out of the company's control.

All the energy and material flows, as well as the outputs, for each production phase have been inventoried, as outlined in the Flow Chart (Fig. 2). The input flows excluded from the study fall within the general cut-off regulation of 5 %. Furthermore, the construction, maintenance and decommissioning of infrastructures, such as buildings and machinery, are also excluded from the evaluation.

For each raw material inventoried, the impact due to transport is also quantified.

The main FU i.e. the reference unit of this study, is one wine bottle (0.75 L) but for each phase a specific FU is also proposed (Fig. 3).

Once the energy and material flows are inventoried, it is also necessary to account for the direct emissions for both inputs (such as fossil fuels, fertilizers) and agricultural practices (i.e. crop residues left in the field), to make the inventory complete.

For nitrogen-based fertilizers, emissions of N_2O, NH_3, NO_x (atmosphere), NO_3^- (water) and nitrogen compounds (soil) are quantified.

For N_2O direct emissions into the atmosphere, the "2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories" (IPCC, 2019) provides the equations, specific parameters and emission factors for crop residues left in field, as well as synthetic and organic fertilizers. These default factors must be multiplied by the amount of nitrogen distributed in the ground, to quantify the Nr emitted into the atmosphere (Table S.1 in the Supplementary Material).

Furthermore, indirect emissions for volatilizations and leaching processes needed to be added. These are due to:

- the volatilization of NH_3 and NO_x and subsequent deposition in the soil of NH_4^+ and NO_3^- which, following denitrification processes, produce N_2O emissions, which are released into the atmosphere. These can be calculated using default parameters proposed by IPCC (2006, 2019), which consider the nitrogen fraction that volatilizes;
- the leaching processes, which can lead to an enrichment of NO_3^- in the soil, contributing also to the indirect emission of N_2O, which in this case is introduced back into the air compartment.

In Table S.1 in the Supplementary Material, a list of compounds, equations, parameters and sources, for the interested inputs, is provided.

According to the Joint Research Centre (JRC, 2019), the contribution of agrochemicals impact of nitrogen on the environment cannot be overlooked. For this reason, the European Union suggests modeling the environmental fate of pesticides (i.e., glyphosate) by considering 90 % of emissions in the soil compartment, 9 % in air and 1 % in water (Margni et al., 2002).

To quantify Nr emissions in the soil, a nitrogen balance is realized, subtracting from the overall Nr inputs (e.g., fertilizers, fossil fuels, other raw materials, electricity), all the stocks (vine and harvested grape) and the outputs (emissions to the environment and production wastes).

The biological fixation can be neglected as input, and it is also assumed that mineralization and immobilization are at a steady state, thus, the system being constant over time and the fertilizers are applied based on the growth needs of the plant. The nitrogen quantity, supplied to the soil through atmospheric fixation in a given period, depends on the amount of precipitation and the concentration of nitrogenous compounds in rainwater; these parameters present strong variations between geographical areas and months of year. In Tuscany the quantity of nitrogen in the rainfall can be considered around 2 mg/L (Masoni and Ercoli, 2010); therefore, the quantity of Nr introduced in the system by atmospheric fixation is calculated multiplying the specific data relating to the total rainfall of 2021, measured by the company's meteorological control unit (570 mm), by the nitrogen concentration in rainwater.

To calculate the Nr stocked in the harvested grapes, the coefficients of N absorption in grapes defined within the "National Integrated Production Guidelines 2023", proposed by the Ministry of Agriculture, are used: in this case an average coefficient equal to 0.24 % for vines cultivated in different conditions (i.e., hilly, mountainous and flat areas) is applied (Rete Rurale Nazionale, 2023). Multiplying this factor by the annual grapes production (5375 t), the quantity of nitrogen stocked in the grapes is obtained. After harvesting the nitrogen contained in the grapes leaves the Vineyard (Phase 1) to enter the Vinery (Phase 2).

The storage of N in different parts of the plant (i.e., primary shoots, secondary shoots and leaves) is quantified considering the vegetation parameters expressed in g of fresh weight biomass and the concentration of N in these vine elements, as measured by Ferrara et al. (2018) and Natarajan et al. (2017). Specific Details related to these parameters are widely presented in Table S.2 in the Supplementary Material.

Around 75 % of the nitrogen stored in the plant biomass is removed with pruning (Cavalaglio et al., 2007; IPCC, 2019) but the residues return to the system as feedback, in fact, they are crushed and redistributed in the field as an input of organic matter for soil restoration (Niccolucci et al., 2021). Therefore, only 25 % of the nitrogen accumulated in the biomass remains fixed in the wooden parts of the plant for a long-time frame.

The direct emissions due to the fossil fuels consumption are calculated using the emissions factors proposed by the IPCC (2006, 2019) and EMEP/EEA (2016), quantifying the nitrogen emitted to the atmosphere with the release of nitrogen oxides (NO_x), nitric oxide (NO), nitrogen oxide (NO_2), nitrous oxide (N_2O), ammonia (NH_3) and particulate matter (i.e., $PM_{2.5}$, PM_{10}) from the owned vehicles (cars and trucks), tractors, heating and cogeneration systems (Table S.1 and Table S.3 in the Supplementary Material).

The reference for the electricity consumption imported from the national grid is the energy produced and provided by Enel Repower operator, which distributes electricity obtained by a higher percentage of renewable sources than the general national mix.

3. Results and discussion

3.1. N-Footprint of wine

The inventories of all inputs (energy and matter) and outputs (direct emissions and wastes), needed to support the production of 1 kg of grapes, 1 L of wine and one wine bottle (0.75 L), have been elaborated and shown in the Supplementary material (Table S.4, S.5, S.6). All the input data are primary (i.e., directly provided by the farmers). Direct emissions are also shown, as well as the processes chosen from the international database selected (Ecoinvent v.3.8, 2020) needed to quantify the upstream and downstream impacts along the supply chain.

The calculation of the N-Footprint begins with an analysis of the LCI results. Approximately 2000 chemical compounds were identified as outputs, 207 of which contain nitrogen. For each of these substances a specific NC has been defined (Table S.7 in the Supplementary Material).

The total sum of reactive nitrogen contributions results in an overall N-Footprint of 5.35 g Nr per kilogram of grapes, 8.52 g Nr per liter of wine, and 7.67 g Nr per 0.75 L wine bottle (Table 1). Although literature is quite scarce; our result (0.013 g Nr/g wine) is in line with data produced by Shindo et al. (2021) for wines produced in China (0.013 g Nr/g wine) and Japan (0.018 g Nr/g wine), and by Klement et al. (2021) for fruits 6.40 g Nr/kg fruits (mean).

Considering the world wine production volume of approximately 260 mhL (OIV, 2024), the wine industry, according to the results of this study, mobilizes an estimated $2.21 \bullet 10^3$ Tg Nr annually. Italy alone contributes about 20 % of this total, underscoring the nation's substantial role in global nitrogen dynamics within the sector.

Considering the main FU (i.e., one wine bottle of 0.75 L), Vineyard is

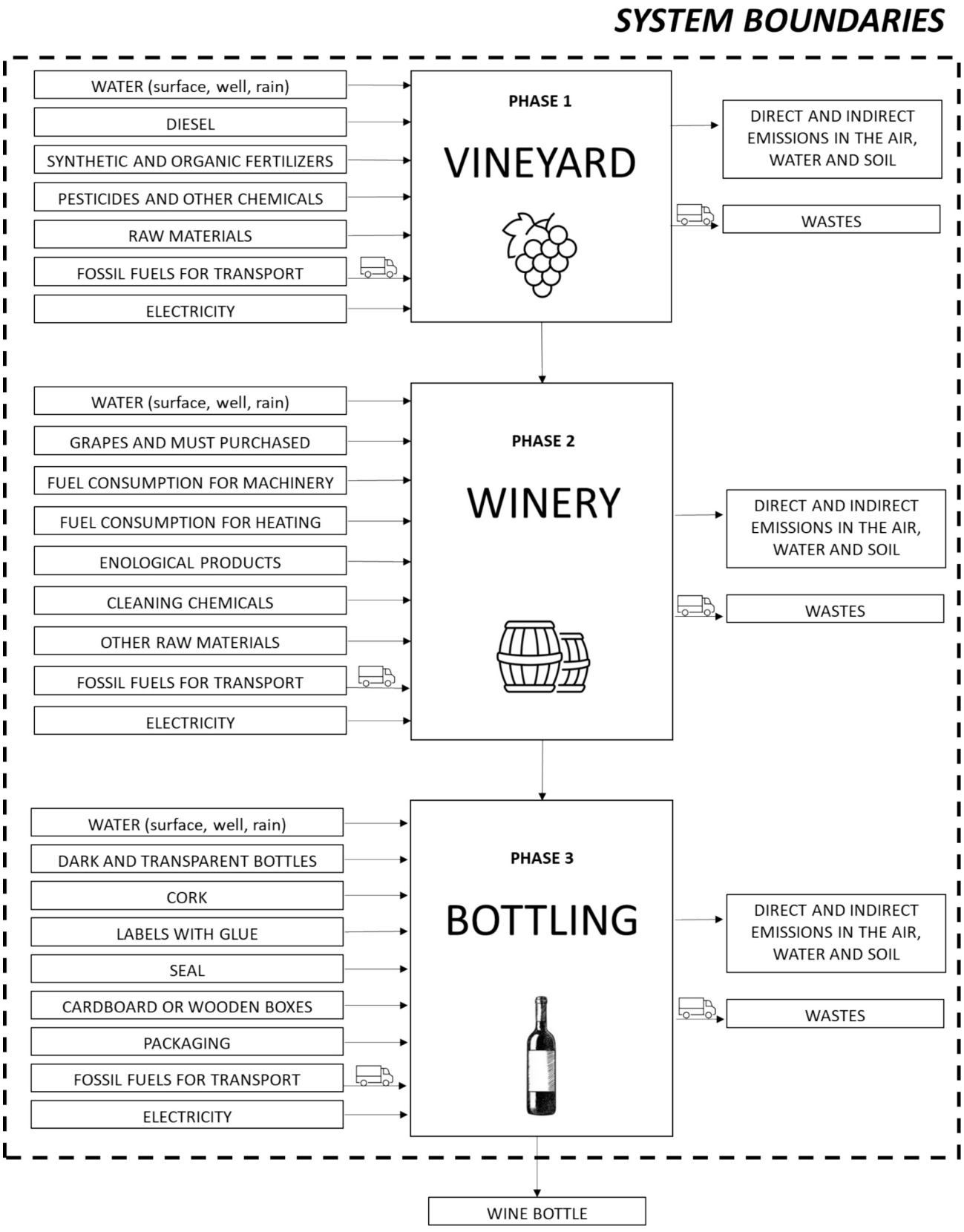

Fig. 2. Flow chart of bottled wine production (FU = 0.75 L).

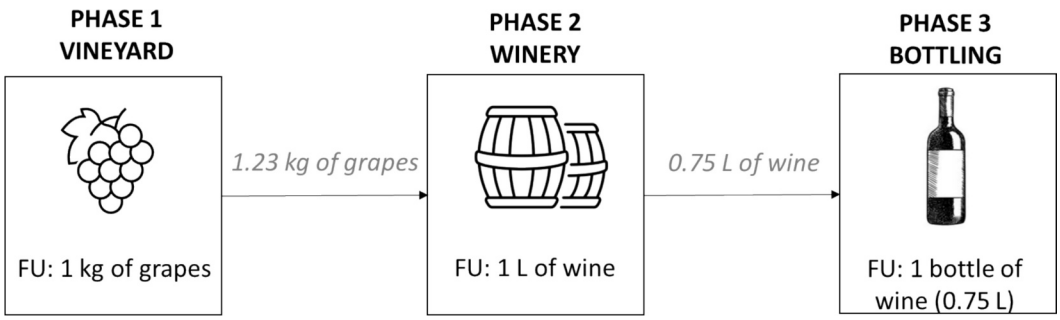

Fig. 3. Bottled wine production: phases and related Functional Units (FUs). In grey line, the mass of grape needed to produce 1 L of wine, and the volume of wine to make 1 bottle.

Table 1
N-Footprint of wine bottled (FU = 1 bottle 0.75 L).

VINEYARD (Phase 1)	g Nr/FU	% on the total NF
Direct emissions from vineyard management	$4.04 \cdot 10^{0}$	*52.6 %*
Chemical fertilizers	$2.31 \cdot 10^{0}$	30.1 %
Manure	$4.34 \cdot 10^{-1}$	5.6 %
Pesticides	$5.54 \cdot 10^{-2}$	0.7 %
Crop residues	$7.45 \cdot 10^{-1}$	9.7 %
Fossil fuels	$4.77 \cdot 10^{-1}$	6.2 %
Indirect emissions	$9.06 \cdot 10^{-1}$	*11.8 %*
Chemical fertilizers	$1.22 \cdot 10^{-1}$	1.6 %
Manure	$2.59 \cdot 10^{-4}$	0.0 %
Urea	$5.36 \cdot 10^{-3}$	0.1 %
Pesticides	$2.39 \cdot 10^{-1}$	3.1 %
Tractors	$3.70 \cdot 10^{-2}$	0.5%
Fuel for heating	$1.92 \cdot 10^{-3}$	0.0 %
Owned vehicles	$4.04 \cdot 10^{-3}$	0.1 %
Transport of input materials	$4.28 \cdot 10^{-1}$	5.6 %
Transport of output materials	$1.31 \cdot 10^{-1}$	1.7 %
Electricity	$4.64 \cdot 10^{-2}$	0.6 %
Wastes	$-1.09 \cdot 10^{-1}$[a]	−1.4 %
TOTAL VINEYARD	$\mathbf{4.94 \cdot 10^{0}}$	***64.4 %***
WINERY (Phase 2)	**g Nr/FU**	**% on the total NF**
Direct emissions from winery management (fossil fuels)	$7.22 \cdot 10^{-2}$	*0.9 %*
Indirect emissions	$1.38 \cdot 10^{0}$	*95.0 %*
Purchased grapes	$1.33 \cdot 10^{-1}$	1.7 %
Purchased must	$7.72 \cdot 10^{-3}$	0.1 %
Diesel for the generator set	$1.73 \cdot 10^{-3}$	0.0 %
LPG for the boiler	$2.00 \cdot 10^{-2}$	0.3 %
Owned vehicles	$5.87 \cdot 10^{-4}$	0.0 %
Tractors	$5.30 \cdot 10^{-3}$	0.1 %
Transport of input materials	$2.10 \cdot 10^{-1}$	2.7 %
Transport of output materials	$6.40 \cdot 10^{-2}$	0.8 %
Products for winemaking	$1.72 \cdot 10^{-1}$	2.2 %
Electricity	$7.20 \cdot 10^{-1}$	9.4 %
Wastes	$4.28 \cdot 10^{-2}$	0.6 %
TOTAL WINERY	$\mathbf{1.45 \cdot 10^{0}}$	***18.9 %***
BOTTLING (Phase 3)	**g Nr/FU**	**% on the total NF**
Bag in Boxs	$2.09 \cdot 10^{-4}$	0.0 %
Dark glass bottles	$1.85 \cdot 10^{-1}$	2.4 %
Transparent glass bottles	$9.66 \cdot 10^{-2}$	1.3 %
Seals	$6.13 \cdot 10^{-3}$	0.1 %
Boxes	$1.04 \cdot 10^{-1}$	1.4 %
Labels	$1.16 \cdot 10^{-2}$	0.2 %
Packing material	$4.92 \cdot 10^{-1}$	6.4 %
Corks	$1.86 \cdot 10^{-3}$	0.0 %
Transport of input materials	$3.86 \cdot 10^{-1}$	5.0 %
TOTAL BOTTING (Indirect emissions)	$\mathbf{1.28 \cdot 10^{0}}$	***16.7 %***
TOTAL (FU = 1 bottle 0.75 L)	$\mathbf{7.67 \cdot 10^{0}}$	**100.0 %**

[a] Negative value, related to wastes, is due to the recycling and recovery of some waste fractions (e.g. plastics, metals, and paper/cardboard).

the dominant phase (64.4 %), while Winery and Bottling are less relevant (18.9 % and 16.7 %, respectively). When single inputs are considered, the highest impact is due to direct emissions from vineyard management (52.6 % of the total; Table 4). In particular, the Vineyard phase contributes to 4.94 g Nr/wine bottled and the direct emissions, due to chemical fertilizers, manure, crop residues and fossil fuels use for tractors, are very relevant in this production phase (81.7 %) (Fig. 4a). This result confirms the importance of including direct emissions in the N accounting framework. The activities at the Winery produce an N-Footprint of 1.45 g Nr mainly due to the electricity consumption imported from the national grid (49.7 %) (Fig. 4b). The Bottling phase emits 1.28 g Nr/wine bottle, due to the packing material (38.8 %; EUR-flat pallets and transparent packaging films) and the transport of glass bottles in input to the process (30.1 %; fossil fuels consumption for tracks) (Fig. 4c).

Molecular analysis shows that the N-Footprint is mainly determined by nitrates (NO_3^-; 62.9 %), nitrogen oxides (NO_2 and NO_x; 25.5 %), ammonia (NH_3; 5.9 %) and dinitrogen monoxide (N_2O; 4.0 %).

Environmental compartment analysis shows that most Nr is present in water (55.7 %), and air (35.5 %) and the remaining part in soil (8.8 %) (Table 2).

Ammonium ion (96.5 %), nitrate (87.0 %) and nitrite (100.0 %) are mainly released in water (Table 2). On the other hand, dinitrogen monoxide, nitrogen monoxide, nitrogen oxides and ammonia are only emitted to the atmosphere, while ammonium carbonate and amines can be found both in air (92.7 %) and in water (7.3 %).

The other N compounds are present basically in the soil (86.3 %) (Table 2). The contribution of the other N compounds (including pesticides) is negligible because of the low value of NC, although the large quantity of distributed pesticides. A detailed list of the emitted compounds in various environmental compartments is provided in Table S.8 in the Supplementary Material. Additionally, the distribution of molecules across different environmental compartments and production phases is presented in Table S.9 in the Supplementary Material.

Looking at the environmental compartment's distribution, Nr is mainly concentrated in water in the form of NO_3^- after leaching and run-off (98.2 %). In the atmosphere (35.5 %) is present as NO_x from combustion processes (71.1 %), NH_3 (16.7 %) and N_2O (11.4 %) due to the fertilizer's application, releasing direct emissions from the vineyard management. In the soil (8.8 %) Nr is mainly in the form of nitrates (92.5 %) from chemical and organic fertilizers use. The other N compounds present in the soil (7.4 %) are mainly related to the use of pesticides, which accumulate in soil and subsequently leach into water (Fig. 5).

Specific focus is given to direct emissions due to vineyard management, considering that it is the main hotspot of the analysis.

Fig. 6a shows the N-Footprint of the Vineyard phase, subdividing the contribution of impacts between direct (81.7 %) and indirect emissions (18.3 %) in different environmental compartments. About half of Nr quantity (direct and indirect emissions) due to Vineyard is released into water (55.9 %), followed by air (30.4 %) and soil (13.7 %). More than 90 % of the Nr of this production phase is released into water and soil as direct emissions; on the other hand, direct emissions represent 57.1 % of those in air (Fig. 7a). Fig. 6b illustrates the spreading of different compounds that promote direct emissions of Vineyard phase. Nitrates (NO_3^-)

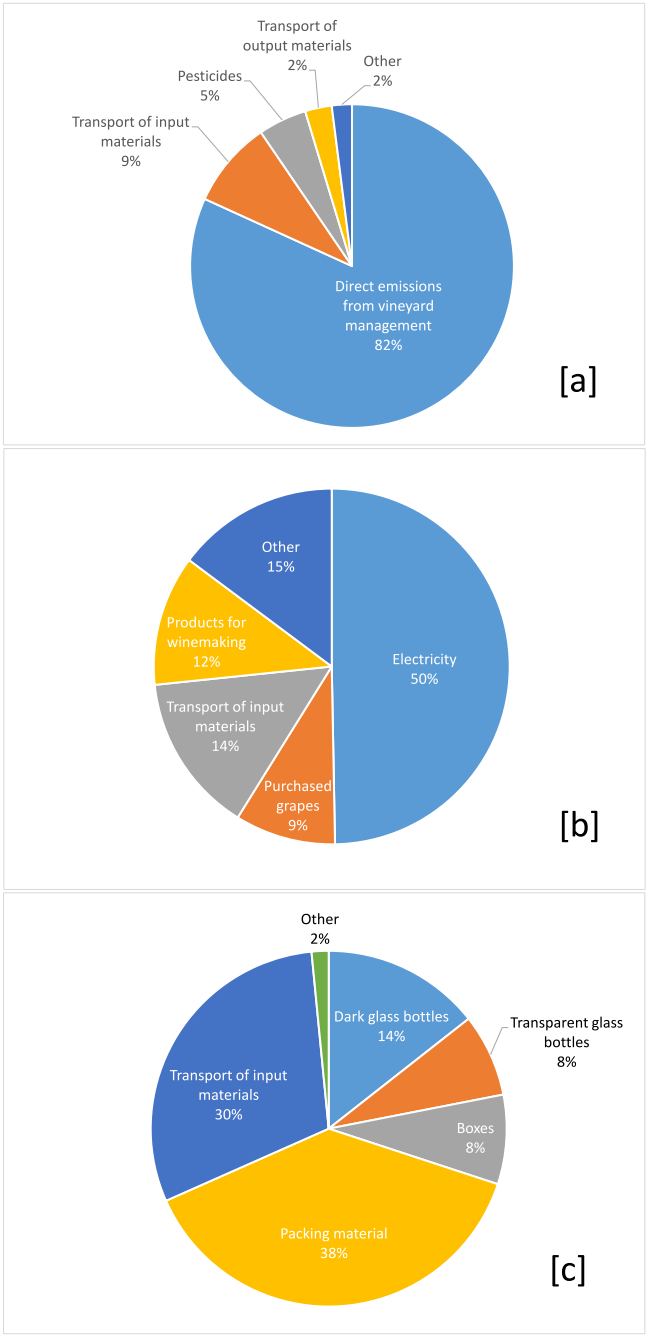

Fig. 4. Percentage distribution per production phase: Vineyard (a), Winery (b) and Bottling (c).

are the only suppliers to direct emissions into water and soil, while nitrogen oxides (NO_x; 47.8 %), ammonia (NH_3; 32.0 %) and dinitrogen monoxide (N_2O; 19.2 %) are released into air.

Fig. 7 illustrates the nitrogen dynamics associated with a single wine bottle (0.75 L), including inputs, outputs, and N losses to the environment (air, water, and soil). For validation purposes, the nitrogen balance - calculated by summing the inputs (+) and subtracting the outputs (−) - yields a result of zero g Nr/FU.

The fertilizers (chemical and organic) and pesticides represent 76 % of input flows to the Vineyard, while the output flows are shared between the environment (58 %), the harvested grapes (26 %) and the vine plants (16 %). Vine can stock nitrogen in the plant tissues in a semi-permanent way, considering that it has a lifetime of over 20 years. In the Winery phase, grapes and must (self-produced and purchased) cover 58 % of the input flows and only 8 % is due to the winemaking products (of which 6 % derives from yeasts and mono-lactic bacteria). The output flows to the environment (34 %) and to the marc (66 %), transported to nearby distilleries. The bottled wine does not contain nitrogen, thus, the Nr released during the botting phase is due to the purchased input materials (1.28 g Nr/FU), 55 % emitted into the water and 44 % into the air.

The Virtual Nitrogen Factor (VNF), i.e. the ratio between the total Nr losses to the environment and the total N intake by the product, is 2.75 g Nr/g N_{intake} for one wine bottle (0.75 L) and 2.29 g Nr/g N_{intake} for 1 L wine. The wine is an N-free product, therefore, the VNF could not be calculated as 'g Nr losses/g N_{intake}' (Klement et al., 2021). However, in this study the N intake in wine is quantified as the nitrogen amount incorporated in the products for winemaking, the self-produced grapes, the purchased grapes and must, used in input to the Winery phase, and leaving the system like marc (2.79 g N_{intake}/wine bottle). These flows of matter are essential to obtain the wine: their properties and characteristics must be -memorized from the production phases to the final product. On the other hand, the VNF of 1 kg grape is equal to 2.28 g Nr/g N_{intake}, considering 2.35 g N_{intake}/kg grape. These values of VNF are about half those quantified by Klement et al. (2021) for generic alcoholic beverages (6.72 g Nr/g N_{intake}) and fruits (6.48 g Nr/g N_{intake}).

Since VNF represents the ratio of Nr released to the environment during grape and wine production per unit of N incorporate, our result indicates that this Italian wine demonstrates greater nitrogen capture efficiency compared to other case studies. However, it is important to note that this comparison is not entirely homogeneous, as the literature data are based on medium-sized fruits and generic alcoholic beverages, without specific reference to wine and grapes.

3.2. N-Footprint comparison

As a further validation of the N-Footprint accounting framework, the results of this study are compared with those of various references, published in the last 10 years and carried out on different crops, cultivated applying conventional agronomic practices (Table 3). For this purpose, only the cultivation phase is taken into consideration, referring to 1 kg of product (in our case grapes) as FU. The comparison with the literature is made with other crops (Table 3), because the N-Footprint of vineyard cultivation and winemaking has not yet been fully investigated, despite the relevant and abundant researches about the Water and the Carbon Footprint applied to this production sector (Rinaldi et al., 2016; Miglietta et al., 2018; Borsato et al., 2019; Pinto da Silva and Esteves da Silva, 2022; Gueddari-Aourir et al., 2022). For each reference analyzed in Table 3, the accounting methodology has been taken into consideration to provide the methodological consistency and reliability of the obtained result.

The N-Footprint of 1 kg of grape is 5.35, value in line and of the same order of magnitude as those found for other agricultural products i.e. tubers and vegetables, despite differences in accounting and approaches.

Analyzing the N-Footprint amounts in Table 3, the mean value is 8.73 g Nr/kg product, and the median is 5.18 g Nr/kg product, suggesting that the grapes production analyzed in this study is one of those products that emits the least Nr quantity into the environment.

All the studies unanimously agree that fertilizers are the main cause of Nr emissions into the environment.

To reduce the impacts from the vineyard phase, it is necessary to decrease the quantity of nitrogen distributed to the field, to use the water resources in a sustainable way and to maintain the integrity of the soil with the aim to improve the organic matter concentration and the biodiversity index (Baulch et al., 2019; Wang, 2022; Naorem et al., 2023).

These aspects can positively affect the vigor of vines and the quality of product, reducing soil tillage practices to increase the capacity of preserving the fraction of the green water and maintain the chemical/biological functions of the soil (Lehman et al., 2015; Usharani et al.,

Table 2
Contribution to the N-Footprint of selected compounds (FU = 1 bottle 0.75 L).

Compound	Air		Water		Soil		Total compound	
	g Nr/FU	% total compound	g Nr/FU	% total compound	g Nr/FU	% total compound	g Nr/FU	% total compound
Ammonium ion (NH_4^+)	$2.74 \cdot 10^{-3}$	3.5%	$7.54 \cdot 10^{-2}$	96.5 %	\	\	$7.82 \cdot 10^{-2}$	100.0 %
Dinitrogen monoxide (N_2O)	$3.09 \cdot 10^{-1}$	100.0 %	\	0.0 %	\	\	$3.09 \cdot 10^{-1}$	100.0 %
Nitrate (NO_3^-)	$2.76 \cdot 10^{-3}$	0.1 %	$4.20 \cdot 10^{0}$	87.0 %	$6.26 \cdot 10^{-1}$	13.0 %	$4.82 \cdot 10^{0}$	100.0 %
Ammonia (NH_3)	$4.56 \cdot 10^{-1}$	99.9 %	$3.88 \cdot 10^{-5}$	0.0 %	$5.90 \cdot 10^{-4}$	0.1 %	$4.57 \cdot 10^{-1}$	100.0 %
Nitrogen monoxide (NO)	$1.84 \cdot 10^{-7}$	100.0 %	\	\	\	\	$1.84 \cdot 10^{-7}$	100.0 %
Nitrogen oxides (NO_2 and NO_x)	$1.94 \cdot 10^{0}$	100.0 %		\	\		$1.94 \cdot 10^{0}$	100.0 %
Nitrite (NO_2^-)	\		$4.53 \cdot 10^{-4}$	100.0 %	\	\	$4.53 \cdot 10^{-4}$	100.0 %
Ammonium carbonate $[(NH_4)_2CO_3]$and Amines	$1.03 \cdot 10^{-2}$	92.7 %	$8.06 \cdot 10^{-4}$	7.3 %	\	\	$1.11 \cdot 10^{-2}$	100.0 %
Other N compounds	$6.56 \cdot 10^{-3}$	11.2 %	$1.45 \cdot 10^{-3}$	2.5%	$5.04 \cdot 10^{-2}$	86.3 %	$5.84 \cdot 10^{-2}$	100.0 %
Total compartment	$\mathbf{2.72 \cdot 10^{0}}$	**35.5%**	$\mathbf{4.27 \cdot 10^{0}}$	**57.7 %**	$\mathbf{6.77 \cdot 10^{-1}}$	**8.8 %**	$\mathbf{7.67 \cdot 10^{0}}$	**100.0 %**

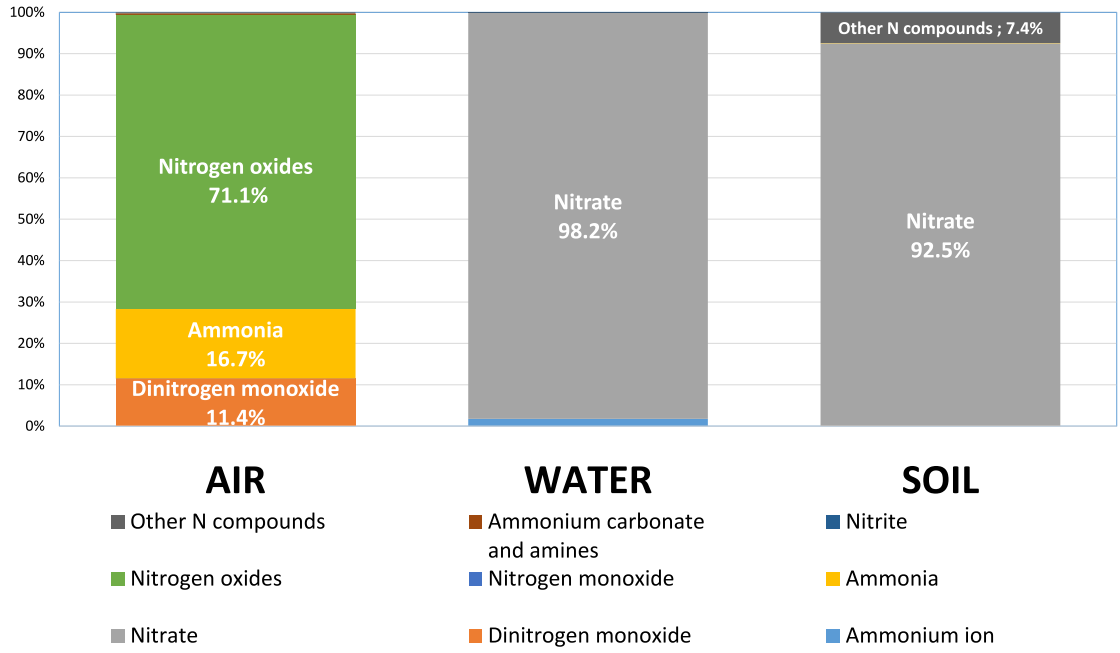

Fig. 5. Distribution of compounds in different environmental compartments.

2019; Angon et al., 2023). It is essential to adopt water-saving irrigation, as water consumption directly affects the transport of nitrates into groundwater and indirectly affects the nitrous oxide emissions into the atmosphere (Jourdain et al., 2020; Liu et al., 2023; Zhao et al., 2023).

A large contribution can also be made by implementing high-precision agriculture, which allows treatments and resources distribution, based on the actual needs of plants (mainly fruit trees) without excessive use of resources (Finger et al., 2019).

A significant reduction of Nr emissions due to the Winery phase would be correlated to a decrease in the consumption of electricity imported to the national grid. A potential mitigation strategy in this context is the installation of photovoltaic panels on existing company buildings and construction (e.g., roofs and car parks).

The integration of photovoltaic panels into vineyards is an emerging solution for renewable energy generation. In this approach, photovoltaic surfaces are installed over the vines using the existing trellis structure, ensuring minimal shading between consecutive rows. The vertical orientation of the panels allows for complete irradiation of the plants below (Ahn et al., 2022; Padilla et al., 2022).

To mitigate the environmental impacts associated with the bottling phase, it is recommended to select lighter and less impactful packaging materials, such as pallets and glass bottles. Additionally, suppliers should adopt more sustainable practices throughout the production cycle and minimize transport distances (Robertson et al., 2014).

3.3. *Future perspectives*

This refined methodology can be applied to a diverse range of agricultural products generating valuable data, that uncover previously overlooked issues, and enhance understanding of nitrogen dynamics within agricultural systems. By addressing these aspects, the approach has the potential to produce more comprehensive assessments of nitrogen-related impacts. It can also support the development of targeted, evidence-based policies that promote sustainable agricultural practices and mitigate their impacts.

Applying the methodology across multiple product categories provides insights into the variability of nitrogen dynamics in different agricultural contexts. It also enables the identification of critical points where nitrogen losses can be minimized, helping to reduce inefficiencies and potential environmental harm.

As further refinement, efforts shall be focused on addressing current limitations of the methodology. These enhancements would have the effect of improving its applicability and replicability, particularly for use within a broad spectrum of agricultural contexts and production systems. A key challenge lies in improving the reliability of results, which depends on the availability of high-quality primary data from individual

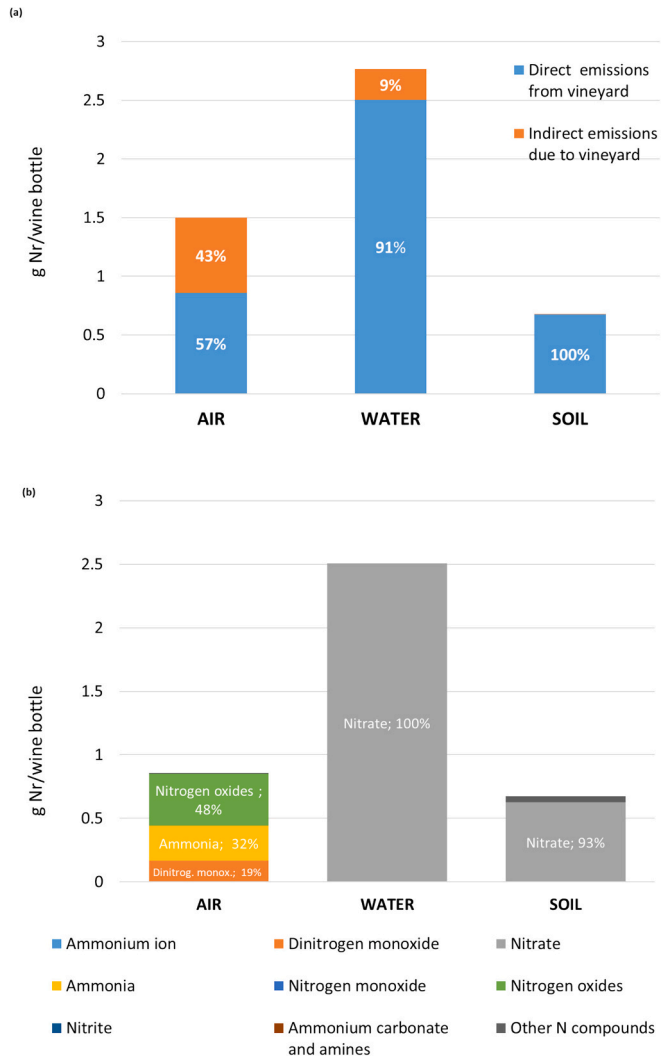

Fig. 6. Distribution of direct and indirect emissions in the Vineyard phase (a) and sharing of different compounds that cause direct emissions of vineyard (b).

enterprises. This includes accurate information on material and energy consumption, as well as detailed data on the characteristics and specificities of agricultural production systems.

A further area of refinement involves the disaggregation of nitrogen dynamics across different environmental matrices, with particular emphasis on soil-related processes. Soil, as a fundamental component of agricultural systems, plays a key role in the nitrogen cycle, influencing both storage and loss pathways. For example, accurately quantifying nitrogen storage within biomass and understanding its interactions with soil processes are critical to developing a more holistic view of the nitrogen cycle.

Factors such as soil composition, water bioavailability, local climate conditions, and nutrient dynamics are integral to understanding nitrogen behavior in different contexts. While the IPCC methodology relies on equations with default parameters, it encourages the use of specific information to reflect the nuances of individual systems. By integrating localized variables into the framework, it is possible to provide a more precise and context-sensitive representation of nitrogen dynamics.

4. Conclusions

Due to growing concerns over environmental thresholds in biogeochemical cycles (Richardson et al., 2023; Schulte-Uebbing et al., 2022), this study centers on the nitrogen cycle and its dynamics within the agrifood supply chain, an area that remains underexplored with a significant gap in scientific literature. Although recently developed, the Nitrogen Footprint (N-Footprint) is recognized as a promising and versatile method for quantifying reactive nitrogen emissions (Nr). However, the methodology still requires development, with ongoing debate regarding standardization and procedural specifics.

To address these gaps, a refined version of an N-Footprint accounting method is presented in this paper, to generate a comprehensive nitrogen emissions profile, capturing both direct and indirect nitrogen losses across environmental compartments—air, water, and soil—in full alignment with Life Cycle Assessment (LCA) principles.

This method has been tested through an application to the wine industry, a key sector in Italian agriculture with substantial internal demand and international exports. Nr emissions were measured for one of the most renowned Tuscan wines, used as proxy of the Italian wine production, across its life cycle, from grape cultivation through winemaking and bottling. The case study is robust, relying entirely on primary data for all inventory information. Results indicate nitrogen emissions of 5.35 g Nr per kg of grapes, 8.52 g Nr per liter of wine, and 7.67 g Nr per 0.75 L wine bottle, aligned with the limited existing literature on this subject. The water compartment emerged as the most affected, accounting for 55.7 % of total nitrogen emissions. This impact is primarily due to nitrate molecules, which make up 98.2 % of the nitrogen emissions in this compartment, significantly contributing to eutrophication. The vineyard stage was found to be the most nitrogen-intensive, accounting for 64.4 % of the nitrogen impact, largely due to fertilizer use.

The Virtual Nitrogen Factor (VNF) of 1 kg of grapes has been found to be 2.28 g Nr per gram of nitrogen intake, indicating that this wine production process is relatively nitrogen-efficient compared to other fruit-based products available in literature (Klement et al., 2021).

The lack of standardized N-Footprint procedures limits the comparability and applicability of findings across different studies and sectors, presenting a significant barrier to managing and mitigating nitrogen-related environmental impacts effectively. This refined accounting approach, both transparent and replicable, offers a significant step toward standardization.

Achieving this standardization will not only enhance the credibility and utility of the N-Footprint but also establish it as a critical tool for policymakers, industry stakeholders, and researchers. By providing a consistent framework for evaluating nitrogen management practices, the methodology can support the identification of best practices, inform regulatory standards, and encourage innovation in nitrogen use efficiency.

Ultimately, a well-standardized N-Footprint will facilitate cross-sector comparisons and enable tracking of progress toward more sustainable agricultural systems. It will empower decision-makers with actionable insights to mitigate the environmental impacts of nitrogen emissions, optimize resource use, and support the transition to a more sustainable agricultural future.

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Ethics approval

The article respects ethical responsibilities, proposed by the Publishing Ethics Resource Kit, approved by authors.

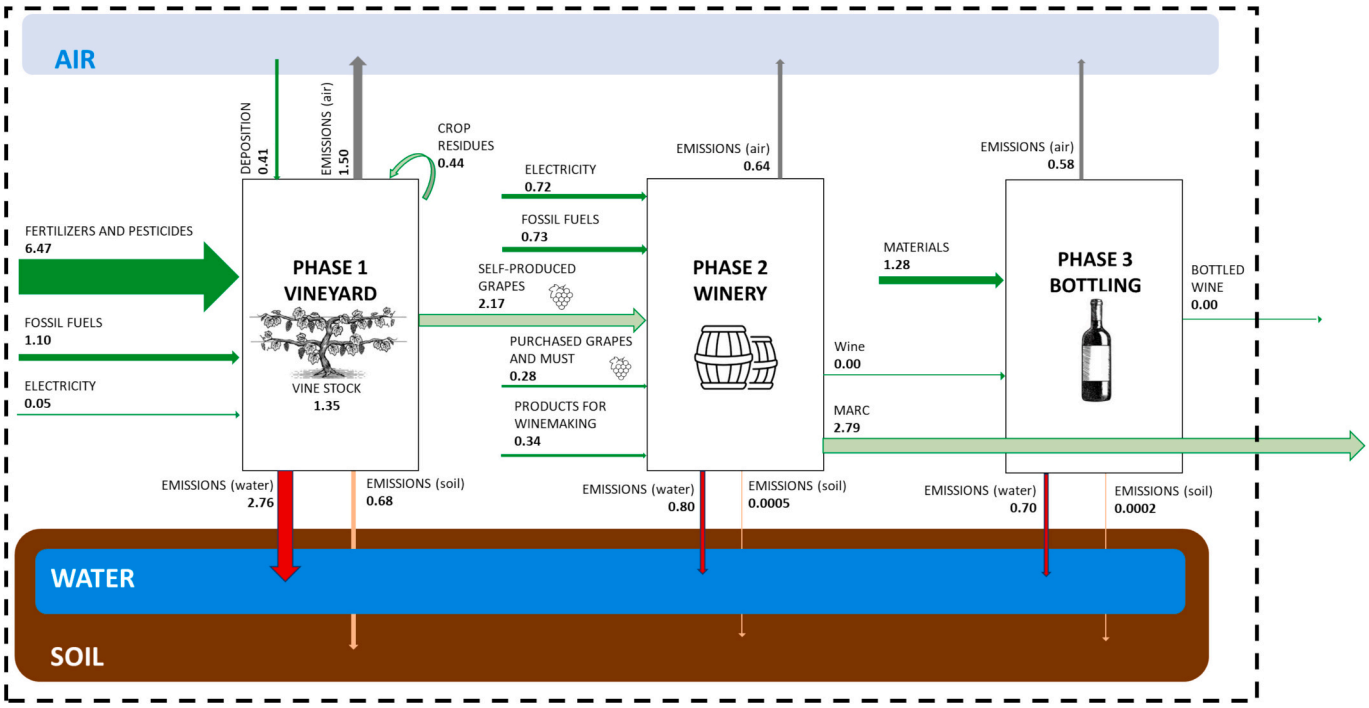

Fig. 7. Nitrogen dynamics associated to wine production (FU: g Nr/wine bottle). The Black Dotted line indicates system boundaries. Grey, Red and Orange lines show N losses in air, water and soil respectively. Green lines show N inputs/outputs, while light green lines are the internal flows and feedback. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
N-Footprint for various case studies of crops, cultivated with a conventional agronomic practice (FU: g Nr/kg product).

Crop	g Nr/kg product	Reference	Accounting methodology
Grapes	5.35	This study	Calculation of direct and indirect emissions, following a life cycle approach and a mass balance (representing the Nitrogen cycle)
Cereals	14.70	Zhang et al., 2018	Product between the Virtual Nitrogen Footprint (VNF) and the N content of the consumed product (Leach et al., 2012)
Tubers	4.10		
Vegetables	4.10		
Fruits	14.20		
Rice	17.11	Xu et al., 2022	Life Cycle Assessment
Wheat	14.26		
Maize	7.83		
Cereals	17.46	Xu et al., 2020	Life Cycle Assessment including both direct and indirect emissions
Tomato	1.18	Wang et al., 2020	Calculation of direct and indirect Nr emission applying specific emissions factors (Leach et al., 2012). The total Nr emission is divided by the product yield (fresh)
Potato	5.00	Pierer et al., 2014	Products between the VNF and the N content of the consumed product (Leach et al., 2012)
Legumes	22.00		
Cabbage	2.57–3.06	Liang et al., 2021	Calculation of direct and indirect Nr emission applying specific emissions factors (Leach et al., 2012). The total Nr emission is divided by the product yield (fresh)
	3.04–3.77		

Consent to participate

All authors have agreed to participate and collaborate in elaborating the manuscript.

Consent for publication

All authors have agreed to the final version of the manuscript.

CRediT authorship contribution statement

Valentina Niccolucci: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Visualization, Writing – original draft, Writing – review & editing. **Michela Marchi:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Visualization, Writing – original draft, Writing – review & editing. **Ilaria Minardi:** Methodology, Investigation. **Nadia Marchettini:** Conceptualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eiar.2025.107830.

Data availability

Data will be made available on request.

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