AMMONIA EMISSION REDUCTION IN MEDITERRANEAN AGRICULTURE WITH INNOVATIVE SLURRY FERTIGATION TECHNIQUES

LIFE ARIMEDA
LIFE16 ENV/ES/000400

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ARIMEDA

This document has been produced as a result of the work carried in the project LIFE ARIMEDA:
Ammonia emission reduction in Mediterranean agriculture with innovative slurry fertigation techniques
(LIFE16 ENV/ES/000400)

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ISBN: 978-84-09-40599-2
LEGAL DEPOSIT: Z 557-2022
GRAPHIC DESIGN AND LAYOUT: AISA PUBLICIDAD

ACKNOWLEDGEMENT: We would like to dedicate a special thanks to all those who have worked and collaborated in the project, researchers, technicians and field officers of the participating entities as well as all the farmers who have been directly or indirectly involved in the execution of the demonstration trials and in the transfer experiences of the project. Our thanks to all the collaborating entities during these 4 years of work, especially to the Ebro River Basin Authority for their collaboration and support in the execution of the demonstration trials at the Agronomic Centre of La Melusa and to the COAPA group of the Polytechnic University of Madrid for their contribution to the work of measuring ammonia emissions.

The LIFE ARIMEDA project has received funding from the LIFE Programme of the European Union.

Any communication or publication related to the project, made by the beneficiaries jointly or individually in

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La coerenza del progetto Arimeda rispetto agli obiettivi comunitari è molto solida: risparmio di risorse idriche, contenimento delle emissioni di ammoniaca, riduzione del consumo di fertilizzanti di sintesi, evidenza della circolarità economica nel riuso delle sostanze nutritive. Sono tutti obiettivi strategici individuabili nelle politiche agricole ambientali comunitarie. Anche in Regione Lombardia da tempo – cioè prima delle armoniche e comunicative sigle che accompagnano lo sviluppo della nuova Pac 2023-2027 quali “Farm to Fork”, “Next Generation EU”, “FFA” (Forum for the Future of Agricolture) si stanno portando avanti in varie operazioni del Piano di Sviluppo Rurale ma anche attraverso altri bandi con risorse esclusivamente regionali/ nazionali che hanno le medesime finalità, molte iniziative di sostegno e sviluppo che puntano a far sì che le aziende agricole si dotino di attrezzature, impianti e strutture in grado di migliorare le loro prestazioni ambientali. Peraltro, anche la politica regolatoria in primis quella specifica sui nitrati e sull’applicazione dell’omonima Direttiva insiste progressivamente da anni per contenere le perdite ammoniacali incentivando le pratiche agronomiche efficienti. La tecnica della fertirrigazione utilizzata e analizzata attraverso gli scenari del progetto Arimeda rende evidente ma soprattutto percorribile un concetto all’apparenza banale nella sua semplicità. Alle tecniche di irrigazione che sfruttano tecnologie impiantistiche che puntano a ridurre i consumi di acqua si può utilmente aggiungere la componente nutritiva normalmente apportata al campo da apposite distinte operazioni di distribuzione dei reflui zootecnici. Le tecniche di irrigazione della coltura unitamente alle basse concentrazioni ammoniacali e quindi alla stabilità chimica della soluzione fertirrigante fanno sì che l’operazione agronomica non rilasci né odori né emetta ammoniaca. È un doppio vantaggio di cui non si può non tenerne conto.

Luca Zucchelli
Regione Lombardia
D.G. Agricoltura, Alimentazione e Sistemi Verdi

En la Comunidad Autónoma de Aragón, existe un gran desarrollo del sector porcino con una alta importancia económica, pero que implica la producción de grandes cantidades de purín de ganadería intensiva. La forma más sostenible e interesante de valorizar este tipo de estiércoles, es su aplicación a los cultivos como fertilizante. Tiene gran interés poder adaptar las aplicaciones de purín a los momentos de necesidad de nutrientes de los cultivos, para que el impacto ambiental por emisiones y lixiviaciones sea mínimo.

El desarrollo de las plantas, como en el caso del maíz, cultivo muy extendido en el regadío aragonés, complica o imposibilita la aplicación del purín por los sistemas tradicionales de distribución en parte del ciclo vegetativo cuando el cultivo esta crecido, en ese momento los agricultores se ven obligados a utilizar fertilizantes minerales, aunque dispongan de purines porcinos.

El proyecto LIFE ARIMEDA, desarrolla y analiza técnica y ambientalmente la aplicación del purín como fertilizante, con prácticas alternativas a las tradicionales, de forma que permite ampliar las dosis y los momentos de aplicación de estos estiércoles en los cultivos, de forma sostenible, minimizando los impactos sobre la emisión de amoníaco y la contaminación de las aguas por nitratos de origen agrario.

El desarrollo, la información y resultados del proyecto son importantes para lograr una adecuada transferencia al sector agroganadero por parte del Centro de Transferencia Agroalimentaria del Gobierno de Aragón, de los técnicos de las entidades y de los servicios de asesoramiento existentes. Es necesario disponer de los conocimientos necesarios para la implantación de la fertilización con purines mediante riego por aspersión y por goteo, conociendo sus ventajas, inconvenientes y adecuado manejo y esta publicación aporta información y conocimiento para una adecuada implementación.

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1

AMMONIA EMISSIONS: SOURCES AND IMPACTS ON THE ENVIRONMENT, ECOSYSTEM QUALITY AND HUMAN HEALTH

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1.1 WHAT IS AMMONIA?

Ammonia is a compound of nitrogen and hydrogen with the formula NH_3. It is colourless and has a distinct pungent smell. It is irritating and toxic. In the presence of oxygen, and therefore when present in air, it can attack aluminium, copper, nickel and their alloys. It is a weakly basic compound and reacts with acids to form their respective ammonium salts.

Ammonia is one of the reactive forms of nitrogen (N) and, like the other reactive forms of N, is generally scarce in the natural environment. Ammonia is less dense than air and therefore tends to rise when it is produced. As ammonia is very soluble in water, it is often found in liquid form. In this state, it dissociates to form ions (NH_4^+ + OH^-):

$$NH_3 + H_2O \leftrightarrow NH_4^+ + OH^-$$

The ionized form (NH_4^+) is not volatile and therefore does not cause emissions to air. Although it can be released into waters causing eutrophication. The main factors affecting ionization are pH and temperature (Figure 1.1 a). When these parameters rise, the percentage of ammonia in free form (NH_3), increases, and volatilization is more likely to occur.

Effective ammonia volatilization is influenced by the resistance to gas movement and the characteristics of the surface of exchange between liquid and air. The other main factors include temperature and the partial vapour pressure over the liquid surface, which is reduced when the air velocity increases (Figure 1.1 b).

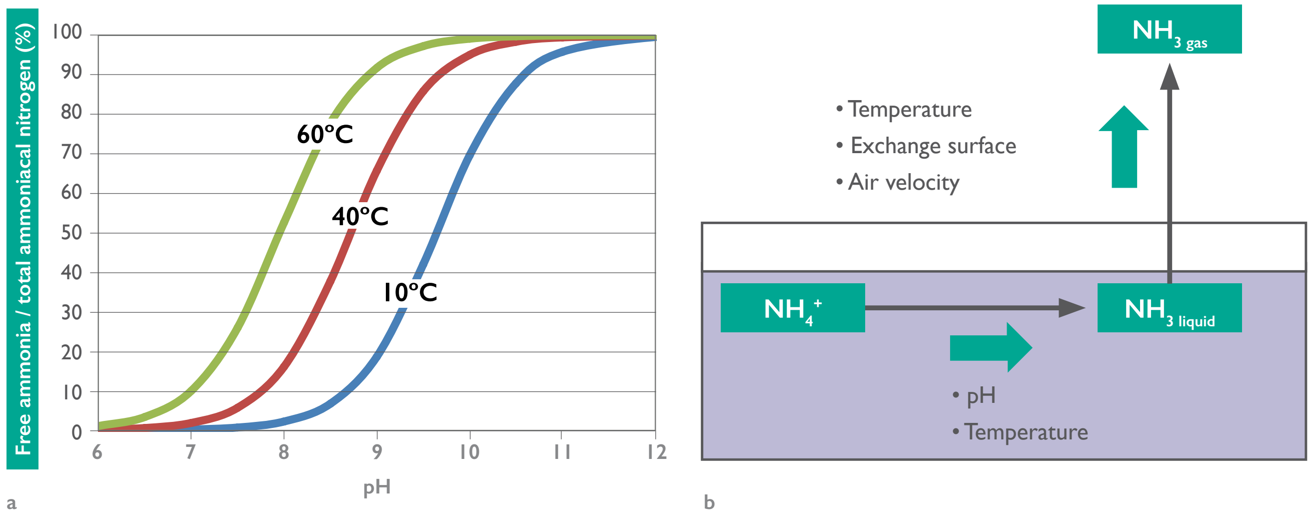
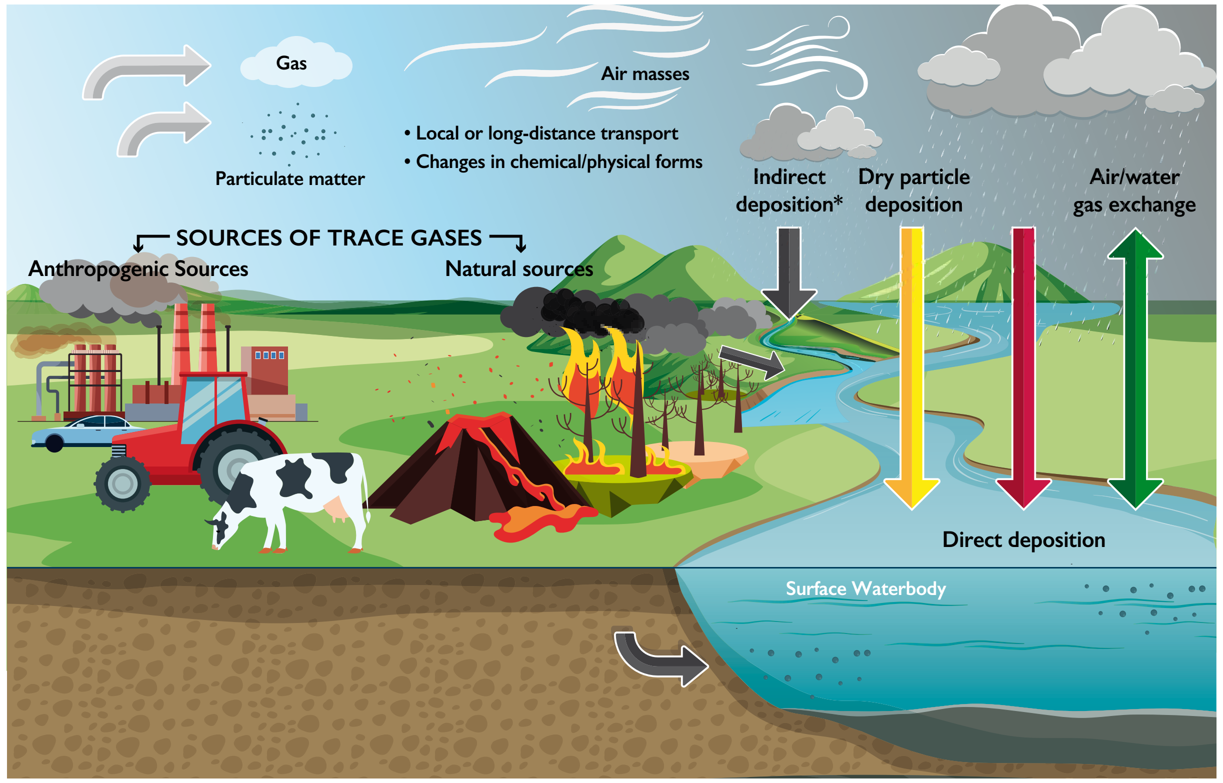


Figure 1.1. Factors influencing ammonia dissociation and emissions

1.2 AMMONIA IN THE ATMOSPHERE

Ammonia (NH_3) is released into air (volatilization) from all ammonium (NH_4^+) containing products. Ammonia from anthropogenic and natural sources participates in atmospheric reactions (e.g., gas-to-particle conversion), is transported by wind and returns to the surface through wet and dry deposition processes, leading to adverse effects on the environment and increased public health risks (Behera et al, 2013) (Figure 1.2).



* Indirect deposition is direct deposition to land followed by runoff or seepage through groundwater to a surface waterbody.

Figure 1.2. Atmospheric emissions, transport, transformation and deposition of trace gases (adapted from Behera et al., 2013).

Ammonia is an alkaline gas and plays an important role in determining the overall acidity of precipitation, cloud water and airborne particulate matter (PM or aerosols). Ammonia and ammonium undergo dry and wet deposition in the areas downwind of their major sources.

Chemical reactions under the influence of sunlight and the presence of other materials lead to the formation of nitrate (NO_3^-), ammonium (NH_4^+) and nitric acid (HNO_3, gas phase). Ammonia and ammonium are the dominant N-containing ions in water droplets in clouds, fog and precipitation. Ammonia reacts rapidly with acids, producing ammonium salts such as $(NH_4)_2SO_4$ and NH_4NO_3 and forming small solid particles (so-called aerosols) (Figure 1.3). The conversion into aerosols is of importance for transport distances. Dry deposition is the direct deposition or absorption on vegetation and in soil and water. Most of the ammonia emitted is deposited a short distance from the source, while aerosols can travel long distances (after 1,000 km, over 20% of the original ammonia is still in the atmosphere in some form according to Ferm (1998)). Gases and particles can also reach the earth as wet deposition and be deposited with rain on vegetation, soil and water. The third mechanism is called occult deposition and is related to the incorporation of these substances in fog droplets that reach the earth.

Dry deposition is estimated to contribute 68% of the total, and wet deposition contributes 25-30%, while occult deposition contributes only 2%. This share can vary significantly under different meteorological conditions (Bobbink et al., 2013).

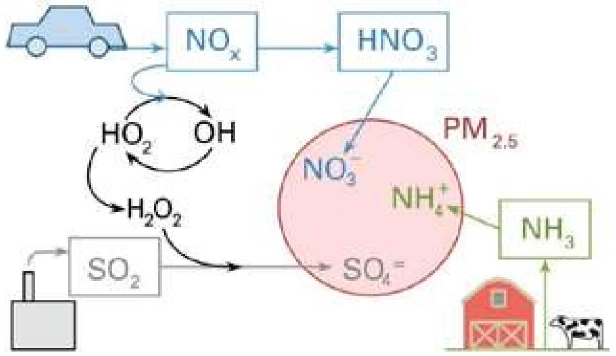


Figure 1.3. Particulate formation mechanism in the atmosphere.

1.3 NEGATIVE EFFECTS OF AMMONIA EMISSIONS

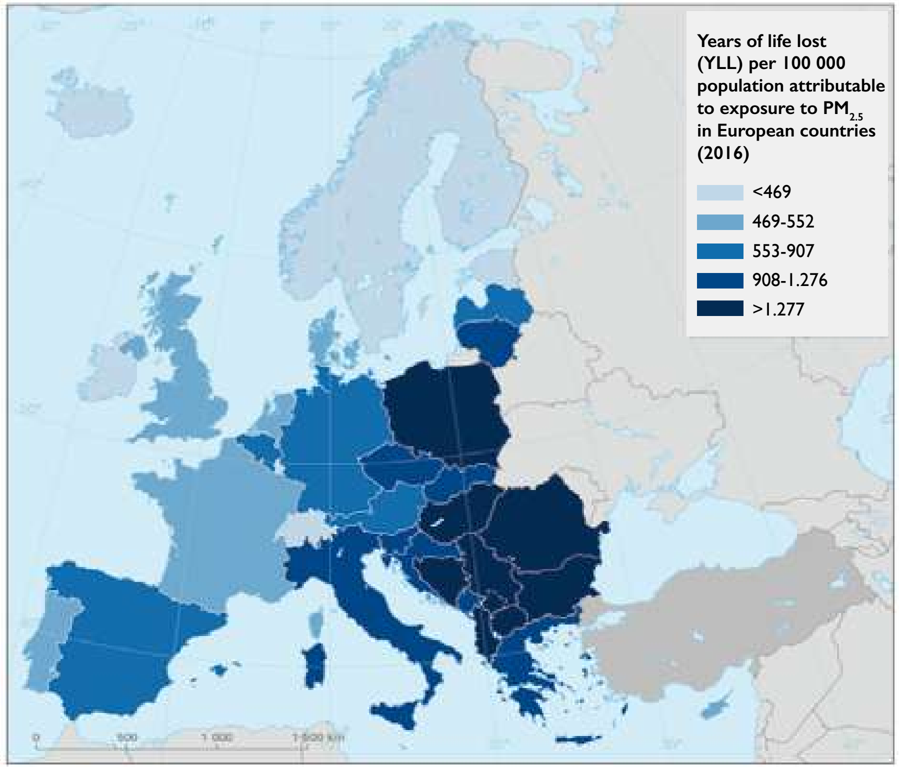
The emission and further deposition of ammonia is harmful to ecosystems because it causes acidification and disrupts plant communities. Furthermore, NH_3 is a precursor for the formation of particulate matter, which has adverse effects on human health, affecting the respiratory and cardiovascular systems and causing premature death. Ammonia is also a precursor of nitrogen oxides and can be, in certain situations, a source of nitrous oxide (N_2O), which is a potent greenhouse gas.

Particulate matter

Fine particulate matter ($PM_{2.5}$) and even particles below 10 µm (PM_{10}) include inhalable particles that are small enough to penetrate the thoracic region of the respiratory system. The health effects of inhalable PM are due to exposure over both the short term (hours, days) and long term (months, years) and include respiratory and cardiovascular morbidity, such as aggravation of asthma, respiratory symptoms and increased hospital admissions.

Fine particulate exposure can cause mortality from cardiovascular and respiratory diseases and from lung cancer. According to EEA (2019), in Europe, approximately 400,000 premature deaths per year are attributable to long-term exposure to $PM_{2.5}$ concentrations. Long-term exposure to $PM_{2.5}$ is associated with a 6-13% increase in the long-term risk of cardiopulmonary mortality per 10 µg/m^3 of $PM_{2.5}$ (WHO, 2013).

Exposure to $PM_{2.5}$ reduces average life expectancy by approximately 8.6 months (Figure 1.4). The average life expectancy in the most polluted cities could be increased by approximately 20 months if the long-term $PM_{2.5}$ concentration were reduced to an annual mean level of 10 µg/m^3 (WHO, 2013).



Note: YLL, Years of Life Lost. The classification of values in map legends is quantiles, so one fifth of countries fall in each class. The calculations are made for all of Europe and they may differ for specific studies at country level.

Figure 1.4. Estimated years of life lost per 100,000 population attributable to exposure to ($PM_{2.5}$) in European countries in 2016 (EEA, 2019).

Acidification

Acidification occurs when airborne particles are deposited on the ground by acid rain, snow, or fog and are transformed to nitric acid. Other gases, such as sulphur dioxide (SO_2) and nitrogen oxides (NO_x), which are mostly produced by industry and transport, also contribute to acid rain formation and subsequent acidification. However, ammonia plays an important role and has been estimated to be responsible for 24 % of acidification of terrestrial ecosystems (Sarteel et al., 2016).

Acid rain damages forests and other vegetation both directly and indirectly. Directly, because dissolved chemicals in acid rain damage the leaves/needles and bark of trees and other vegetation, leaving them more vulnerable to disease and insect damage. Indirectly, because chemicals in acid rain impact soils by changing its pH, killing soil microorganisms and reacting with nutrients in the soil, causing some nutrients to dissolve and be washed away by rain before they can be absorbed. Another indirect effect of acid rain is the mobilisation of harmful chemicals such as aluminium, which are then released into the soil and harm trees or vegetation. The impact of acid rain on cultivated crops can be minimised by the application of lime and fertiliser to correct (i.e., raise) the pH levels of the soil and replace lost nutrients; however, this is generally not an option for non-cultivated areas, e.g., forests (Sarteel et al., 2016).

Eutrophication and biodiversity

Ammonia deposition contributes to nitrogen enrichment of waters and can therefore be a secondary cause of eutrophication, although most nutrients reaching waters derive from other sources.

Eutrophication consists of a progressive over-enrichment of water by nutrients (mainly nitrogen and phosphorous), resulting in increasing biological production leading to excessive growth of algae and plants (e.g., microscopic algae such as diatoms and other phytoplankton, filamentous algae, macroscopic algae and higher plants); their decomposition by bacteria consumes dissolved oxygen, killing fish and aquatic life. Harmful algal blooms caused by many different types of algae can be triggered by nutrient enrichment. Eutrophication naturally occurs in water bodies that accumulate nutrients over centuries but is also reinforced by excessive fertilisation or wastewater discharge into aquatic ecosystems. In potentially affected areas, the risk of eutrophication increases with high temperature, high light availability, and low water flow. This explains why eutrophication impacts surface waters, from lakes and rivers to saline lagoons and coastal water.

Through water contamination and disruption of the balance in biotic communities, eutrophication represents a direct threat to public health (e.g., by making water non-potable) and biodiversity (e.g., by leading to the extinction of certain populations and the proliferation of invasive species). It also affects key economic sectors, such as fisheries and tourism, through inconvenient smells and colours, spoilt landscapes, and restriction of economic and recreational (e.g., fishing) activities with high socio-economic returns (Sarteel et al., 2016).

1.4 SOURCES OF AMMONIA EMISSIONS

In Europe, UNECE (2021) reports that ammonia emissions are relevant and mainly concentrated in intensive agricultural areas (Figure 1.5).

The main causes of NH_3 emissions are livestock farming (including management of manures and slurries) responsible for over 70% of ammonia emission and the application of synthetic fertilisers contributing with 20%.

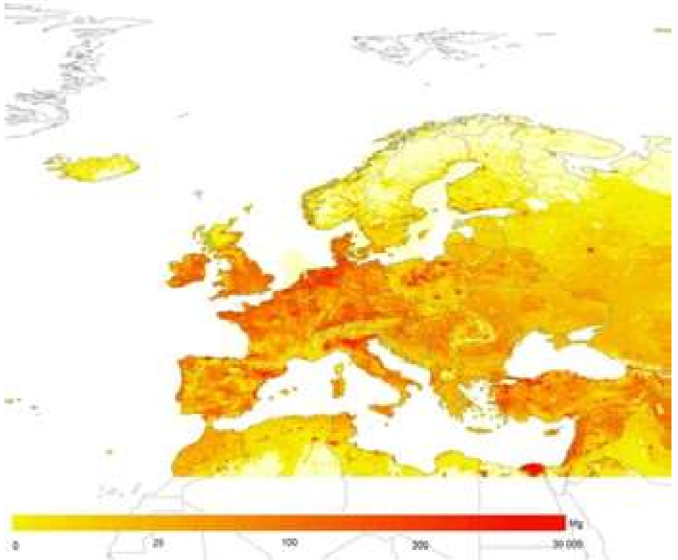
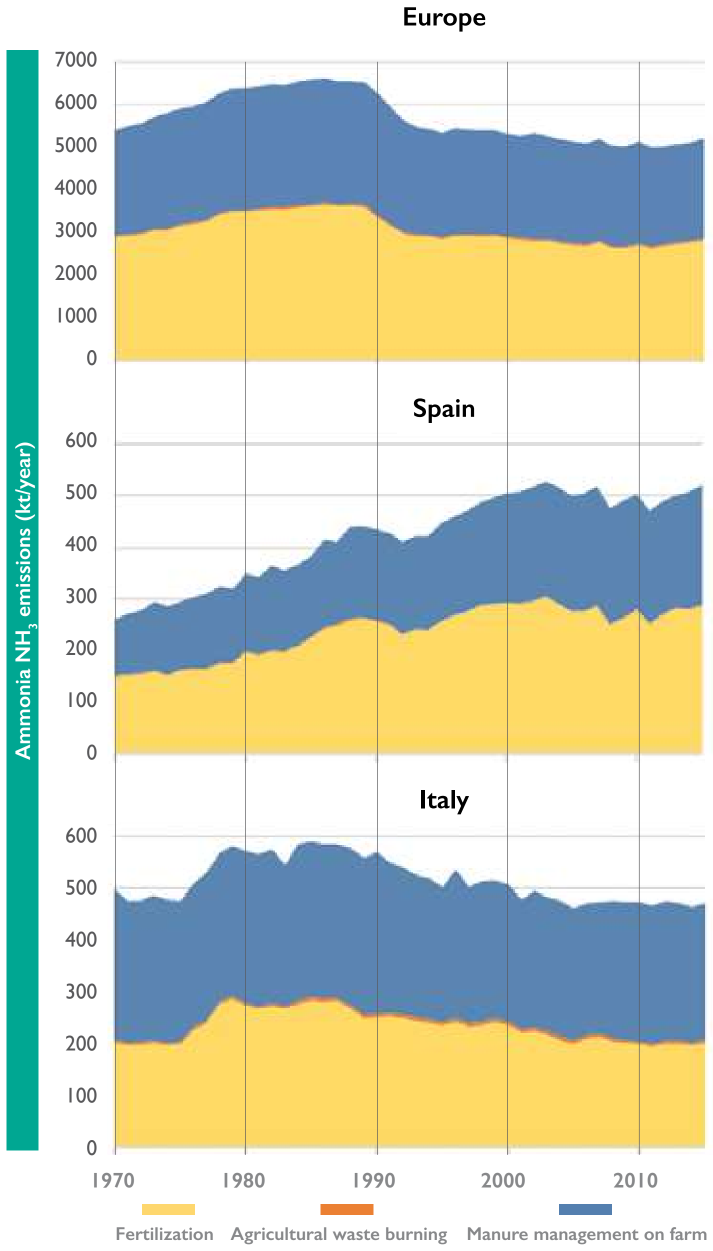


Figure 1.5. Ammonia emissions in 2018 in kg NH_3 per km^2 (UNECE, 2021).



Due to greater demand for meat and milk for consumption, animal production has increased considerably, resulting in a rapid rise in the number of farm animals. For example, it has been observed that between 1960 and 2000, the human population roughly doubled, while the number of livestock animals roughly tripled during the same time period (Behera et al., 2013).

The two main sources are crop fertilization and manure management on farms (Figure 1.6). The trend shows a relevant reduction in ammonia emissions in Europe after 1995; however, there is a slight increase in recent years of the time series to pay attention to.

Figure 1.6. Trend of ammonia emissions by agricultural sector in Europe, Italy and Spain (*Dataset was compiled from EDGARv4.1*, 2021).

Trends can differ considerably among countries. For example, the trend in Spain shows a marked increase in ammonia emissions due mainly to an increase in livestock numbers but also an increase in mineral fertilisers (Eurostat, 2021), while in Italy, the emissions from livestock are almost constant, and the absence of an increasing trend might be attributed to better fertiliser management (Figure 1.6).

Approximately 50% of the emissions from livestock are from cattle, 30% from pigs and 20% from poultry (Figure 1.7). Housing (40%), storage (20%), application (35%) and grazing (5%) are the main stages in the manure chain that cause ammonia emissions. These stages are not independent of each other. For example, cleaner animal housing means more nitrogen is retained in the manure. Coverage of manure storage has the same effect. This may result in greater emissions of ammonia during application on land. Therefore, low-emission manure application is the cornerstone of an effective ammonia abatement strategy. The fertigation techniques demonstrated in the LIFE ARIMEDA project may contribute significantly at this stage. However, it would be necessary to approach an integrated management bearing in mind all potential trade-offs and cascade effects of the practices implemented throughout the whole slurry and manure management system while adopting efficient techniques at every stage.

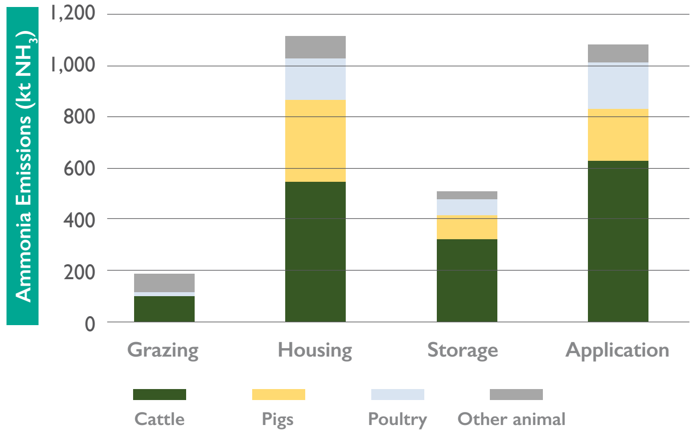


Figure 1.7. NH_3 emissions from livestock farming emerging during the different stages in the manure management chain (IIASA, 2017).

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2

AGRICULTURE IN THE MEDITERRANEAN REGIONS: TOWARDS A CIRCULAR MODEL OF NUTRIENTS AND THE ROLE OF FERTIGATION PRACTICES

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2.1 INTRODUCTION

Mediterranean agriculture is characterized by the production of the so-called Mediterranean products, such as olive oil, wine and fruit and vegetables. The regions have similar bioclimatic characteristics with low agricultural production in general due to water scarcity, but with a high production potential capability under irrigation. Most of the farms are family-owned, but the farm structures show great diversity in the different countries (CIHEAM, 2010). In the Mediterranean areas of Europe (Italy, Greece, Spain) large irrigated areas have been implemented that have changed traditional agriculture for a more competitive one based on extensive crops with higher added value (corn, alfalfa) and sweet fruit crops. In livestock there has also been a significant transformation, in particular in some regions of Spain and Italy, with a change from extensive livestock based on sheep and some cattle to a more intensive production of cattle and pigs, which has grown vertiginously in recent years.

The crops in irrigated areas have a high production capacity and, associated with it, high fertilization needs; thus, the use of synthetic fertilizers has been increasing as the irrigated surface has increased. The traditional practice of using livestock manure as a good organic fertilizer has been abandoned, replacing these with chemical fertilizers due to easier handling and application, which has hindered in many areas a proper management of the nutrients in slurries and manure. It has been estimated, back to 2006, that in some regions of the Mediterranean area the amount of N contained in animal manure was sufficient for the fertilization of all existing crops (Orús and Sin, 2006). However, the consumption of nitrogenous fertilizers increases progressively, boosting N-excess in agricultural systems that generates diffuse emissions of nutrients, both to the atmosphere and to watercourses.

The reduction of ammonia emissions (95% of ammonia emissions associated to agricultural production) and greenhouse gases to the atmosphere and the reduction of water pollution by nitrate are two key aspects of European Union policy, envisaged within the European Green Deal which has the objective of reduction of nutrient losses by 50% without reducing soil fertility by year 2030, through the reduction of the use of fertilizers by 20%. Within this scheme, the efficient recycling of nutrients is essential and the fertigation techniques developed and fine-tuned in the LIFE ARIMEDA project are destined to have an exponential development in areas with high livestock production and large irrigated areas, since they are relatively easy to implement, increase the economic return of the farms, reduce ammonia emissions to the atmosphere, promote the substitution of synthetic fertilizer by slurry throughout the whole crop cycle and reduce nitrogen doses by distributing the application throughout the entire crop cycle.

The characteristics of the agricultural and livestock sector in the two areas where the LIFE ARIMEDA project has been developed (Aragon and Lombardy) and the prospects for applying the fertigation techniques developed in the context of each of the regions are presented.

2.2 THE CASE OF ARAGON (SPAIN)

2.2.1. INTRODUCTION

In the last 10 years, the Aragon Agricultural Final Output (AFO, value of agricultural products, before processing, available for export and consumption) has been increasing until reaching 4.500 million € during the year 2020. The final crop production had smaller increases in this period, while the final livestock production has increased steadily, mainly due to increase of intensive farming, basically the pig meat sector (Figure 2.1). In year 2020, pig meat industry represented 71% of the livestock final output and 49% of the AFO. The most important sectors after pork industry were cereals with 13.5%, fruit trees with 11.1%, and beef meat industry with 5.6%. At the other extreme, there is a very emblematic and traditional sector for Aragon, such as sheep, which hardly reaches 2% of this PFA and which, however, has an essential role in maintaining the environment and the population of the rural areas.

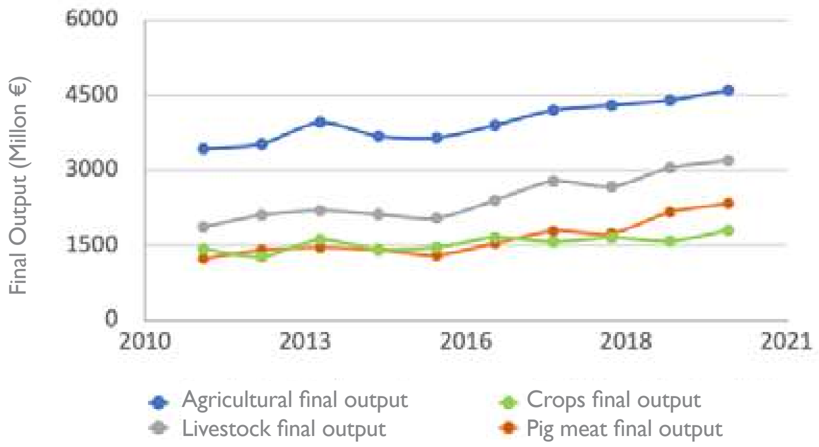


Figure 2.1. Agricultural, crops and vegetable, livestock and pig meat final outputs in Aragon.

Aragon leads, the national ranking in pig production with just over 4,000 livestock farms, and a total of 8,907,098 heads in 2021, which produced 11,793,970 m^3 of pig manure (Government of Aragon, 2022).

Aragon is also the fourth region in Spain in irrigation area (413,482 ha, 11% of total Spanish irrigation), only exceeded by Andalucía, Castilla la Mancha and Castilla y León. Most of the irrigated areas are in the left bank of the Ebro river, where the largest irrigation systems has been developed (Figure 2.2), managed by large Irrigation Communities such as those of Bardenas (88,000 ha), Riegos del Alto Aragon (130,000 ha) or Canal de Aragón y Cataluña (100,000 ha). These systems are irrigated with good quality water from Pyrenean reservoirs. The irrigated lands on the right bank are smaller and in many cases are irrigated with groundwater; irrigation water in these areas is of poorer quality with a higher content of salts.

The main irrigated crops are winter cereals, followed by alfalfa and maize (Figure 2.3). The combination of these two circumstances, a high number of pig farms and a large irrigated areas, highlight the need to carry out responsible agriculture with the environment, seeking innovative solutions that allow maximizing the performance of the farms and minimizing the losses of nitrogen and other nutrients to the atmosphere and to watercourses.

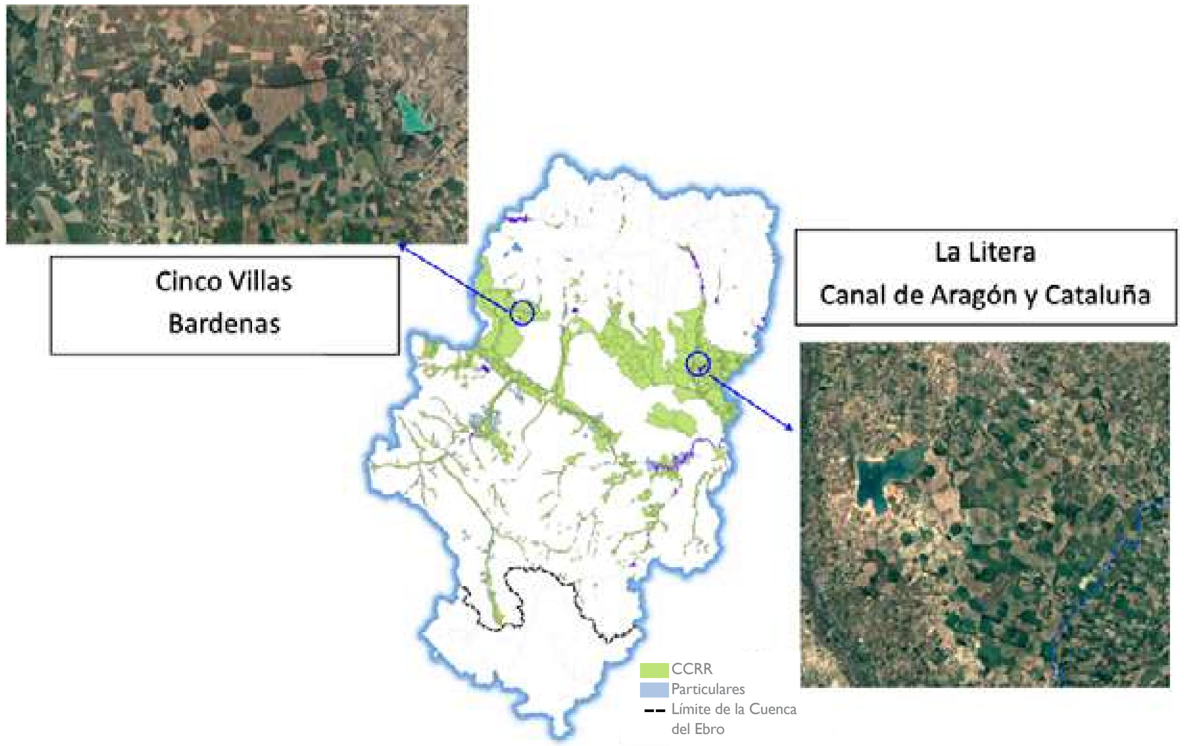


Figure 2.2. Distribution of irrigation in Aragon with details of two areas where irrigation with pivots predominates. (Source: Zapata et al., 2020).

2.2.2 IRRIGATION SYSTEMS

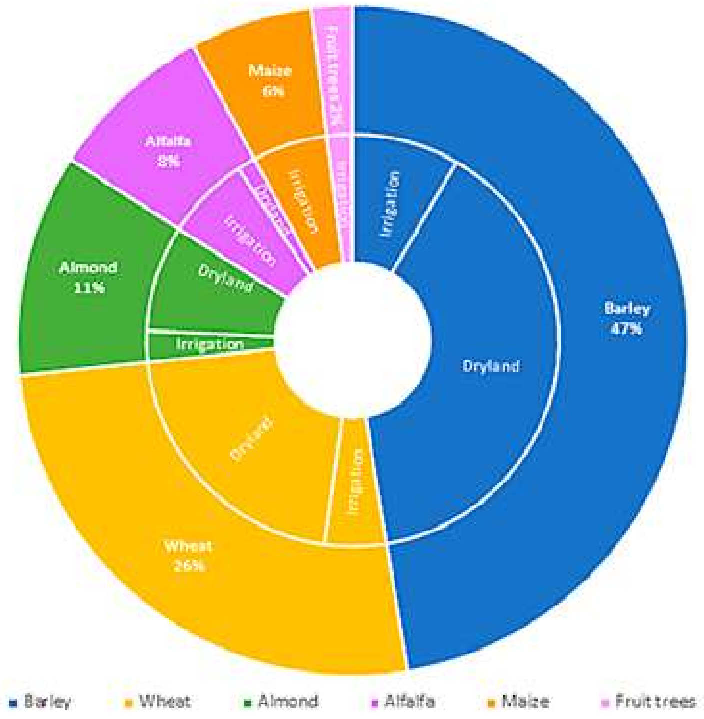


Figure 2.3. Main irrigated crops in Aragon in 2020 (Source: MAPA, 2020).

In Aragon, the predominant irrigation system is flood irrigation with 44.94% of the irrigated surface (185,849 ha), although this irrigation system has been declining over the last ten years. However, the sprinkler irrigation surface has increased in the last decade (38,601 new hectares) since all the new transformations to irrigation are carried out under pressure irrigation and there has been high investment to transform flood irrigation to pressure irrigation systems (modernization irrigation plans). Localized irrigation has also significantly increased its extension with a significant increase in woody crops (almond, olive, vine, walnut) where this localized irrigation system is used. However, this irrigation system is not used in extensive crops except in exceptional situations (Figure 2.4).

The automotive irrigation surface (pivots and lateral machines) has increased slightly, but without experiencing an increase parallel to that of the sprinkling surface. Automotive irrigation accounted for 22% of the surface irrigated under pressurized irrigation in 2020, 34,408 ha (MAPA, 2020). Pivot irrigation systems are distributed throughout the territory of Aragon, as can be seen in the satellite images in Figure 2.2, that show specific areas inside the irrigated areas of Bardenas and Canal de Aragón and Cataluña. Demonstration plots of the project were implemented in these two areas due to the optimum possibility of transfer offered by their irrigation. The modernized irrigation systems under pressure and the new irrigation systems are highly technical in irrigation management.

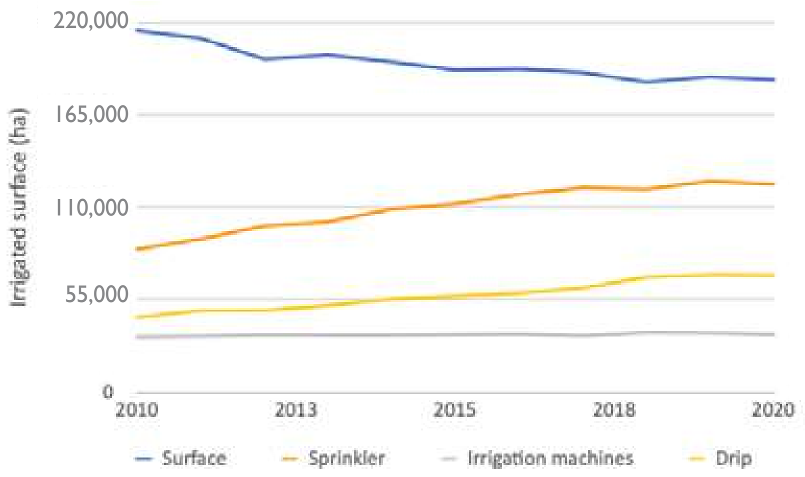


Figure 2.4. Irrigated surface (ha) in Aragon with different irrigation system in the period 2010-2020 (Source: MAPA, 2020).

2.2.3 LIVESTOCK FARMS AND CROP FERTILIZATION

In the region of Aragon, there has been a very large development of intensive pig production in the last 20 years, being at the moment the European region with the largest number of pig heads (≈ 9 million). This increase has occurred in two ways: either with the installation of new farms or with the expansion of existing farms, with a concentration of farms in specific areas of the Aragon's territory. The rapid development has led to the regional government to the declaration of areas with livestock overload due to excess nitrogen of organic origin from livestock activity in 11 municipalities of Aragon and in many others, there are regulations that limit the expansion of livestock farming. In areas with overload, a higher amount of nitrogen is produced with manure than the N that can be applied to crops, which creates problems in its management and over-fertilization often occurs, resulting in emissions and pollution, with the consequent loss of the fertilizer value of the manure produced.

However, an important and positive aspect of the concentration of farms in specific areas is that has encouraged the creation of businesses based on the collective management of manure and slurry. These management centres, which have larger and more efficient equipment for the slurry application, take care of the distribution of the slurry generated in the farms in the agricultural fields, maximizing recycling efficiency, and distributing

the costs of manure management between the animal farm and the agricultural farm that benefits of its application as fertilizer.

Although slurry and manure are used increasingly in the fertilization of crops given the large amount available, the purchase of inorganic fertilizers is also high. Thus, a significant increase in slurry production is observed, currently exceeding 11 million m^3 /year (Figure 2.5), which is equivalent to approximately 65,000 t N/year, and on the other hand, an increase in the sale of fertilizer products, which in 2020 amounted to 136,811 t N with an increase of 36% between 2016 and 2020 (Table 2.1). It is not surprising that the last Nitrogen balance carried out by the Ministry of Agriculture (MAPA, 2018) shows a positive balance (excess N) of 22.5 kg N/ha for the entire territory of Aragon.

Figure 2.5. Number of pig heads and manure production (m^3 /year).

Table 2.1. Consumption of synthectic fertilizers in Aragon. (Source: ANFFE Asociación Nacional de Fabricantes de Fertilizantes, 2022).

	2015/2016	2016/2017	2017/2018	2018/2019	2019/2020
Nitrogen fertilizers (t N)	99,978	103,706	143,834	132,769	136,811
Potassium fertilizers (t K_2O)	33,593	39,377	42,011	34,662	35,337
Phosphate fertilizers (t P_2O_5)	43,570	56,696	54,608	60,190	65,610

There are some factors that can help to improve the management of pig slurry and value it as a good fertilizer in Aragon. The implementation of manure and slurry management centres in the territory that are responsible for the correct management of organic N with full traceability of the work carried out is considered a key aspect to improve slurry management. These centres sell the slurry application as a fertilizer application and ensure that the amounts are those required by the crop, are applied at the right time and following existing regulations.

On the other hand, and on a smaller scale, it must be considered that in recent years, with the implementation of irrigation modernization and the change from flood irrigation to pressure irrigation (both sprinkler and pivot), many farmers in the middle valley of the Ebro have decided to switch to double cropping practices, growing barley, wheat, ryegrass or a legume such as peas in winter-spring, followed by shorter-than-usual corn in summer. This practice has been extended to increase income and to be able to amortize the investments made in the irrigation modernization, but it also implies an increase in the N needs of the crops that would allow a greater and more efficient recycling of the nutrients contained in the slurry produced.

There are some limitations in the management of slurry as a fertilizer related to the application practices that are commonly used. Slurry can only be applied when it is possible to enter the field with heavy machinery, that is, it can be applied on bare soil before sowing or with the crop at the beginning of its development, for example, in the cover of winter crops, however, it is not possible to apply when the crop is already grown, which forces the application of synthetic fertilizers even when manure is available and cheaper. In this sense, the developed fertigation techniques allow fertilizing throughout the entire crop cycle and permit the replacement of synthetic fertilizer by slurry at all times, since it is not necessary to enter the field for its application. In the trials carried out in the project, it has been possible to fertilize the maize crop only with the liquid fraction of slurry, obtaining satisfactory yields and reducing the doses of N applied.

In the irrigated lands of Aragon there are more than 35,000 hectares irrigated by pivots and lineal irrigation systems that could benefit from the fertigation system. In addition, 125,000 ha of sprinkler irrigation where ferti-irrigation could also be applied (although in the ARIMEDA project the reduction in ammonia emissions that would be achieved in this system has not been measured). Fertigation techniques can be easily applied on farms with crop fields nearby where the slurry injection could be made directly from the farm pond to the field through a pipe, (avoiding the transport of slurry by truck or tank). In these cases only the investment in separation equipment, which for sprinkler irrigation does not need to be sophisticated due to the size of the particles that need to be filtered (<500 μ m) and an injection pump is necessary. If the field is not near the farm and it is necessary to transport the slurry a storage system in the field should be installed, and the collective management centres could play an important role in separation and transport, it must be considered that the pivots surface is usually large and it is necessary to transport a large volume of filtered manure.

Drip irrigation is widespread for horticultural and woody crops (more than 40,000 ha) but it is not common in extensive crops (MAPA, 2020). On the other hand, the separation process is more demanding than in sprinkler irrigation and two separators in line are necessary to obtain an adequate liquid fraction, to obtain a liquid fraction with admissible particle sizes, below 100μm.

It is considered that the fertigation techniques have the possibility of being used in an important part of the area under sprinkler irrigation in Aragon, especially in the plots close to the farms, the installation of the fertigation and the fertilization only with the liquid fraction obtained in the separation would improve the recycling of nutrients from the slurry, it would replace part of the synthetic fertilizers at a cheaper cost, it would reduce ammonia emissions into the atmosphere and it would help to adjust the N balances in the system by reducing the excesses of N that currently exist. The farmers in the area are very interested in the development and application of fertigation techniques using the slurry from their farms. However important effort is still needed to improve the different normative that limits the application of livestock manure to the fields, generating sound data that could help for a better recycling of nutrients in animal manures.

2.3 THE CASE OF LOMBARDY (ITALY)

2.3.1. INTRODUCTION

Lombardo livestock farming has internationally recognized excellence for the production of meat, milk and products derived from them. In Lombardy Region the livestock structure is mainly linked to a production system that is based on the binomial intensive cereal-fodder crops and a high livestock load raised per unit area.

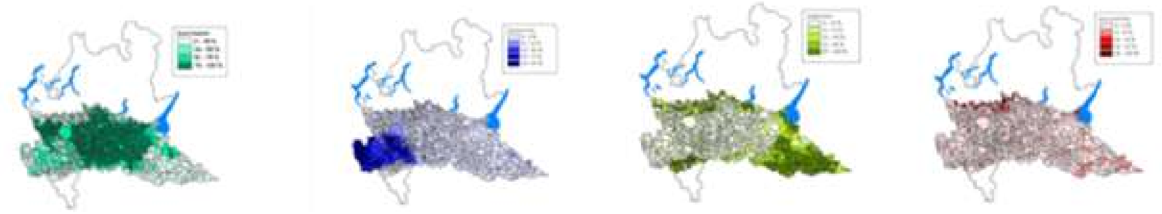
This situation entails a significant responsibility for diffuse pollution of surface and groundwater due to agronomic use of fertilisers and livestock and digested manure and slurries. In more recent years, the relationship between effluent management and air quality has also been highlighted. In particular with focus in the acidifying emissions of ammonia and its relation to particulate matter and to greenhouse gases emissions (nitrous oxide and methane).

The aim of the LIFE ARIMEDA project has been to propose a livestock management model based on fertigation, in order to increase the nitrogen use efficiency of livestock manures and reduce emissions into the atmosphere.

2.3.2 IRRIGATION

In Lombardy, the National Statistic Institute data from the "2010 Census of Agriculture" show an irrigated land characterized by a large availability of water, especially in the plains area. Although not showing supply problems, water is a good that should not be wasted. So, it is very important to design and implement systems that can improve the use of water in our irrigation systems.

The use of different irrigation techniques in Lombardy follows a zonal specificity, in the regional central plain and in the plain of Pavia the furrow and flood irrigation techniques are predominant and represent more than 70% of irrigated surface, continuous flooding is the main technique in the west on the rice fields, while sprinkling techniques are mainly extended in the eastern part of Mantua and Brescia. Drip irrigation systems, on the other hand, are currently adopted for a few specific realities. The techniques described differ in the use of water, energy, labour, capital, the possibility of automation and the adaptability to certain types of soil.



57,6 %
flooding

14,6 %
continous flooding

25,8 %
sprinkler

1,4 %
drip irrigation

Figure 2.6. Distribution of the different irrigation systems in Lombardy.

A key issue which needs to be consider is the efficiency of the different irrigation methods, which is usually calculated as irrigation volume evapotranspirated by the crops. As it is easy to guess, the efficiency of flood system is very low and rises according to the precision of the method adapted, following sprinkler and drip irrigation the system with the highest efficiency.

Table 2.2. Efficiency of different irrigation systems

Efficiency	Flood	Sprinkler	Drip
Potential (%)	60-80	75-90	90-95
Effective (%)	30-80	50-80	65-90

2.3.3 FERTILIZATION

Over the years, the contribution of organic matter with manure has been the subject of critical discussion. If historically it was seen as an absolute wealth for soil fertility, with the introduction of chemical fertilizers, this concept has become increasingly more attenuated. However, in recent years, technical evolution and economic sustainability of farms have led to concentration of animal farms in the plains, this aggregation process has drawn attention on manure management, which have to be well managed in order to avoid environmental problems. Therefore, the use of manure based on good and effective management in the application to the fields is essential for a correct nutrients supply, improve nutrient recycling and reduce environmental effects.

The diagram in Figure 2.7 presents the losses of N of slurries and digestates according to different distribution techniques: splash plate, splash plate with manure incorporation after 24 hours, trailing hose, trailing shoe, open furrows, closed furrows and fertigation. As the distribution techniques adopted are refined (towards the right), the emission of ammonia contained in the effluent decrease, consequently there is an increase in nitrogen efficiency, which ensures a higher availability for crops. From a technical point of view, it is clear that increasing the efficiency and uniformity of application methods, the efficiency of nitrogen content of slurry and digestate increases, and allow to satisfy the crop needs exploiting farms' manures and slurries. It is also clear, that switching to more efficient practices make it possible to significantly reduce losses, especially those related to ammonia emissions to the atmosphere.

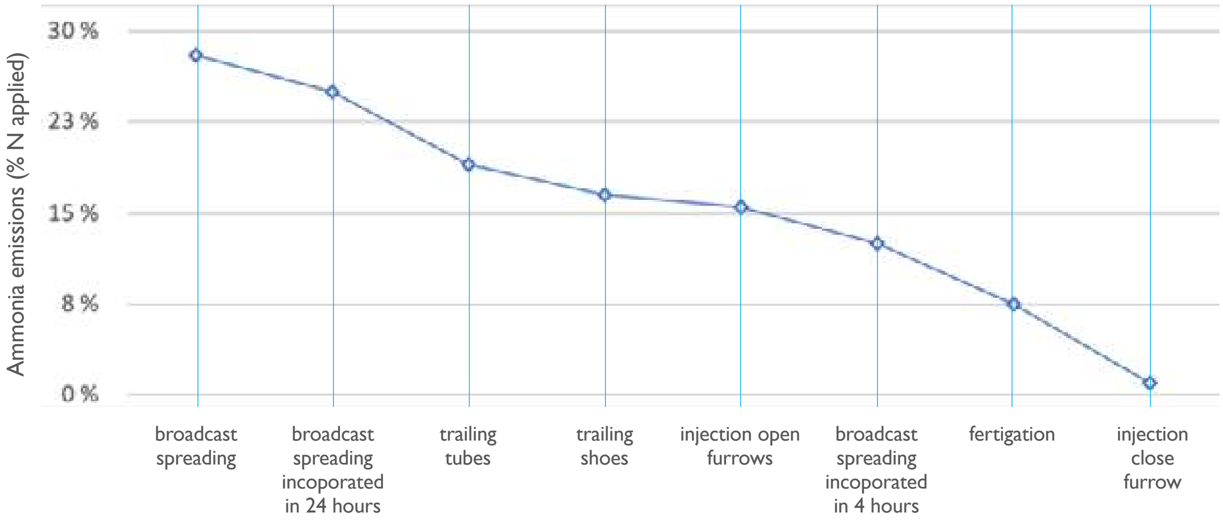


Figure 2.7. Ammonia emissions in the application of digestate using different distribution techniques.

The reduction of losses is becoming an increasingly urgent requirement of civil society. Although at this moment it is not easy to estimate its direct economic value, it is possible to predict in the near future how the consumer's attention can turn mainly to products of greater environmental sustainability.

From the economic point of view, digestate and slurry fertigation is a technique that can combine the objectives of Community policies on economic circularity in the reuse of nutrients.

Support and development measures have been in place in the Lombardy Region for a long time, aimed at enabling farms to equip themselves with equipment, plants and facilities that will improve their environmental performance, using the resources provided for by the various Rural Development Programme Measures, as well as through calls for proposals with exclusively regional/ national resources.

The fertigation technique carried out and analysed through the scenarios of the LIFE ARIMEDA project makes clear but above all practicable, an apparently simple and intuitive concept: the combination of irrigation practices using plant technologies that reduce water consumption, with the distribution of livestock effluents that provide nutrients to crops. The irrigation techniques of the crop concurrently with the distribution of slurry and digestate diluted, with lower ammonia concentrations, ensure agronomic operation, has high efficiency, and reduce odours and ammonia emissions.

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3

HOW CAN WE FERTIGATE WITH ORGANIC FERTILISERS?

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3.1 INTRODUCTION

The LIFE ARIMEDA project intends to contribute to the development of strategies to reduce ammonia emission by developing and fine-tuning technologies to apply slurries and digestates in pivot and drip irrigation systems.

Fertigation techniques convert liquid slurries and digestates available from farms or biogas plant storage tanks or ponds into high-value fertiliser at the moment they arrive at field-cropped soils. The fertigation process requires different steps that should be considered and analysed in detail to design, from the beginning, a fine-tuned system adapted to the requirements of each specific case. Additionally, it is essential to develop correct management practices for each of the steps to avoid problems or malfunctioning that may adversely affect the quality of fertigation.

In this chapter, we analyse each of these steps and provide general recommendations for the correct design and management of the fertigation process with liquid fractions of pig slurry and digestate.

3.2 STEPS AND REQUIREMENTS

Many steps are involved in the process of fertigation (Figure 3.1): solid-liquid separation of the slurry and digestate, storage of the obtained liquid fraction (LF) at the farm or biogas plant, transport of the LF to the field, LF storage in the field, design of the injection system, knowledge of the composition of the liquid fraction, design and splitting of the fertilization amounts and management of the irrigation system. Some of these aspects are related, and we have approached the analysis by grouping together some of the steps with the following scheme:

> 1. Solid-liquid separation of the slurry and digestate and storage of the liquid fraction at the farm or biogas plant.
>
> 2. Transportation of the liquid fraction to the field, storage in the field and operation and maintenance of the injection system.

3. Composition of the liquid fraction.
4. Design of the fertilization plan: rates and splitting of the nitrogen (N) application.
5. Design, management and maintenance of the irrigation system.

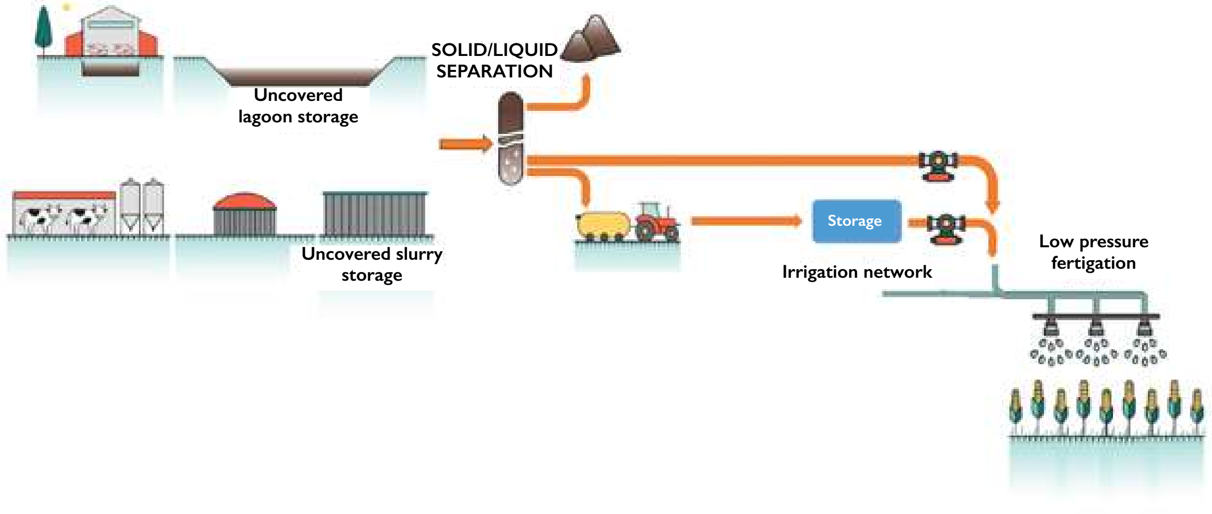


Figure 3.1. Flowchart for fertigation with liquid fraction of slurry and digestate.

3.2.1 SOLID/LIQUID SEPARATION AND STORAGE ON FARM

To inject slurry or digestate into an irrigation water network, the organic fertiliser (slurry or digestate) first needs to be filtered to remove solid particles that can clog irrigation systems. It is essential to establish adequately the requirements of the filtration equipment, in particular the maximum particle size that each specific irrigation system can support without obstruction. Solid-liquid separation must remove particles with sizes greater than the openings of the nozzles or drippers. The nozzle orifice size of centre pivots varies between 1.6 and 10.0 mm (Senninger, 2020), while the recommended filtration for drippers on driplines is approximately 130-200 µm (Netafim, 2020).

As a general rule, particles larger than 600 µm should be removed to avoid clogging problems in the nozzle plates of pivot irrigation systems, and particles larger than 100 µm should be eliminated to avoid blockage of filters or obstruction of drippers in drip irrigation systems. Specific requirements and recommendations can be obtained from the technical information of each irrigation system or from the irrigation supplier company.

Mechanical separation has a lower operating cost and needs less maintenance than chemical separation (with additives), but the use of chemical products should be considered if the requirements of the irrigation systems are not fulfilled by mechanical systems. It is recommended that the total solid content of the filtered liquid fraction remain below 10% to enable the use of a traditional pump.

Among the techniques available for solid-liquid separation of livestock slurry and digestate, the screw press (Image 3.1) is the most common in some cases involving previous separation with a filtering ramp (Image 3.2). This equipment features a filter pore size usually ranging between 500 and 1000 µm and is thus a method suitable for fertigation in pivot systems. The screw press allows the largest quantities of nitrogen (N), phosphorus (P), and potassium (K) to be maintained in the liquid fraction (Moller et al., 2000; Guilayn et al., 2019).

Filtering of digestate entails more critical issues than filtering of raw slurry. Digestate contains a greater number of small particles than does slurry due to the digestion process. These small particles remain in the liquid fraction, and there are also higher levels of nutrients that are dissolved in water or adsorbed to small particles (Akhiar et al., 2017; Marcato et al., 2008).

The use of a screw press separator is suitable for fertigation with livestock slurry in sprinkler systems. However, the screw press is not adequate for digestate separation, as it is not able to retain a large proportion of the dry matter (Tambone et al., 2019) or large particles (Moller et al., 2002) present in this product and cannot prevent clogging of the irrigation system during fertigation events.

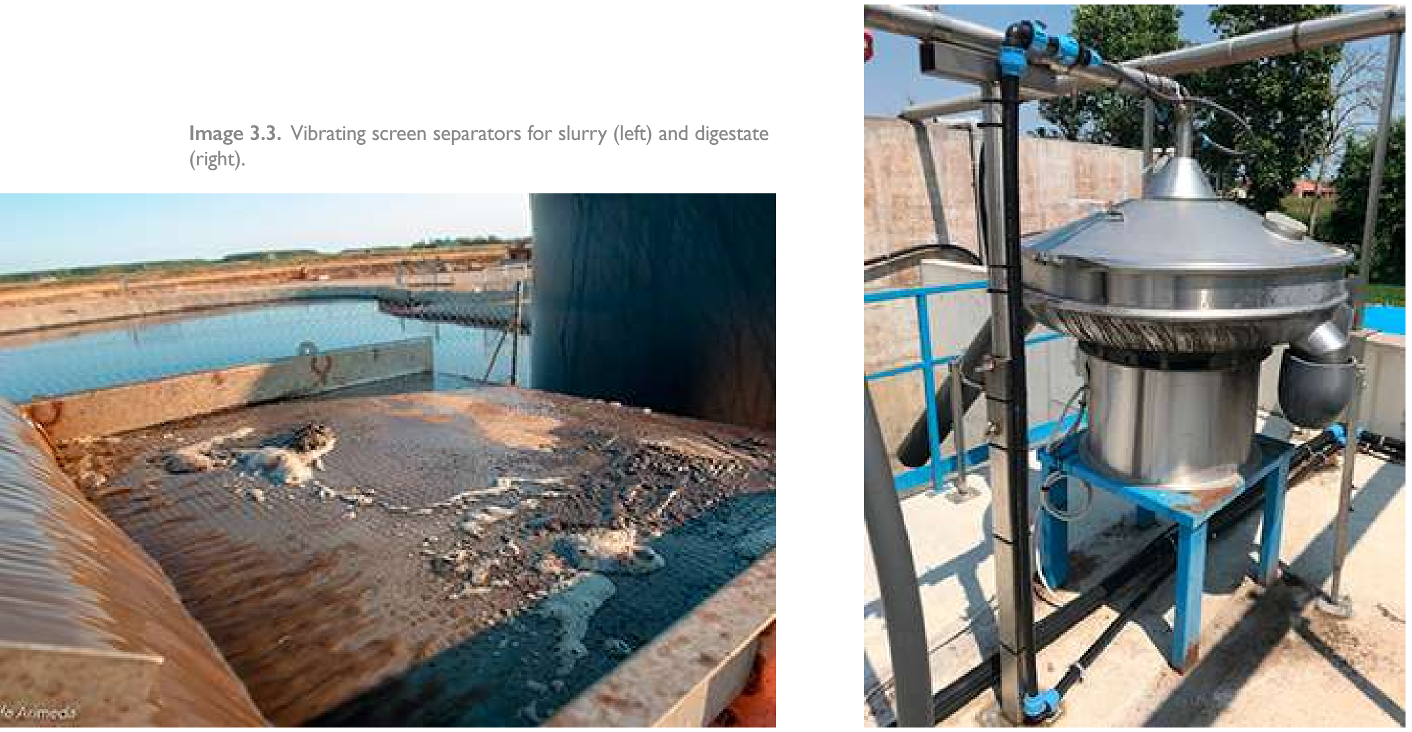
Other techniques that can operate alone, removing small particles from slurry and digestate, include decanter centrifugation and membrane filtration. The decanter centrifuge is more efficient than the screw press at removing both solids and nutrients and effectively retains particles larger than 20–25 µm in the solid fraction (Hjorth et al., 2010; Moller et al., 2002). However, the main drawback of a decanter centrifuge is the high operating cost (Moller et al., 2000). The advanced technique of membrane filtration allows a relevant separation of nutrients and solids, but its use is limited to large facilities and requires economies of scale (Guilayn et al., 2020).

Other mechanical separation techniques, such as screen separators and microfilters, retain small particles efficiently but require a previous filtration

Image 3.1. Screw-press separator working with livestock slurry.

Image 3.2. Screw-press separator with a filtering ramp.

Image 3.3. Vibrating screen separators for slurry (left) and digestate (right).



stage to remove coarse solids. A microfilter uses centrifugal force and has screen openings up to 25 µm in diameter, while a vibrating screen uses mechanical vibration and can have a sieve size as small as 100 µm (Pieters et al., 1999; Zhang and Westerman, 1997) (Image 3.3).

The performance and flow rate vary greatly among separators. A screw press can supply 15 m^3/h of filtered fraction, while vibrating screens and microfilters are in the range of 3-4 m^3/h. The operational parameters of the separators, and thus the yield, depend on the characteristics of the input slurry or digestate; yield can be reduced if the particulate matter content is high. Because the variability in the composition of these products is high and they are stratified during storage, with the solid phase settling at the bottom or floating over the surface, installation of a stirrer in the digestate/slurry storage tank or lagoon is highly recommended to obtain a homogeneous product for filtration (Image 3.4). In addition, the functional parameters of the separator should be reviewed and adjusted when there is a change in the quality of the input product. The installation of monitoring systems is also highly recommended for remote control of performance and is necessary in farms without periodic surveillance of the separators.

Image 3.4. Stirring in the storage lagoon of a pig farm.

Usually, separators stay fixed on farms, but use of a portable separator can also be an option for companies or organizations dedicated to the centralized management of organic fertilisers. When the separator is moved to a new farm, the characteristics of the product to be filtered change, and exhaustive tuning of its operational parameters is needed. Additionally, it is very common to find in reception storage facilities or lagoons large quantities of degraded slurry complicating separation or strange elements that can block the machines. Therefore, adoption of a minimal set of operational measures at the farm is highly recommended to reduce operational risks in the separation process. It is important to have fresh manure; if the manure is older than six months, it is recommended to avoid treating it.

A mechanical separator that uses sieves is recommended to have an automatic cleaning system either with water or with an acidic solution (Image 3.5); cleaning the sieve periodically during operation improves the separation yield. It is also recommended to clean the separator with a pressurized water hose after each working period if the process is not done automatically; otherwise, digestate and pig slurry will dry and stick to the sieve, clogging the sieve pores easily. To achieve more effective cleaning, an acidic solution can also be used.

Image 3.5. Automatic cleaning tubes installed in a vibrating screen.

The volume of slurry or digestate that needs to be filtered and the length of the period of application of the liquid fraction are additional important variables to consider in the design of separators. The performance of the equipment (volume/time) should correspond to the volume of liquid fraction required for fertigation (amounts and periods). The volume requirements can be calculated by multiplying the N rate to be applied by fertigation (kg N/ha) by the area of the field and dividing by the ammonium N concentration of the liquid fraction.

$$\text{LF (m}^3\text{)} = \text{(N rate (kg N/ha)} * \text{Area (ha)/LF ammonium concentration (kg/m}^3\text{)}$$

Thus, to apply 250 kg N/ha using fertigation to a 30-ha pivot maize field using a liquid fraction of 2.5 kg N/m^3, 3000 m^3 of liquid fraction is required (250 kg N/ha * 30 ha/2.5 kg N/m^3). If the period of application is 50 days and the separation system works 12 hours/day, a separation system with a minimum flow rate of 5 m^3/hour [3000 m^3/(50 days *12 hours)] will be needed.

$$\text{Flow rate required (m}^3\text{/h)} = \text{LF Volume (m}^3\text{)/available separation time (h)}$$

The liquid fraction obtained after separation should be stored in lagoons or tanks at the farm or biogas plant (Image 3.6). Large storage ponds or tanks on the farm can be filled before fertigation starts to help reduce the peak operation equipment requirements during the fertigation period.

Image 3.6. Storage lagoon for liquid fraction in a pig farm.

Existing ponds can be used, but they should be thoroughly cleaned before liquid fraction storage. Separated liquid fraction emits more ammonia than does raw product (Balsari et al., 2013), and losses can be reduced significantly with natural crust (or straw) or with a tent or concrete (Giner Santonja et al. 2017). Thus, if possible, storage ponds should be covered to reduce ammonia emissions and to prevent the entrance of small objects that could affect the cleanness of the process. In any case, a liquid fraction storage system should be kept clean to avoid small objects used on the farm from entering the injection system and causing malfunction or breakage of the injection pump or obstruction of the irrigation system components.

3.2.2 TRANSPORT, STORAGE IN THE FIELD AND INJECTION IN THE IRRIGATION SYSTEM

Image 3.7. Direct injection of digestate liquid fraction from the farm storage tank in the irrigation system.

The liquid fraction in a farm storage system can be injected directly into the irrigation system. This is the best option if the fields are at reasonable distances from the LF storage and if it is possible to connect the LF storage with the irrigation system through a pipeline (Image 3.7). This option avoids road transport to agricultural fields and the need for storage in fields.

Where farm storage cannot be connected directly to a field irrigation system, an on-site covered storage system should be installed next to the agricultural fields to stock the LF prior to being pumped into the irrigation system during application periods (Image 3.8). In addition, the transport of the liquid fraction from the farm or biogas plant to the field should be carefully scheduled and planned. Detailed analysis of the distance from the field to the nearest farms, the nitrogen concentration of slurry or digestate at each farm and the amount of product that needs to be transported depending on the farm is recommended to make the best selection and optimize operations. The transport requirement and the associated cost decrease when using liquid fractions of higher N concentrations.

Tanks or trucks used to transport the liquid fraction should be kept very clean to avoid malfunction or breakage from small objects entering the fertigation system. It is recommended to have dedicated tanks to move only the liquid fraction and to use a protection net in the inlet of the absorption tube. In the case of drip irrigation, thorough cleaning of the transportation tank is necessary for successful fertigation.

Image 3.8. Storage tanks in the field and truck uploading slurry liquid fraction from the farm storage.

A field LF storage tank should be sized according to the volume of liquid fraction to be injected. This volume should be slightly overestimated to avoid injection from the lowest part of the tank, where solid particles may settle during the season.

The tube connecting the tank to the injection pump should be some height (20 cm) above the bottom of the deposit to ensure that the solid matter that will flocculate inside the deposit does not enter the injection pump and from there the irrigation system. If a large deposit is observed, the storage tank should be cleaned; for this purpose, additional output tubing should be incorporated at the bottom of each storage tank.

The injection pump should be sized based on the volume of the liquid fraction to be injected, which depends on crop requirements and the liquid fraction nitrogen content. When selecting a pump, it is important to consider the pressure of the irrigation system because the injection pump will need to overcome that pressure. In general, pivot and drip irrigation systems work with relatively low pressure, so requirements should not be very demanding. Additionally, it is important to select a pump that is robust against the small particulate matter usually present in the liquid fraction. Electric and gas oil pumps are both adequate and capable of injecting the liquid fraction into the irrigation system (Image 3.9).

Performance of injection pumps tends to decline with time in service, even with diligent maintenance, so a good recommendation is to check the yield-price relationship and, if reasonable, over-dimension the flow.

The injection pump should be installed with a system that permits the backflow of water into the pump for cleaning purposes. Additionally, it is relevant to consider the installation of a nonreturn valve to avoid backflow of the liquid fraction into the general water supply system. Maintenance of the pump includes cleaning at the end of each irrigation event, periodic changing of the rubber seals in electric pumps and complete cleaning at the beginning and end of the season.

Image 3.9. Filling the liquid fraction storage tank in the field and injection into the drip system.

It is also necessary to calibrate the injection pump or install a flowmeter to accurately determine the amount of liquid fraction (and thus nitrogen) injected into the irrigation system. Another option is to install level meters in the field storage tanks and record the levels at the beginning and at the end of each fertigation event.

The storage tanks in the fields should be sized according to the volume of liquid fraction to be injected, which depends on liquid fraction composition, crop requirements, and the area of the plot but also on the logistics of the transportation, mainly in the case of pivot irrigation systems covering broad areas. Typical injection rates per irrigation event can range between 15 and 30 kg N/ha. For instance, to apply 25 kg N/ha to a 30-ha surface pivot field using an LF of 2.5 kg N/m^3 in 1 irrigation event, 300 m^3 of liquid fraction is needed. For an irrigation period duration of 24 hours, if transportation is possible over the entire 24-hour period, a 60 m^3 tank could be installed and filled 6 times during the period of 24 hours; i.e., the tank should be refilled every 4 hours even during the night. If that is not possible, there are two possible solutions: to use larger volume storage deposits, for instance, 120 m^3, that will reduce to 3 times the filling needs (every 8 hours) or to reduce the flow rate of the injection pump. To pump 300 m^3 of liquid fraction in a period of 24 hours, the pump flow should be working at 1.2 m^3/h, but the flow can be lowered to 0.6 m^3/hour, reducing the volume of LF injected to 150 m^3 and the rate to 13 kg N/ha. Lower injection flow rates reduce the requirements for storage and transportation but increase the number of fertigation events necessary. For drip irrigation fields, smaller in area than pivot fields, storage needs are lower. For a typical 2-ha drip-irrigated field, and to inject 25 kg N/ha with a LF of 2.5 kg N/m^3, 20 m^3 of liquid fraction needs to be injected. However, considering that the irrigation time is usually shorter and that dilution could be less, the flow of the injection pump would be similar to that of a pivot system, between 0.7-1.0 m^3/h.

3.2.3 COMPOSITION OF THE LIQUID FRACTION

The liquid fraction obtained after filtering should be analysed to determine its nutrient content: total ammonium-N (TAN), total Kjeldahl-N (TKN), phosphorous and potassium concentrations. TAN and TKN should be analysed separately, as ammonium-N is readily available for crops after application, while organic-N (obtained as TKN-TAN) is less available and creates a residual effect that should be considered in the following years. TAN is the main form of nitrogen in the liquid fraction, while organic N remains in the solid fraction after separation. The TAN content in the liquid fraction is similar to or slightly higher than that in the original product.

The composition of slurry and digestate is highly variable among farms and even within the same farm or biogas plant; thus, the composition of the liquid fraction could also show high variability. This led to the need for LF analysis at different moments during the season. The ammonium N content of the liquid fraction can be analysed in the field using on-site rapid methods such as Quantofix or conductivity (Martínez-Suller et al., 2008; Suresh et al., 2009; Yague et al., 2008). The use of these methods permits a reduction in the number of laboratory analyses by restricting focus to critical times in the season when relevant changes in the composition of the product may occur, such as with the introduction of new piglets to a farm, changes in feedstuff in biogas plants (Image 3.10), and addition of water (from rainfall or cleaning) to storage systems.

Samples collected to characterize the LF should be taken from storage tanks in the field or from the injection system to avoid taking samples from farm storage systems, as the liquid fraction can remain there for long periods before being injected. Samples are only taken from farm storage systems if LF is directly injected from there into the irrigation system. To obtain a representative sample, the storage system should be completely stirred.

Image 3.10. Anaerobic digestion plant in Lombardy.

3.2.4 FERTILIZATION RATES AND SPLITTING

The amount of LF to be injected should be calculated based on the optimal level of fertiliser for the crop in the field and the liquid fraction nutrient content.

The optimal rate of fertiliser (N-P-K) application should be established based on the potential crop yield of each plot, which the farmer usually knows from previous years, and unitary nutrient extraction. For P and K fertilization, the levels of P (in general, P Olsen is recommended for neutral and alkaline soils and P Mehlich for acidic soils) and K (ammonium acetate) in the soil should be considered to correct the application depending on the texture of the soil.

For nitrogen, contributions from other sources should be considered. Particularly relevant are the soil mineral N content in the topsoil before the first fertiliser application is scheduled, the mineralization of soil organic matter (for summer crops, it can contribute over 100 kg N/ha), the amount of N applied with irrigation water (1000 m^3/ha of irrigation water with a concentration of 50 mg nitrate/L provides 15 kg N/ha), the contribution of previous leguminous crops (an alfalfa field terminated during the previous year can contribute 100 kg N/ha) and atmospheric deposition.

Fertigation permits the application of the liquid fraction as the crop develops. Because phosphorus and potassium are also present in the liquid fraction, in general, no synthetic P-K fertilization is needed at pre-sowing. However, because most of the phosphorous is linked to the solid phase of organic fertilisers, the concentration of P in the liquid fraction should be carefully evaluated to check whether LF provides the right amount for correct crop development.

Where existing normative limits or regulations do not permit the application of the optimal N rate with slurry or digestate, as in vulnerable zones where the application of animal manure is limited to a maximum of 170 kg N/ha, the excess over the normative limit should be made up with synthetic fertilisers, following local recommendations.

In winter cereals fertigation should start at the tillering stage, continue to elongation and finish at flowering, with an approximate distribution of 50%-30%-20%, respectively. For corn, application should start at 4 leaves and continue until silking with a distribution similar to that of irrigation water; when the crop needs more water it also needs more nutrients, approximately 25% at 4-6 leaves, 30% at 6-8 leaves, 30% at 8 leaves-tasselling and 15% at tasselling-silking. In case digestate or slurry are applied at pre-sowing, as is usual in Lombardy, fertigation can be delayed until the 6-leaf stage, with a general distribution of 35% at 6-8 leaves, 35% at 8 leaves-tasselling and 30% at tasselling-silking. The number of fertigation events will depend on the amount of N that needs to be applied, the nitrogen concentration of the liquid fraction and the injection flow and can range from 1 to over 20.

The ARIMEDA tool* helps to establish the optimal N-P-K rates for a field, the amount that can be applied with organic fertiliser through fertigation considering the existing normative and regulations, and the distribution of fertigation among crop stages.

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* Available at www.lifearimeda.eu

3.2.5 MANAGEMENT OF FERTIGATION

In the fertigation process, fertiliser is applied with the irrigation system, and the spatial distribution of nutrient levels depends on the quality and uniformity of the irrigation system. Therefore, for optimal fertigation, irrigation systems should be designed for high uniformity and efficiency while avoiding water application outside the limits of the plot, and management must be focused on achieving high irrigation efficiencies and avoiding runoff, deep percolation, wind drift and evaporation losses.

Some important key points for favourable fertigation functioning follow:

> **1.** The irrigation system installation should be reviewed at the beginning of the irrigation season to ensure that it is functioning correctly.
>
> **2.** It is important to plan the irrigation rate weekly using irrigation advisory services or decision support tools and schedule the number of irrigations considering the soil characteristics; in soils with low water retention capacity (coarse-textured soils or those with shallow depth), it is necessary to divide, if possible, the weekly application into more frequent events. If irrigation is excessive, a fraction of the nutrients applied with fertigation can be lost through deep percolation.
>
> **3.** The mixture of filtered digestate and irrigation water must reach an adequate dilution ratio, sufficiently low to avoid nozzle or dripper clogging and high enough to maximize the contribution of fertigation to the overall crop fertilization. It is desirable for the dilution ratio (defined as the ratio of the volume of LF to the volume of irrigation water) for digestate to be between 3% and 10% (Finzi et al., 2021; Mantovi et al. 2018), but it can be increased to 20% without increasing the risk of clogging in both pivot and drip irrigation systems (Guido et al., 2020). For fertigation with pig slurry LF, the amount of LF can be increased, and desirable dilution values range between 4 and 25% for both pivot and drip irrigation systems.

Image 3.11. Irrigation nozzles installed in LIFE ARIMEDA pivots demonstration fields in Aragon (left) and Lombardy (right).

Pivot irrigation systems

In pivot systems, pluviometry should be lower than soil water infiltration to avoid losses from runoff and soil erosion. The use of low-pressure (LEPA) nozzles that produce large water drops is recommended to avoid drift and evaporation losses of water and fertiliser (Image 3.11). With this type of nozzle, runoff can appear in the outside part of the pivot plot where the nozzle diameters and pluviometry are higher; in this case, it is important to use a pond cultivator (Image 3.12).

Image 3.12. Labour of a pond cultivator to avoid runoff.

It is recommended to use an overhang at the end of the final span instead of a gun. Guns result in high pluviometry, poor water distribution and high drift losses. It is recommended to not start (or stop) irrigation when the wind speed exceeds 2.5 m/s to avoid unfavourable water distribution and large water drift and evaporation losses. This rule is more important when fertigation is applied, as the lack of uniformity and the losses affect not only water but also nutrients. In windy regions, it is recommended to proceed with fertigation at night (if possible). At night, wind speed and temperature are lower and drift, evaporation losses and the risk of ammonia volatilization are reduced. This is not relevant in drip irrigation, as the water is deposited for the dripper right over the soil surface or below the surface and water does not come in contact with the atmosphere. Irrigation events in pivot systems can be long in duration, over 24 hours, so it is not always possible in times of peak water and nutrient demand to select the period for fertigation. An alternative possibility is to lower the nozzles below the crop canopy (≈30 cm above the soil surface); this setup mitigates the wind effects, reducing drift and evaporation losses and ammonia emissions. Seeding in circles can be beneficial but is not essential for this setting.

Close to the end of the irrigation period, the injection of LF should be halted to allow the cleaning of pipes and nozzles. Also, it is desirable to avoid irrigation in complete turns, thus avoiding having the same portion of the plot with no fertiliser application in each turn during the cleaning process. If it is not possible to avoid complete turns, synthetic fertiliser can be applied in the part of the plot where fertigation with liquid fraction is not performed.

Drip irrigation

In general, subsurface drip irrigation is a technique not widespread for irrigation of extensive crops, but if it is necessary to install such a system to apply fertigation with slurry or digestate materials and drippers, it should be carefully selected (Image 3.13). It is important to select drippers with wide filtration areas that are resistant to clogging, i.e., with a large labyrinth of wide cross section. Drippers can be turbulent or pressure compensated; in general, pressure-compensated drippers have a smaller filtration area but ensure uniform pluviometry. If the field is well levelled and with an optimal irrigation design, turbulent drippers should be selected for fertigation with organic products due to their higher resistance to obstruction.

In the ARIMEDA demonstration fields, turbulent (Netafim Aries) and pressure compensating (Netafim Dripnet) drippers were tested without signs of obstruction after three seasons of injection with organic fertiliser.

It is important to ensure that the irrigation system is working correctly, so it is necessary to install water metres and control them before and after each fertigation event to monitor pluviometry and detect poor functioning that could indicate the presence of obstructions. The filters located after the injection point should be disassembled periodically and cleaned, with higher frequency during the injection periods (this is not necessary for self-cleaning filters). Pressure after the filters should be controlled during fertigation events to ensure that the filters are not plugged with dirt. Lack of pressure in the system for both types of drippers result in unfavourable distribution of water and fertiliser.

Maintenance should include cleaning with water at the end of each fertigation and cleaning the drip lines and components using an adequate product (H_2O_2), when necessary and at least once during the irrigation season.

Image 3.13. Drip irrigation system for fertigation with the liquid fraction of digestate in Lombardy (Italy).

3.3 BENEFITS

Fertigation with the liquid fraction of digestate and slurry in extensive crops has several agronomic, socio-economic and environmental benefits:

> - It allows the reduction of ammonia losses to the atmosphere, consistent with the European Farm to Fork strategy that seeks a 50% reduction in nutrient losses by 2030.
>
> - It allows the use of animal manures during periods of crop development when these organic products cannot be applied using traditional application systems (splash plate, trailing hose, incorporation, injection, etc.). In this sense, fertigation extends the period when organic fertilisers can be taken from a farm or biogas plant to be applied as crop fertilisers (Image 3.14).
>
> - It reduces the need for transport of digestate/slurry from a farm or biogas plant to the agricultural field in cases where the agricultural farms are located inside or next to animal farms or biogas plants and the liquid fraction is moved through pipes.
>
> - It allows the partitioning of organic fertilization and the distribution of nutrients along the crop cycle according to crop nutrient requirements. Split of fertilization increases the efficiency of nitrogen use and decreases the risks of nitrate leaching and greenhouse gas (GHG) emissions (in particular, N_2O that is a powerful GHG).
>
> - It permits the replacement of synthetic fertiliser with organic products, reducing the amount of nitrogen entering agroecosystems. This is of relevance in areas with excessive nitrogen. Even if all the crop needs in a specific area can be met with the animal manures produced, if those organic fertilisers cannot be supplied to the crops when they need nutrients, synthetic fertilisers need to be introduced to the system leading to surplus N in the nutrient balance of the area. Thus, fertigation with organic products reduces external inputs of N where there are available organic sources in the area and allows the reduction of synthetic fertilization consumption consistent with the Green Deal Farm to Fork strategy that seeks a reduction of 20% in the consumption of synthetic fertilisers by 2030.
>
> - The application of organic fertiliser with irrigation reduces the cost of fertilization, as organic fertilization is less expensive than synthetic fertilization. Agricultural farms located inside or next to animal farms benefit from higher economic savings, as slurry can be injected directly from lagoons into irrigation systems, and transportation and storage in the field are not needed.

Image 3.14. Fertigation with the liquid fraction of pig slurry in a pivot in Cinco Villas (Aragon, Spain).

3.4 LIMITATIONS

Fertigation with slurry/digestate has some burdens and limitations that could constrain the adoption of this technique in some cases:

> - It needs additional equipment and has associated investment costs: separators, storage system on the farm or/and in the field and injection pumps and filters to setup the fertigation systems.
>
> - It is necessary a higher control of farm operations, separation and injection activities tasks, and for maintenance of the systems, including the irrigation systems.
>
> - The existence of Normative that discriminate negatively animal manures and slurries versus synthetic fertilization limiting the amount of animal manures that can be applied to the crops.
>
> - The generally unknown and highly variable nutrient content of slurry/digestate (in comparison to synthetic fertilizers) and the difficulties to stablish correctly the management of fertigation difficult reliable application if there is not a good technical knowledge or advisory service behind.
>
> - The experience in the demonstrative fields in Spain has shown that the transport of liquid fraction from the farm to the field is difficult to manage and can be a bottleneck for fertigation with problems of different types. Pivot systems with large surface area and long irrigation turns need a large and continuous transport of LF from the farm to the field during irrigation events, that can expand for 24 hours or more. The risk of introducing small objects in the LF storage tanks increase (coming either from the transportation tanks or from storage in the farm lagoons) and may block the injection pump spoiling fertigation. In addition, the logistic in transportation has to be checked against equipment availability as some concurrence can arise easily with other agricultural activities during fertilizing season and the time window in which fertigation should be performed is driven by the needs of the crop, not by the availability of the equipment.

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4

AGRONOMIC AND ENVIRONMENTAL MONITORING IN DEMONSTRATION FIELDS

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4.1 INTRODUCTION

The environmental and agronomic benefits of fertigation relative to traditional fertilizing practices using either organic or synthetic fertilisers should be assessed qualitatively and quantitatively on the basis of sound and scientifically proven methodologies. The monitoring protocols and measurement methods developed in the LIFE ARIMEDA project have made it possible to compare this fertigation technique with the usual fertilization practices in 5 different regions, Cinco Villas and La Litera in Aragon (Spain) and Brescia, Cremona and Mantua in Lombardy (Italy).

The organic fertigation techniques demonstrated in this project were implemented during three consecutive seasons, from 2018 to 2020, in large-scale extensive maize plots (Image 4.1). The analysis of the potential for transfer of these innovative techniques to other Mediterranean areas, based on their benefits and limitations, has been based on the results obtained by implementing common monitoring and evaluation protocols that have allowed comparable data and reliable information to be obtained.

The assessment addressed a case/control approach comparing the results of environmental and agronomic monitoring between fertigated and reference plots where farmers performed traditional fertilization practices. The selection of the demonstrative fields and the monitoring design were thoroughly planned at every site. Representative fields were sought for the project, far from animal farms, to avoid or reduce interference in monitoring activities. However, bearing in mind that the work took place in highly intensive agricultural areas and should be representative at a broad scale, this target could not always be easily achieved.

Image 4.1. Drip fertigation demonstration plot monitored in Cinco Villas (Aragón, Spain).

4.2 ENVIRONMENTAL MONITORING

4.2.1 AMMONIA EMISSIONS

The application of either organic or synthetic fertilisers in the fields involves direct nitrogen losses in the form of ammonia emissions to the atmosphere. Many methodologies have been reported in the scientific and technical literature for measuring emission of this gas. However, scarce information is available in Mediterranean agricultural systems. Additionally, most of the available studies have been carried out on small plots, with specific dimensions and shapes to meet the needs of the measurement methodologies used. There have been few studies in which ammonia emissions were measured under real field conditions because, although working on large-scale production plots provides valuable information, it also involves significant challenges:

1. Measuring large, irregularly shaped emission surfaces is difficult.

2. Plots need to be located in areas in which intensive agricultural activity occurs during the monitoring periods, which may interfere with measurements.

3. Measurements are generally made on tall crops, such as maize, which implies an irregular surface as a source of emissions.

4. It is possible to measure a wide range of emissions in the same trial due to the use of a wide variety of both synthetic and organic fertilisers (pig slurry, digestate and its liquid fractions) injected into fertigation systems and under quite variable meteorological conditions.

In addition, the long period of fertiliser application and the diverse soil and climatic conditions of the assessed plots add to the complexity of the measurements. This requires the use of a robust and reliable emission measurement methodology that responds adequately in all circumstances.

The monitoring activities were carried out continuously in each season from early spring (April-May) through the warm Mediterranean summers until the end of November when temperatures were milder. Depending on the practices assessed at each time, the average ammonia concentrations measured in the air can range from as low as 10 $\mu g/m^3$ in background measurements in low-concentration areas up to 4000 $\mu g/m^3$ after surface application of pig slurry before seeding and in warm periods.

The LIFE ARIMEDA project faced the challenge of designing a robust NH_3 emission measuring method since the very beginning. In the early stages of the project, the methods considered were micrometeorological mass balance integrated horizontal flux (IHF) with passive flux samplers and semi-open chambers (SOCs) based on the methodology developed by Jantalia et al. (2012). The IHF method, originally presented by Denmead (1983), is considered a reference and has been validated, in combination with passive flux samplers (Leuning et al., 1985), by several research groups worldwide (Laubach et al., 2012; Misselbrook et al., 2005; Sanz-Cobena et al., 2008; Sintermann et al., 2012; Sommer et al., 2005; Yang et al., 2019). Alternatively, SOCs are frequently used in small plots to compare treatments. However, the use of these scientifically proven techniques presents certain limitations in large productive fields with irregular shapes, and spatial representativeness may be hindered, especially in the case of SOCs.

Researchers from the Agrifood Research and Technology Center of Aragon and from the Department of Agricultural and Environmental Sciences, University of Milan, in close collaboration with the Research Centre for the Management of Environmental and Agricultural Risks (CEIGRAM-Universidad Politécnica de Madrid), worked thoroughly during the first months of the project seeking and testing the best techniques to successfully achieve the goals pursued. Monitoring methods should comply with the following requirements:

1. A favourable balance between complexity and precision.

2. Easy to replicate and transfer to other scenarios.

3. Low-demanding sampling procedure in order to spare time on the field and in the laboratory.

4. Sampling devices easy to handle and robust to minimize sample contamination risks and facilitate laboratory work.

Image 4.2. Method comparison field trial at CITA's experimental facilities.

The selection of the measuring method, after considering all the technical aspects and main strengths and weaknesses of the different methods, was based on:

1. A thorough bibliographic review of the existing methodologies.
2. A method comparison field trial in which 4 different techniques were tested simultaneously under controlled conditions in a fertilized plot at CITA's experimental facilities (Herrero et al., 2021): semi-open chambers, IHF and inverse dispersion modelling combined with acid bubblers and ALPHA® (Adapted Low-cost Passive High Absorption, Centre for Ecology and Hydrology, UK) (Image 4.2).
3. Initial tests carried out in the project's demonstration plots during the first season simultaneously compared the results obtained with different methods: ALPHA® samplers and semi-open chambers.

As a result of this collaboration among research centres, a common protocol was defined based on the use of ALPHA® samplers for the measurement of ammonia concentration in the air and the application of an inverse dispersion model using the free software program WindTrax v.2.0.8.9 (Thunder Beach Scientific, Halifax, Nova Scotia, Canada) for the calculation of ammonia emissions.

The results obtained and the knowledge and experience gained during the three sampling campaigns allowed us to improve and optimise the design and implementation of this technique.

According to this protocol, the steps followed in each of the plots were as follows:

Image 4.3. Ammonia emission monitoring in Lombardy (left) and in Aragon (right).

Step 1. Layout design and sampling procedure

Every plot was equipped with several sampling points evenly distributed over the plot area. Each sampling point consisted of a mast with a shelter holding 3 ALPHA® samplers at a height that ranged from 1.2-1.5 m above the emitting surface (bare soil or crop canopy) (Image 4.3). The number of masts/sampling points in each plot depended on its area and shape and varied from 1 to 5 (Image 4.4 c). Additionally, between 1 and 3 masts were placed outside the plot according to the prevailing wind direction to collect information on the background NH_3 concentrations in the surrounding area during monitoring.

Each ALPHA® sampler had a filter coated with a solution of citric acid and methanol and was exposed to the air with a protective PTFE membrane that ensured a laminar air flux inside the badge (Image 4.4 a and b). The ALPHA® samplers operate on the principles of the diffusion of gases. NH_3 air concentration is calculated according to the air volume sampled (V) and Fick's law: $V = (D \times A \times L \times t)$, using the expression $C_{NH3} = M_{NH3} \times V$, where M_{NH3} is the average mass of NH_3 (µg) collected in triplicate samplers at every exposure time, t is the time of exposure (h), D is the diffusion coefficient of NH_3 ($m^2\ s^{-1}$) at 20 °C, A is the cross-sectional area (m^2) of the sampler and L is the length (m) of the stationary air layer. The exposure time ranged between 24 hours (during N fertigation events) and 7 days.

The concentration of ammonia ($C_{N\text{-}NH3}$) in the air was calculated by considering the mass of nitrogen captured on the ALPHA® units (as ammoniacal-N, $N\text{-}NH_4^+$) and the volume of air sampled $C_{N\text{-}NH3} = M_{N\text{-}NH4+} / V$; where $M_{N\text{-}NH4+}$ is the average amount of $N\text{-}NH_4^+$ (µg) captured on the filters of the three ALPHA® units during the exposure period. Ammonium was extracted from each filter in the laboratory using 3 ml of deionized water, and the mass $M_{N\text{-}NH4+}$ captured on the filter was obtained by multiplying the $N\text{-}NH_4^+$ concentration measured in the extract (mg/l) by the extraction volume (3 ml). The ammonium concentration in the extract was analysed in Aragon by colorimetry following the salicylate method with nitroprusside (Searle, 1984) on a segmented flow analyser (AutoAnalyser3, Bran + Luebbe, Norderstedt, Germany) in the CITA laboratories. In Italy, an analysis based on selective dialysis of ammonium through a membrane at high pH with subsequent determination by spectrophotometry (λ = 590 nm) was carried out using a flow injection analysis system (FIAS).

The meteorological data recorded during the collector exposure periods were wind speed (m/s), wind direction (°, clockwise, north = 0°), temperature (°C), relative humidity (%) and precipitation (mm). Mean values were obtained over 30-minute periods. In Spain, they were collected from weather stations installed next to the experimental plots or from nearby stations of the SIAR network (agro-climatic information system for irrigation). In Italy, records were obtained with a weather station (Vantage Pro2, Davis Instruments Corporation, Hayward, CA, USA) installed near the demonstration plots (Image 4.4 d).

Step 2. Ammonia emission flux determination

The emission fluxes were calculated using WindTrax simulation software (Image 4.4 e) that uses a backward Lagrangian stochastic inverse dispersion model (bLS IDM). This model infers emission rates from a known emitting surface using upwind and downwind air NH_3 concentrations measured over the demonstration fields and background points referenced to the emitting source, surface roughness length (z_o, cm), and atmospheric stability and considering wind data (speed and direction) (Flesch et al. 2004, Loubet et al., 2010). The large sizes of the monitored plots in LIFE ARIMEDA ensures the spatial homogeneity of the emitting surface (Carozzi et al., 2013; Loubet et al., 2010). To simplify the method, z_o was considered 1 cm above the crop canopy (set as the emitting surface), and ALPHA® samplers were placed 1.2-1.5 m above this position.

One of the main factors limiting the bLS IDM is the necessity of using short sampling periods that ensure homogeneous atmospheric stability. The monitoring protocol followed the recommendations of Sommer et al. (2005), which have also been discussed and adopted in other research works (Carozzi et al., 2013; Ni et al., 2015; Sanz et al., 2010), and longer intervals were adopted (ranging from 24 hours to 1 week) assuming continuous neutral atmospheric stability.

Although the monitoring was carefully planned, certain additional difficulties occasionally arose. Thus, in some scenarios, problems appeared in placing an APS at the correct height when the maize canopy (reference position) was over 2 m, as the masts interfered with the pivot spam movement, or when background NH_3 air concentration levels were high, which made it difficult to assess emissions derived from a single plot surrounded by highly dense agricultural production areas. These exceptional circumstances, inherent to fieldwork at the demonstration scale, required additional effort to monitor training and planning as well as to discuss the follow-up activities and results at each site.

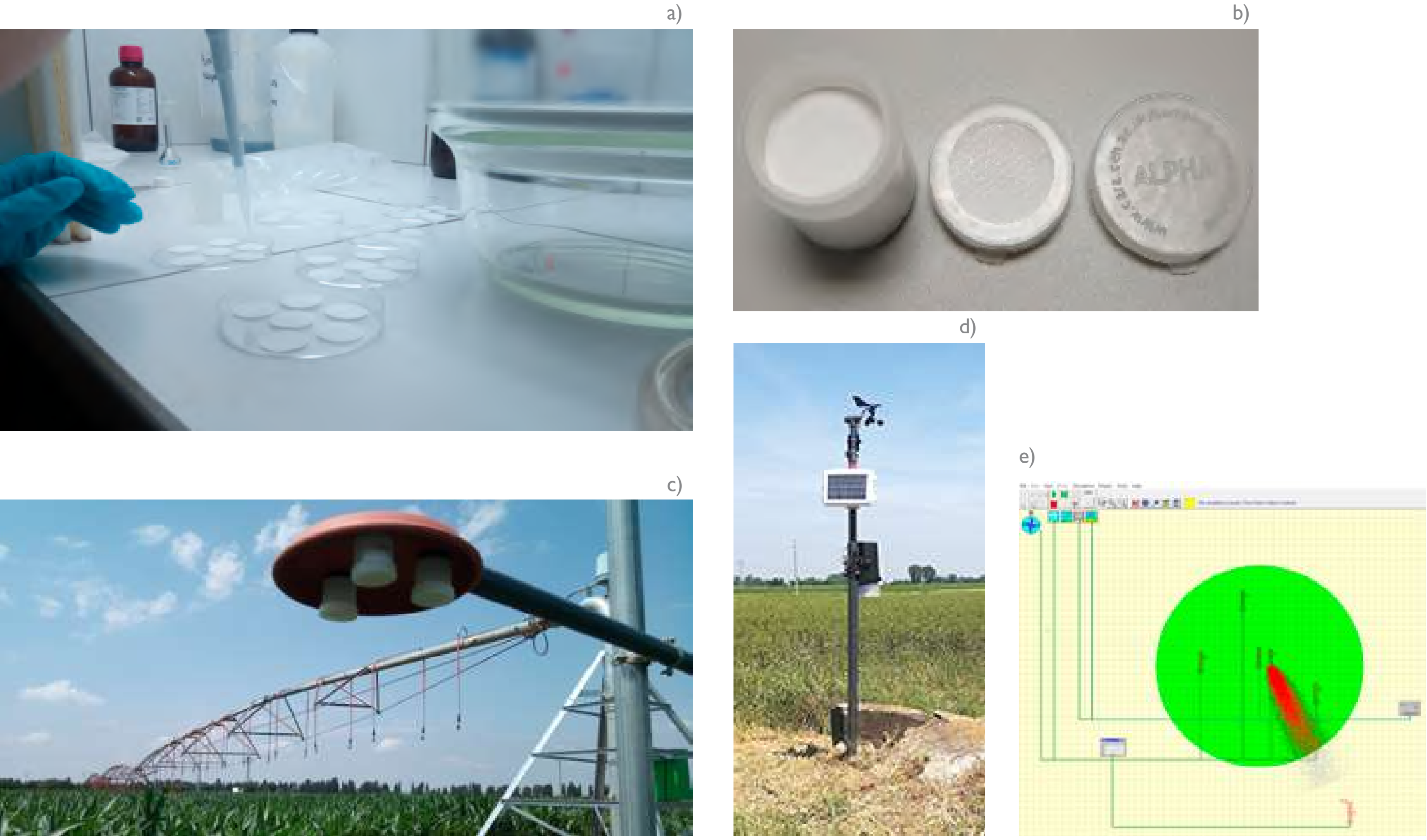

Image 4.4. APS filter preparation in the laboratory, b) ALPHA® sampler, c) ALPHA® samplers placed in the field, d) meteorological station and e) WindTrax simulation software.

4.2.2 RISK OF NITRATE LEACHING

It is crucial to verify that the effectiveness by which fertigation reduces NH_3 emissions to the air does not imply higher nitrogen losses in the form of nitrate towards water bodies.

Nitrate concentration in soil solution was used as a qualitative indicator of leaching risk, setting the basis for a comparative assessment of the concentrations measured in fertigated and traditionally fertilized (reference) plots. The mass of nitrate leaching was not calculated, as it requires the additional estimation of water draining below the crop root zone.

The soil solution was sampled with porous ceramic capsules (suction cups) buried below the crop roots. Depending on the area of each plot, between 5 and 7 probes were installed, evenly distributed in a W configuration as proposed by ERSAF (Ente Regionale per i Servizi all'Agricoltura e alle Foreste de Lombardy), at depths varying between 45 and 120 cm depending on the soil profile (Image 4.5). The suction cups made it possible to easily collect samples of the soil solution at the same point at the required frequency.

During the irrigation season, the soil solution was extracted from the suction cups once a week, 24 hours after creating a vacuum inside (≈ - 0.7 bars) and usually after irrigation and precipitation events. The extraction was performed using syringes or automatic vacuum pumps. In Spain, ammonium and nitrate concentrations in aqueous soil solutions were analysed in the laboratory using standard colorimetric methods. In Italy, the extracted samples were analysed for nitrate with the FIAS (flow injection analysis system). This analysis is based on the reduction from nitrate to nitrite through a copper cadmium column and a subsequent spectrophotometric analysis ($\lambda = 525$ nm).

Image 4.5. Ceramic suction cups installed in LIFE ARIMEDA plots..

4.3 AGRONOMIC MONITORING

For good management of fertigation techniques, different agronomic features need to be considered. Key aspects include the crop nitrogen demand and the contributions of the soil and additional sources, such as previous leguminous crops and irrigation water, to the supply of these necessities. Accordingly, the total N requirements are estimated and divided throughout the overall crop cycle by applying doses adjusted by time and quantity. The LIFE ARIMEDA project demonstrates fertigation techniques that supply the total crop N requirements with the liquid fractions of pig slurry and digestate injected into pivot and drip irrigation systems, capable of totally replacing synthetic fertilisers.

Farmers managed the crop fields involved in the project according to usual local agricultural practices: sowing, pesticide and herbicide treatments, fertilizing seasons, harvest, etc. All these activities were recorded in all monitored fields and used as a basis for the definition of standardized scenarios for life cycle assessment (Chapter 7) and socioeconomic studies (Chapters 8 and 9) related to the implementation of the fertigation techniques in the LIFE ARIMEDA project. The records included:

> Crop information: date of sowing, maize cultivar, date of harvest and yield.
>
> Phytosanitary treatments: date and product applied, dose and technique (machinery).
>
> Labour: Type of labour, depth, date, management of maize residues, etc.

A common protocol set the key parameters, indicators and sampling procedures for the agronomic assessment of the LIFE ARIMEDA demonstrative plots. The objective pursued was to obtain comparable data at every site. The field monitoring activities performed in both fertigated and reference plots at each site included the following:

Soil texture

The soil of the selected fields was characterized at the beginning of the fieldwork. The soil profile was sampled with an auger every 30 cm, and texture; pH (1:2.5); organic matter content; salinity (electrical conductivity in 1:5 extract); total nitrogen; available phosphorus, potassium and magnesium; and carbonates were analysed in the laboratory.

Soil mineral nitrogen

Field trials started at all sites with soil sampling before sowing, repeated at the 4-leaf crop stage and after harvest at 30-cm intervals to the maximum soil depth (maximum 1.20 m) (Image 4.6). At the 4-leaf stage, only the upper soil layer (0-30 cm) was sampled.

In Aragon (Spain), five compound soil samples were taken in each plot from different points evenly distributed over its surface and usually coinciding with the suction cup and mast positions. A compound sample was prepared at every sample and depth using a manual auger, with 3 subsamples. Samples were sieved fresh and analysed for ammonium and nitrate concentrations in soil extracts (10 g fresh soil:30 mL 2N KCl) by colorimetry.

Imagen 4.6. Soil sampling in demonstration plots of the LIFE ARIMEDA Project.

In Lombardy (Italy), soil sampling in each plot also followed the same W-distribution, with 5 samples taken next to the position of the suction cups to which other points were added when necessary; thus, the number of points varied in each sampling campaign (between 5 and 10) depending on the results from the previous campaign. Nitrate and ammonium concentrations were determined from soil extracts (10 g fresh soil:100 mL 2N KCl) by FIAS.

The amount of nitrogen to be applied with fertigation was estimated on the basis of the potential crop yield, the unit nitrogen uptake of maize and the nitrogen provided by the soil and other sources. Based on this information and in agreement with the farmers, recommended nitrogen doses and an optimal fertilization schedule were established for each plot.

Irrigation plan

Irrigation was managed in close collaboration with farmers, following weekly recommendations, considering irrigation shifts at each farm if necessary and bearing in mind the specific characteristics of each system. The water supply was calculated on a weekly basis using reference evapotranspiration (FAO, Penman Monteith) and precipitation provided by the SIAR (Sistema de Información Agroclimática del Regadío) meteorological stations (MAGRAMA) in Spanish fields and by ARPA (Agenzia Regionale per la Protezione dell'Ambiente) and ERSAF (Ente Regionale per lo Sviluppo Agricolo e Forestale) in Italy. The data gathered comprise daily average temperature, relative humidity, precipitation, reference evapotranspiration and wind records (speed and direction).

In Spain, the crop coefficients were adjusted using thermal units (Martinez-Cob, 2008). A spreadsheet was prepared to calculate weekly water requirements for each demonstration plot, adjusting needs to each maize cycle in real time according to the actual crop development (phenology) (Image 4.7).

In Italy, irrigation was performed by farmers according to their experience and, in some cases, depending on the water availability.

The volume of irrigation water supplied to every plot was recorded with flowmeters when possible; otherwise, was calculated using monitored irrigation shifts, irrigation hours and the pluviometry of the irrigation system (mm/h).

Liquid fraction composition

The composition of the liquid fractions of pig slurry and digestate at every site were analysed before starting the fertigation period to determine the volumes required to supply all the crop N requirements. The efficiency of the liquid fraction was calculated on the basis of its content of nitrogen readily available for the crop (ammonium-N concentration).

Once the fertigation campaign started, to control nutrient doses applied to the crops, the slurry and digestate liquid fraction used in each fertigation event was sampled and analysed periodically. The real-time slurry N concentration was analysed for ammonium-N ($N-NH_4^+$) in situ using rapid methods such as Quantofix® (Image 4.8) or conductivity methods. A thorough study on rapid and inexpensive methods to measure the "in situ" N concentration in slurry (raw and digestate) and its liquid fractions improved these techniques.

Additionally, several samples were collected on a regular basis in 500-ml bottles and transported refrigerated to the laboratory. The technicians analysed the samples according to standard methods (APHA, AWWA, and WEF, 2012) for pH, salinity (electrical conductivity, EC), organic matter, dry matter, total Kjeldahl nitrogen, total ammonia nitrogen, phosphorus, and potassium.

Image 4.7. Fertigation in a demonstrative plot of LIFE ARIMEDA project.

Image 4.8. Rapid analysis of ammonium-N content in the liquid fraction of pig slurry used for fertigation with Quantofix ® in La Melusa (Aragon, Spain).

Nitrogen fertilizing units applied in every fertigation event

The number and duration of fertigation events depended on the liquid fraction nitrogen concentration, the crop irrigation requirements and the performance of the injection systems. The volumes of both the irrigation water and liquid slurry/digestate injected were carefully monitored and recorded in each event to determine the dilution rates.

In Aragon, the 50-m^3 tanks for liquid fraction storage installed next to the demonstration plots were graduated, and at each fertigation event, the volume of liquid fraction inside each tank at the beginning and at the end of the event was recorded (Image 4.9). In Italy, level sensors and flowmeters were used to monitor these variables.

A spreadsheet was developed to distribute the application of N along the crop cycle, considering the total amount of liquid slurry/digestate required. A complete record of the date of application, injection time, amount and type of fertiliser (pig slurry, digestate, liquid fraction or synthetic fertiliser), and N concentration was maintained for every plot.

Image 4.9. Instruments for volume injection control in the drip irrigation plot fertigated in Cinco Villas.

Crop yield and nitrogen use efficiency (NUE)

The crop yields and nitrogen content in the biomass were used to calculate nitrogen use efficiency (NUE) in all the plots. The results enabled comparison of the potential capacity for nutrient recycling in the different fertigation systems.

The plots were harvested with a combine harvester, and in Spain, preharvest manual biomass control was performed at 3 to 5 evenly distributed points in each plot with an area of 2.4 m^2 each (Image 4.10), from which the harvest index was obtained and the total aboveground biomass of the maize was calculated. The yield results in the manual control were compared with those obtained in the harvest of the whole plot, and corrections were made where necessary.

In Italy, maize grown was forage that was sampled during harvesting of the fields. In contrast, in Spain, maize was used for grain, and the N uptake was analysed separately for grain and the remaining aboveground biomass (leaves + stalks + cobs).

NUE was calculated as the ratio of nitrogen uptake by the plant in the aboveground biomass to the total N applied with fertilisers,

NUE = N uptake by plant / N applied

In addition, NUE was also quantified by including as an additional source of N the soil mineral nitrogen (Nmin) at the beginning of the crop cycle (4 leaves). This index enabled the comparison of demonstration and reference plots differing in initial availability and comparison among demonstration plots at different sites.

NUE (soil)= N uptake by plant / (N applied + Nmin)

Field-monitoring work during the three seasons was extremely demanding and required a huge effort to obtain the data necessary for a sound and accurate assessment of the fertigation techniques demonstrated.

Image 4.10. Biomass monitoring by CITA technicians during harvest of 2018.

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5

FERTIGATION WITH PIG SLURRY IN DEMONSTRATION FIELDS IN ARAGON (SPAIN)

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5.1 INTRODUCTION

The number of pigs in Aragon has increased during the last 20 years, reaching almost 9 million head in 2020. Some municipalities in the region have been declared "livestock overload" areas (ORDEN DRS/333/2019, BOA 8/04/2019) due to nitrogen (N) loads exceeding 220 kg N/ha in the manure-N produced on their farms. Pig slurry is usually applied to field crops as fertiliser using surface application methods such as splash plates (banned in Aragon since 2020) or band spreaders. Although ammonia emissions have been reduced due to the prohibition of the splash plate method, application is generally accomplished with broadcast applicators (band spreaders, trailing shoes, etc.) that leave the slurry over the soil surface exposed to the air and prone to cause ammonia volatilization. Ammonia emissions after spreading of slurry on fields with broadcast spreaders can be as high as 20-40% of the total ammoniacal nitrogen applied, although emissions stop after a few days. The application of animal slurries to fields is responsible for 35% of the ammonia emissions linked to manure management, which represent more than 70% of the total ammonia emissions in Europe (UNECE, 2021). For this reason, the use of techniques that reduce these emissions to the atmosphere from slurry fertilisation can provide environmental benefits and greater efficiency in the use of locally available resources to improve farm yields, minimize nutrient losses and promote nutrient circularity.

In the LIFE ARIMEDA project, we have worked to evaluate the performance of fertigation techniques with slurries and digestate from agronomic and environmental points of view. Assessment of techniques involved several steps:

1. Solid-liquid separation
2. Transport of the liquid fraction to the fields by tanks, lorries or pipelines
3. Injection of the liquid fraction into the plot irrigation systems

In this chapter, we present the main results obtained from the demonstration plots monitored in Aragon (Spain). Pivot (P) and drip irrigation (D) fertigation techniques using the liquid fraction of pig slurry were implemented after a solid-liquid separation process, and the observed performance was compared with traditional fertilization practices (reference fields, R).

5.2 FIELD TRIALS DESCRIPTION

The demonstration plots were located at two sites characterized by different types of soil (Figure 5.1, Table 5.1), Cinco Villas (ES-S1) with shallow (ca. 45 cm) and stony soils and La Litera (ES-S2) with deep (ca. 100 cm) and heavy soils.

Two demonstration fields (1 equipped with a centre pivot and 1 with a subsurface drip irrigated system) and a reference field were installed at each site and cultivated with grain maize.

SITE 1 Cinco Villas

Pivot (ES-S1-P) is located in the Montesaso irrigation community in Biota, with an area of 10.4 ha. It has 4 towers (length of 42 m) and a 14-m overhang. The spray nozzles commonly used in the area were replaced with those that provide a larger droplet size and lower evaporation and wind-drift losses (Nelson D3000). These nozzles were positioned in the same configuration as in the existing installation, 2.8 m above the ground and 3.0 m apart. The system worked at low pressure (0.4 bar) and provided large drops, avoiding spray drops, with a pluviometry of 11 mm in 20 hours (0.55 mm/h).

Subsurface drip-irrigated (ES-S1-D) was located at the Torremira experimental farm and managed by the Acequia de Sora irrigation community. This site is located near the municipality of Tauste and has a surface area of 2.1 ha. Riegos Iberia REGABER S.A. equipped the plot with a self-compensating Netafim Dripnet at 30 cm below the soil surface with a pluviometry of 4.7 mm/h.

Reference field (ES-S1-R) was located in a different plot in each season depending on plot availability and efforts to shorten travel distances for the monitoring work. Fields were 0.7-4.3 ha in area and were surface-irrigated in 2018 and 2019 and sprinkler-irrigated in 2020.

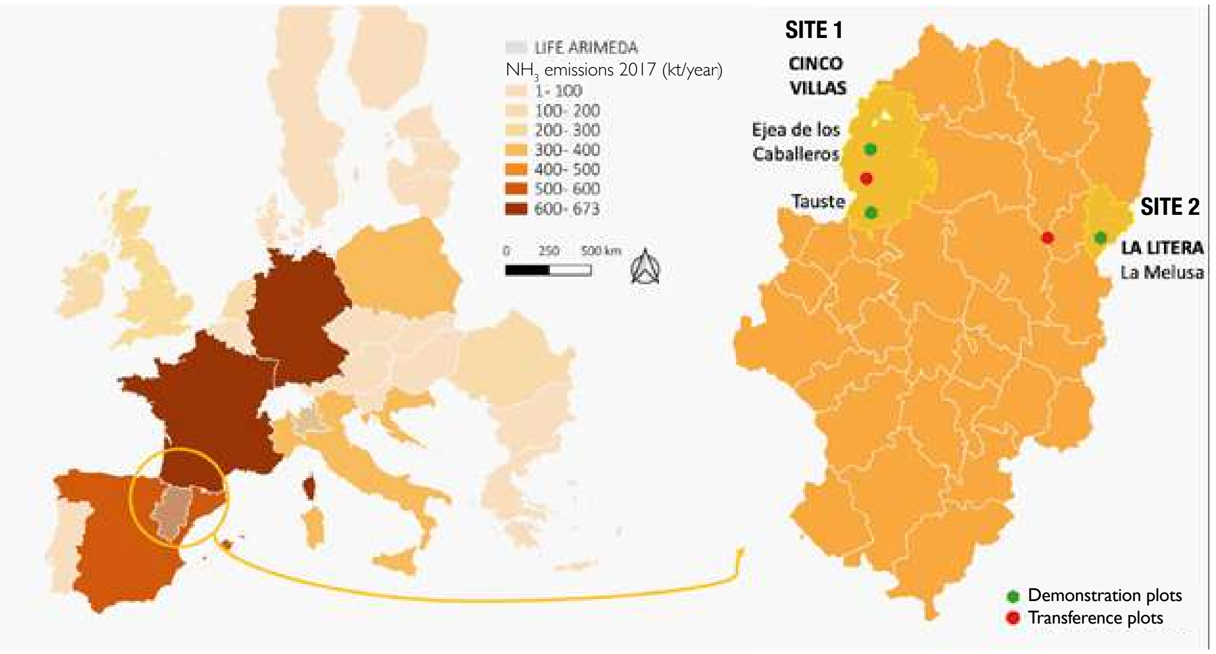

Figure 5.1. Locations of the demonstration fields at each site in Aragon (Spain).

SITE 2 La Litera

The three demonstration plots at site 2 (pivot, drip and reference) were located in La Melusa, an experimental farm belonging to and managed by the Ebro River Basin authority.

Pivot (ES-S2-P) has an area of 6.4 ha. It is equipped with three towers (1 of length 50 m + 2 of length 43 m). As in the case of the Cinco Villas pivot, the nozzles installed were Nelson D3000, but in this case, they were positioned 0.4 m above the soil surface every 1.4 m to irrigate every second row of maize. By lowering the position of the nozzles below the canopy for most of the crop cycle, circle sowing of the plot was necessary. The system worked at low pressure (0.4 bar) and provided large drops, avoiding spray drops, with a pluviometry of 3.8 mm in 5 hours (0.76 mm/h).

Subsurface drip-irrigated (ES-S2-G). In this case, Riegos Iberia REGABER S.A. installed 2 irrigation sectors on a 2.0-ha plot. Irrigation pipelines were installed 30 cm below the soil surface. The type of dripper used in this plot was a turbulent Netafim Aries 16100, and pluviometry was approximately 5.3 mm/h.

Reference field (ES-S2-R). The irrigation installed in this plot, located next to the other two demonstration plots, was sprinkler irrigation. Depending on the season, the plot area on which the monitoring was carried out, a part of a larger plot, varied between 1.1 and 1.5 ha.

Table 5.1 Physical and chemical characteristics of the topsoil (0-30 cm) in Spanish demonstration plots.

Site	$pH_{1:2.5}$	$EC_{1:5}$	OM	P	K	Stones (>2 mm)	Texture
		dS/m, 25°C	%	mg/kg	mg/kg	%	USDA
ES-S1-P	8.20	0.20	2.60	25	458	20	Clay loam
ES-S1-G	8.44	0.17	1.75	8	174	54	Sandy clay
ES-S1-R[1]	8.44	0.16	3.08	29	281	-	Sandy clay
ES-S1-R[2]	-	0.16	1.93	17	251	57	Sandy clay
ES-S2-P	8.30	0.20	2.60	25	458	0	Sandy loam
ES-S2-D	8.26	0.23	2.39	24	204	0	Sandy loam
ES-S2-R	8.25	0.25	2.15	21	177	0	Sandy loam

$EC_{1:5}$: Electrical conductivity in extract 1:5; **OM:** Organic Matter; **P:** Phosphorus; **K:** Potassium.
[1] in 2018-2019, [2] in 2020

5.2.1 AGRONOMIC MANAGEMENT AND FERTILIZING STRATEGY

Grain maize monoculture was cultivated in all the plots due to the extensive use of this cropping system in the area and its high nitrogen demand. Long-cycle maize was grown on all plots except for during the first year when heavy rains in spring 2018 delayed the installation of fertigation equipment and forced the cultivation of short-cycle maize varieties (except in ES-S1-P). Long-cycle maize is usually sown at the end of April or the beginning of May and harvested in November. During the project, maize was sown slightly earlier in Cinco Villas than in La Melusa, which enabled coordination of the fertigation calendar at both sites by following a tight agenda with a short delay margin for moving separation prototypes from Site 1 to Site 2 to obtain the liquid fractions.

Demonstration and reference fields were managed following traditional agricultural practices by the farmers, except for the application of fertigation, and according to each year's needs.

Reference plots were fertilized following the usual local practices for fertilization when using pig slurry. The pig slurry was applied with a splash plate before sowing, and the N dose was adjusted as closely as possible to 170 kg N/ha, the maximum dose allowed in nitrate-vulnerable zones. Fertilization was completed with approximately 150 kg N/ha of synthetic fertiliser as side dressing (Table 5.2).

In the demonstration fields, N was supplied as side dressing with irrigation in several events. Exceptionally, on some occasions, a small dose of N was applied next to phosphorus as base dressing using synthetic compounds (ES-S1-P). In all cases, the liquid fraction of pig slurry was either the only or the major N supply to the crop (Table 5.2).

The irrigation of maize usually starts at the end of May or early June and lasts until September. Fertigation in the demonstration fields took place during June and July, depending on meteorological conditions and on the phenological development of the crop. In the first year (2018), due to the delay in the establishment of some of the demonstration fields, the fertigation season extended to the end of August in affected fields (Table 5.3).

Table 5.2. Total nitrogen (kg N/ha) applied with pig slurry (PS) or pig slurry liquid fraction (LF) and synthetic fertiliser (S) at the two sites during the three seasons monitored. For PS and LF, the amount of N-NH_4^+) applied is also given (kg TAN/ha).

		BASE-DRESSING				SIDE-DRESSING				N
		PS		S	Total	LF		S	Total	**TOTAL**
Site	**Year**	kg N/ha	kg TAN/ ha	kg N/ha	kg N/ha	kg N/ha	kg TAN/ ha	kg N/ha	kg N/ha	kg N/ha
ES-S1-R	2018	180,8	138,6	-	180,8	-	-	150,0	150,0	**320,8**
	2019	166,8	140,4	-	166,8	-	-	176,0	176,0	**342,8**
	2020	171,5	101,0	-	171,5	-	-	130,0	130,0	**301,5**
ES-S1-P	2018	-	-	29,0	29,0	212,5	164,5	77,9	290,4	**319,4**
	2019	-	-	-		206,2	155,5	136,3	342,5	**342,5**
	2020	-	-	-	-	83,1	68,5	186,3	254,8	**254,8**
ES-S1-G	2018	-	-	-	-	188,4	151,7	-	188,4	**188,4**
	2019	-	-	-	-	352,6	272,0	-	352,6	**352,6**
	2020	-	-	-	-	203,8	152,5	83,9	287,6	**287,6**
ES-S2-R	2018	267,1	168,2	-	267,1	-	-	148,2	148,2	**415,3**
	2019	217,7	179,5	-	217,7	-	-	148,2	148,2	**356,9**
	2020	232,0	137,2	-	232,0	-	-	156,0	156,0	**388,2**
ES-S2-P	2018	-	-	-	-	261,7	164,4	-	261,7	**261,7**
	2019	-	-	-	-	221,6	165,0	-	221,6	**221,6**
	2020	-	-	-	-	195,2	161,4	54,8	250,0	**250,0**
ES-S2-G	2018	-	-	-	-	163,9	103,0	26,8	190,7	**190,7**
	2019	-	-	-	-	299,2	224,3	-	299,2	**299,2**
	2020	-	-	-	-	241,5	201,6	-	241,5	**241,5**

Clogging and transport problems faced during the three years in Cinco Villas that could not be solved in time forced the completion of necessary crop nitrogen by application of synthetic fertiliser on certain occasions. However, in 6 of the 12 demonstration field trials, the total N supply was provided using only organic fertigation (%N with fertigation =100%) without jeopardizing agronomic performance (Table 5.3).

Table 5.3. Fertigation events in Spanish demonstration plots. Number of events, average N rate per event, dilution, total N applied in the field, percentage N applied with fertigation and crop yield.

Site	Dates	Events	N rate / event	Dilution	N applied	N applied with LF	Crop yield
			kg N/ha	FL:water	kg/ha	%	t/ha
	2018						
ES-S1-P	12/07-30/07	12	17.7	1:11	319.4	66.5	13.6
ES-S1-D	10/08-05/09	11	18.2	1:5	188.4	100.0	6.6
ES-S2-P	30/07-22/08	11	23.8	1:7	261.7	100.0	11.5
ES-S2-D	27/08-31/08	4	42.4	1:5	195.9	86.3	8.1
	2019						
ES-S1-P	15/06-16/07	12	17.5	1:16	342.5	60.2	15.3
ES-S1-D	28/05-25/07	20	17.8	1:8	352.6	100.0	13.4
ES-S2-P	12/06-24/07	22	9.6	1:14	221.6	100.0	13.5
ES-S2-D	07/06-11/07	10	29.9	1:4	299.0	100.0	4.2
	2020						
ES-S1-P	27/05-07/07	8	10.4	1:19	269.3	30.8	13.6
ES-S1-D	21/05-03/07	17	12.7	1:6	287.6	48.1	7.2
ES-S2-P	15/06-20/07	19	13.9	1:6	250.0	78.1	17.0
ES-S2-D	04/06-26/07	20	11.8	1:7	241.5	100.0	13.6

The dilution ratio of the liquid fraction of the slurry when injected into the irrigation network (slurry liquid fraction:irrigation water) was generally higher in pivot irrigation sites, ranging from 1:6 to 1:19, while in drip irrigation sites, the dilution ratio ranged from 1:4 to 1:8. The liquid-fraction-to-water ratio was constrained by the injection equipment, plot size and field storage capacity. Lower irrigation flow rates and pressure enabled higher rates of liquid fraction injection into the irrigation systems, but field storage limited the amount to be injected in an irrigation event in large fields, such as pivot plots (Table 5.4).

Table 5.4. Average liquid fraction injection flow rates (m^3 LF/h) at the demonstration fields during the three years of monitoring.

		2018	2019	2020
Site	Irrigation system	m^3/h	m^3/h	m^3/h
ES-S1-P	Pivot	6,4	4,7	4,3
ES-S1-D	Drip irrigation	10,4	7,5	8,1
ES-S2-P	Pivot	11,2	5,4	8,3
ES-S2-D	Drip irrigation	12,0	12,2	7,9

5.2.2 PIG SLURRY SOLID-LIQUID SEPARATION

In Spain, the company Mecàniques Segalés S.L. designed and built two portable prototypes for mechanically separating the solid fraction of the slurry. The first prototype provided a liquid fraction suitable for injection into pivot irrigation systems, and the second prototype was designed to separate in a second step the liquid fraction obtained with the first prototype and provide a liquid fraction suitable for injection into drip irrigation systems. Each unit was installed on a separate portable platform that allowed it to be transported from one area to another.

The use of pivot systems facilitates fertigation with pig slurry liquid fraction because of the greater nozzle hole diameter (>2 mm), which admits larger solid particles (<500 µm). Drip irrigation requires removing particles larger than 100 µm and thus a second separation stage that increases costs and time when scheduling the fertilizing season. The use of the same prototypes in all demonstration plots forced the implementation of a very tight schedule in which any delay affected the management of all the other demonstration plots at both sites. These restrictions can be easily mitigated by adequately determining the number and size of separation units required for each season. To do this, it is necessary to know the volume of slurry that needs to be separated according to its composition and the agricultural area to be fertilized. In the planning, the separation performance of the equipment and the working distances to be covered in the transport from farms to the fields must be taken into account.

The pivot prototype consisted of a filtering ramp followed by a screw press where the nonfiltered slurry was pressed to improve separation performance (reducing the water content in the final solid fraction). The first-year prototype sieve had a 600-µm mesh size in both components: ramp and screw press. The mesh size was progressively diminished to 250 µm in the last year. The drip irrigation prototype was a vibrating screen, similar to the equipment used on farms IT-S1 and IT-S3 in Italy (Chapter 6), with a 100-µm separation mesh in the first year that was reduced to 80 µm, as the screen size was reduced from 600 µm to 250 µm in the pivot prototype.

Pig slurry was fed to the pivot prototype, and then the obtained liquid fraction (PLF) was stored in a pond and the solid fraction (PSF) in a manure pad on each farm. When implementing fertigation in a drip irrigation system, the second prototype was fed PLF from the farm pond, the filtered liquid fraction (DLF) stored in tanks and the solid fraction (DSF) stored in a manure pad on the farm next to the PSF pad and managed jointly as a valuable organic fertiliser (Figure 5.2).

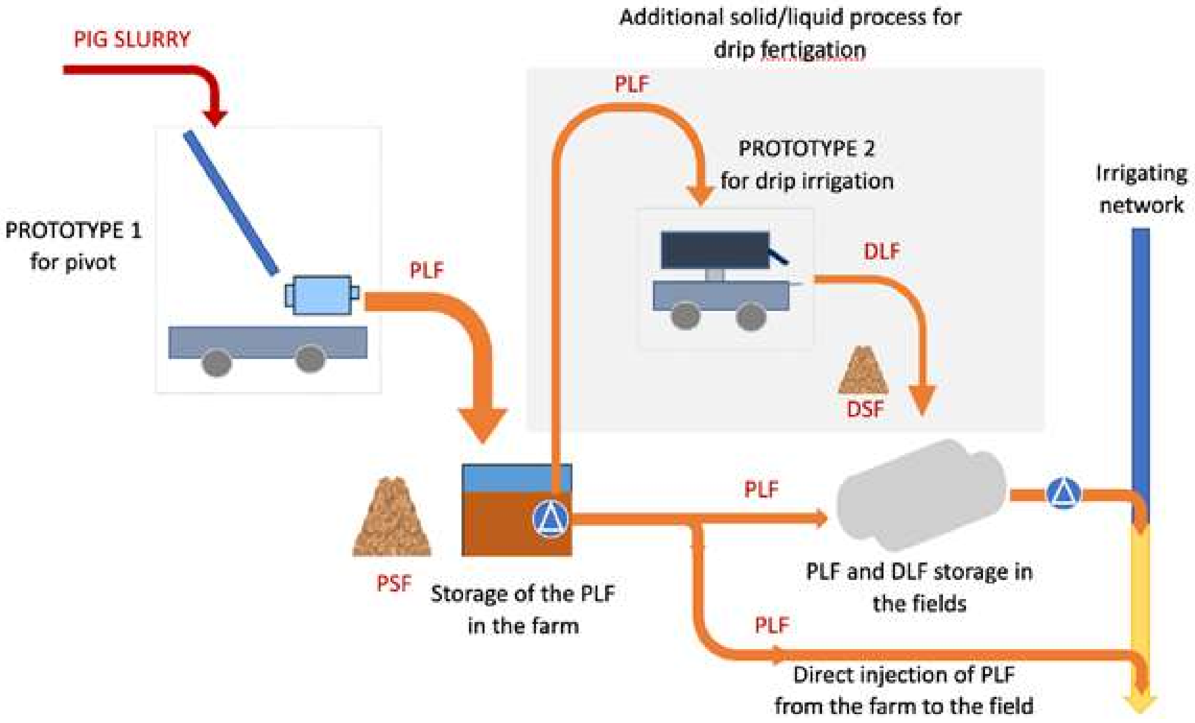

Figure 5.2. Flow chart of the management process in the fertigated plots in Aragon (Spain).

The pig slurry used in the demonstration fields came from three different farms, two farms in Cinco Villas and one farm in La Litera:

Farm 1 (ES-S1-F1) is a fattening pig farm (9,100 heads) in Ejea de los Caballeros (Zaragoza, Spain). A pivot separation prototype was installed on the farm in 2018 to supply liquid fraction for fertigation in the Cinco Villas pivot (ES-S1-P). A drip irrigation separation prototype was installed on this farm for three years and supplied the liquid fraction for the drip irrigation plot (ES-S1-D) in the three field campaigns (Image 5.1). A fixed ramp was installed by the farm owners in 2019, providing a prefiltered fraction that could be fed directly into the drip irrigation prototype during the second and third field trial campaigns.

Farm 2 (ES-S1-F2) is a fattening pig farm (5,880 head) in Ejea de los Caballeros (Zaragoza, Spain). A pivot separation prototype was installed on this farm in 2019 and 2020, and a slurry was used to supply the pivot in Cinco Villas (ES-S1-P).

Farm 3 (ES-S2-F3) is a fattening pig farm (3,150 head) located in Esplús (Huesca, Spain) (Image 5.2). This farm supplied the liquid fraction for the two demonstration fields in La Litera (ES-S2-P, ES-S2-D). An existing concrete lagoon was isolated and conditioned to store the liquid fraction for the pivot (PLF).

In the trials carried out in La Melusa (Site 2, La Litera), the separation prototype necessary for the drip irrigation was installed for the three years near the storage tanks from which the liquid fraction was injected into the irrigation system. In this area, conditioned with a concrete floor, a vertical tank of 30 m^3 was also installed to store the FLP coming from ES-F3 and to enable completion of the second stage of separation.

Image 5.1. Solid/liquid separators, pivot prototype (up) and drip prototype (down) in Farm 1 (ES-S1-F1) that provided liquid fraction for demonstration field at Torremira in Cinco Villas (ES-S1-D).

Image 5.2. Solid/liquid separator for pivot and liquid fraction storage pond at Farm 3 (ES-S2-F3) that provided liquid fraction to demonstration fields at La Melusa in La Litera (ES-S2-P, ES-S2-D).

The operation of the separation prototypes was monitored for 6 trials (3 for the pivot prototype and 1 for the drip prototype) on different farms. Monitoring consisted of recording slurry and liquid-solid fraction flow rates, composition and the equipment operating time and electricity consumption. These data were used to evaluate the system performance through mass balances.

The composition of the liquid fraction that was injected in each field each year is summarized in Table 5.5. In Cinco Villas, the liquid fraction used in the drip irrigation field for the 3 years and in the pivot plot for the 2018 season was taken from the same farm (ES-S1-F1). The raw pig slurry from ES-S1-F1 was very dilute and made filtration easier, but because of the low ammonium concentration (TAN), large volumes of liquid fraction needed to be transported to cover the N demands of the crops. Thus, in 2019 and 2020, fertigation in ES-S1-P was performed using pig slurry from ES-F2, closer to the pivot and with higher N concentrations (average TAN 2.85 and 2.30 kg/t in 2019 and 2020, respectively).

In La Melusa, during the first year in 2018, both prototypes were installed close to the fields, and pig slurry was supplied by several farms. The large variability of the slurry from the different facilities caused severe problems in the prototype operation and required continuous adjustments. In 2019 and 2020, the slurry was provided by ES-F3 during the entire season.

Table 5.5. Composition of the liquid fraction used for fertigation at the different demonstration fields during the 2018, 2019 and 2020 seasons.

Site	Farm	N	Year	TAN	TKN	TAN/ TKN	pH	TS	VS	VS/ TS	P_2O_5	K_2O
				kg/t	kg/t	%		%	%		kg/t	kg/t
ES-S1-P	ES-F1	6	2018	0.94	1.60	81.4	-	1.08	0.47	43.4	0.54	2.73
ES-S1-P	ES-F2	18	2019	2.85	3.13	80.2	7.93	1.9	1.06	53.8	0.05	3.81
ES-S1-P	ES-F2	7	2020	2.30	3.04	75.7	-	2.04	1.10	54.0	0.12	4.26
ES-S1-D	ES-F1	3	2018	1.28	1.64	80.5	-	1.31	0.62	47.3	0.10	3.00
ES-S1-D	ES-F1	7	2019	1.25	1.65	78.4	8.22	1.29	0.55	41.4	0.02	3.64
ES-S1-D	ES-F1	3	2020	1.03	1.39	74.8	-	-	-		0.01	3.64
ES-S2-P	various	2	2018	1.38	2.20	62.8	-	1.85	1.00	56.5	1.25	1.66
ES-S2-P	ES-F3	7	2019	2.31	3.25	74.5	7.90	2.48	1.30	52.4	0.18	3.63
ES-S2-P	ES-F3	8	2020	1.30	1.58	78.1	7.83	1.68	0.51	42.0	0.03	2.88
ES-S2-D	various	0	2018	-	-	-	-	-	-	-	-	-
ES-S2-D	ES-F3	4	2019	1.99	-	-	-	-	-	-	-	-
ES-S2-D	ES-F3	2	2020	2.44	-	-	-	3.37	-	-	-	-

SF: solid fraction, **TAN:** total ammonium nitrogen, **TKN:** total Kjeldahl nitrogen, **TS:** total solids, **VS:** volatile solids, **N** number of samples.

5.3 ENVIRONMENTAL MONITORING

Ammonia emissions

The ammonia emissions derived from the fertilizing activities in the LIFE ARIMEDA project fields were monitored for the three growing seasons, 2018 to 2020, following the protocols described in Chapter 4.

Working at a large scale in productive fields implies facing additional challenges and uncontrolled events that should be considered when evaluating results. However, it also provides a closer approach to real situations than isolated and controlled scenarios in laboratory or experimental facilities at a small scale. For this reason, the results obtained should be analysed within the context of every field campaign and evaluated based on the overall benefits achieved when implementing fertigation in terms of reduction of NH_3 emissions.

Both fertigation systems achieved important reductions in ammonia emissions (Table 5.6 and Figures 5.3 and 5.4). For pivot irrigation, reductions were slightly higher in Cinco Villas, with average decreases in NH_3 emissions of 81% (±2% SE[1]) per unit N applied, while in La Litera, declines averaged 71% (±8% SE). This may contradict expected results considering that nozzles were below the crop canopy in La Litera. In this plot, the nozzles were 40 cm above the soil surface, while in Cinco Villas, they irrigated from a height of 2.4 m. However, it is important to emphasize that other features, such as higher dilution ratios and lower injection volumes per event in Cinco Villas, may have exerted stronger effects on emission rates than nozzle position relative to crop canopy.

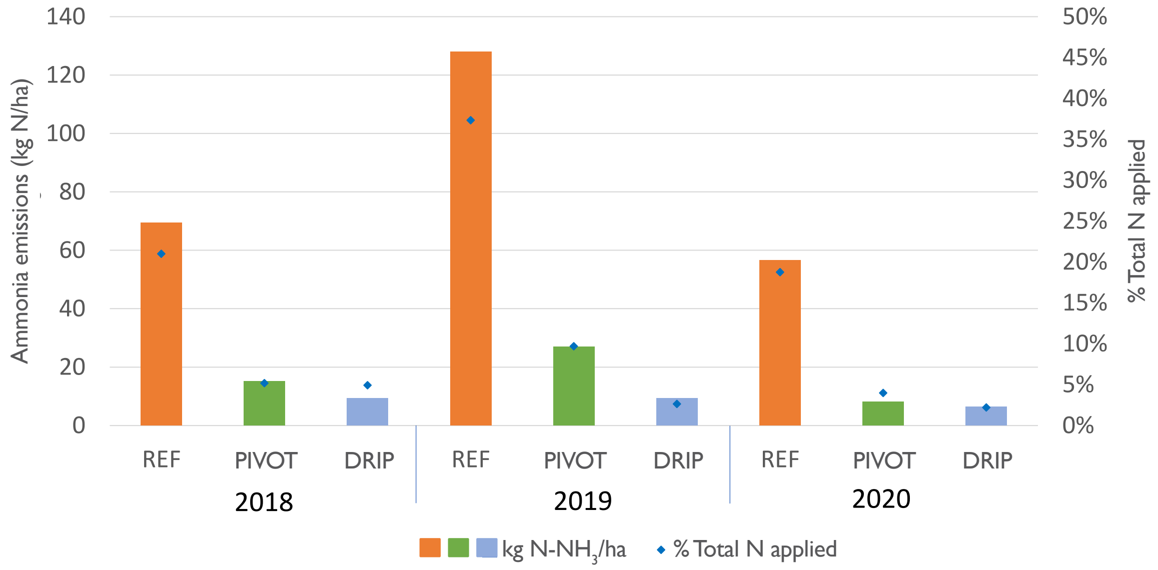

Figure 5.3. Ammonia emissions in demonstration fields at site 1 - Cinco Villas (Aragon, Spain).

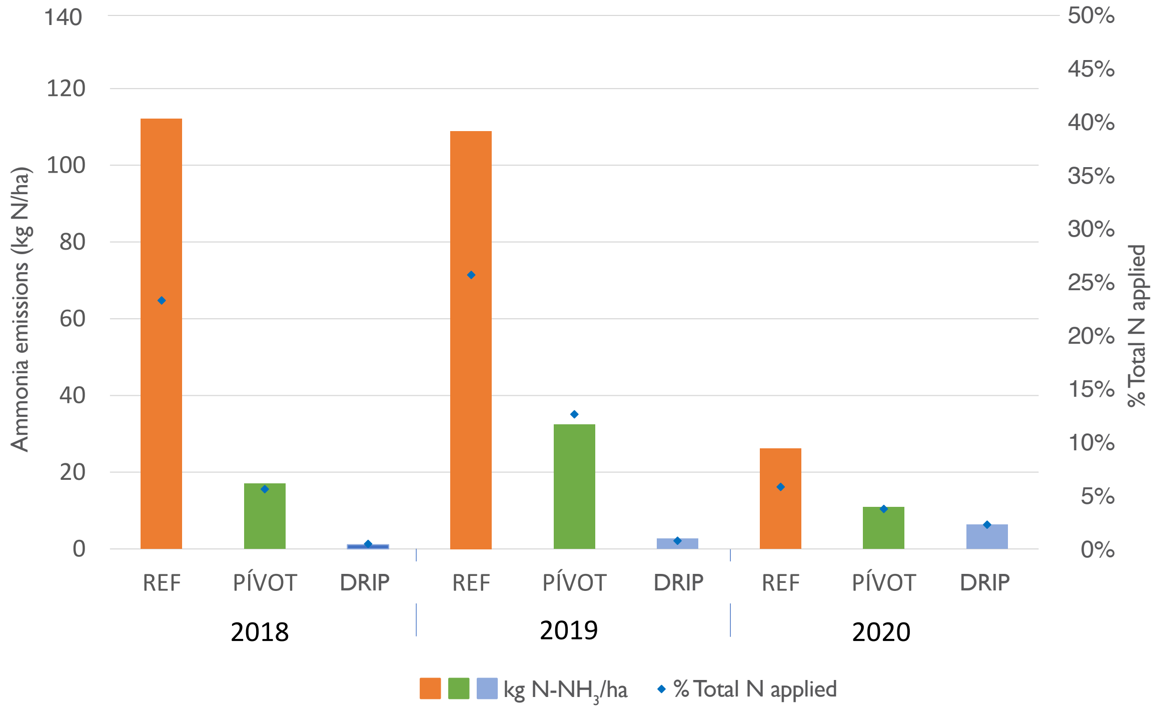

Figure 5.4. Ammonia emissions in demonstration fields at site 2 – La Litera (Aragon, Spain).

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[1] **SE:** Standard Error

The percentage of NH_3 emitted per unit N applied was always higher in the reference plots, mainly due to the base dressing broadcast application of raw pig slurry. On average, 32.3% (±7.7% SE) of the total nitrogen applied was emitted in the reference fields, while 9.5% (±2.1% SE) of the total N applied as side dressing was emitted with synthetic fertilisers. These average emission values observed when using synthetic fertilisers were higher than the average emissions determined in fertigation with organic fertilisers, 7.4% (±1.7% SE) of the total N applied in the case of pivots and 2.3% (±0.6% SE) in the case of subsurface drip fertigation systems (Table 5.6). Drip irrigation permits working with lower dilutions, maintaining low emissions of NH_3 to the air.

However, it must be emphasized that 100% of the total N was not always provided in demonstration fields by the liquid fraction of pig slurry. It was not always possible to adjust the availability of slurry in the field to the times of crop demand due to technical difficulties in setting up the techniques evaluated in some cases and delays beyond the control of the trials in others. Logistics played a crucial role in the implementation of the trials.

Table 5.6. Average ammonia emissions, with the reductions in emissions and the amounts of N applied to fertigated fields with respect to the reference fields monitored in Aragon (Spain).

	N applied (±SE)	N-NH_3 emissions (±SE)		Reduction in N-NH_3[1] (±SE)	Reduction in N applied[2] (±SE)	
	kg N/ha	kg N/ha	% N applied	%	kg N/ha	%
Reference	357.4 (±16.7)	83.6 (±16.0)	23.4% (±4.0)			
Pivot	277.4 (±13.4)	18.4 (±3.8)	7.4% (±1.7)	76.0% (±4.2)	90.6 (±28.0)	29% (±4.5)
Drip	261.5 (±26.6)	5.9 (±1.4)	2.3% (±0.6)	90.0% (±3.5)	95.9 (±36.3)	25% (±9.2)

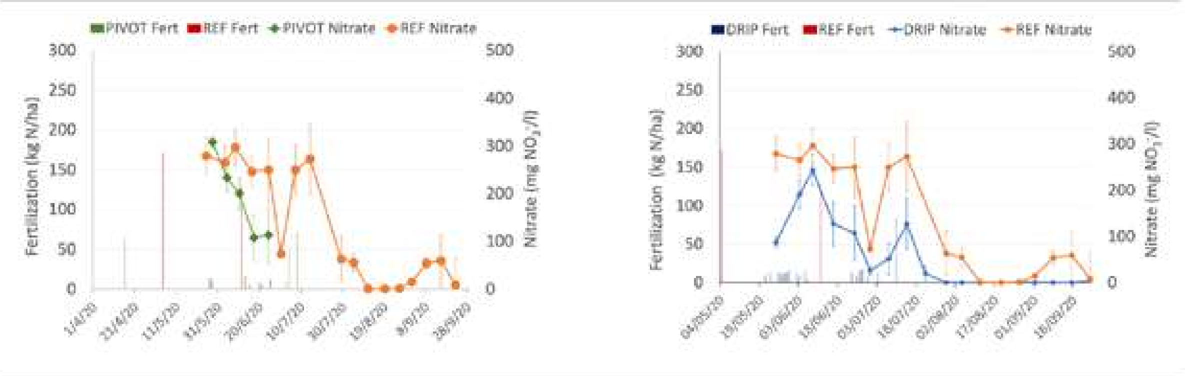
[1] *Relative to N emissions,* [2] *Relative to N applied in reference fields.*

Risk of nitrate leaching

In all the fields, ceramic suction cups were installed at 5 points homogenously distributed over the surface (W distribution) of the field. These cups were buried below the crop root zone according to the soil depth of each plot. In Cinco Villas (shallower soils), their depth was 50 cm, while in La Litera, they were installed at 1.0 m below the soil surface. Once a week, water was sampled after 24 hours of vacuum, and the nitrate concentration was analysed in the laboratory.

The nitrate concentrations observed in the samples collected from the pivots were generally lower than those measured in the drip irrigation systems and in the reference plots, which usually showed values within the same range. This behaviour was particularly noticeable in La Litera (site 2), where deep, clayey soils predominate. In 2019, the average nitrate concentration observed in the drip irrigated plot was higher than usual, related to a red spider mite infestation that attacked the crop and reduced the production. As a consequence, at the beginning of 2020, these nitrate concentration values were also higher than usual, as there was a high amount of N available in the soil from the previous season (Figure 5.5).

CINCO VILLAS 2020



LA LITERA 2020

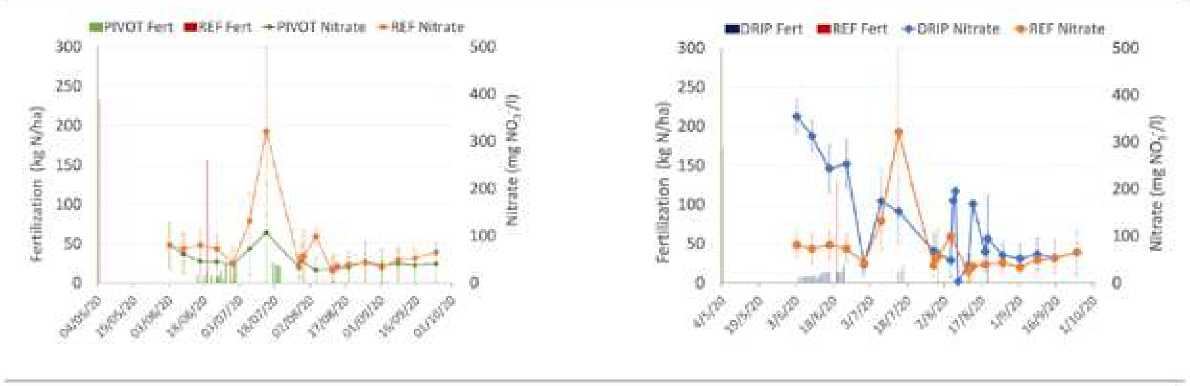


Figure 5.5. Nitrate concentrations measured in the LIFE ARIMEDA demonstration plots compared with reference fields at site 1 (top) and at site 2 (bottom) for the 2020 season.

5.4 AGRONOMIC MONITORING

Fertigation enables the adjustment of N application to real crop demands not only in terms of quantity but also in terms of time of application. Despite the logistical and cleaning challenges, fertigation in the demonstration fields was able to provide 84% of crop N needs in an average of 14 fertigation events with average rates of 19 kg N/ha per event and was able to supply the entire N requirements of the crop in 6 of the 12 demonstration trials.

The total nitrogen supply in reference plots managed by farmers with traditional practices ranged from 301.5 to 415.3 kg N/ha, and the fraction of total N applied in base-dressing with pig slurry ranged from 48.7 to 64.3%. In the fertigated plots, the nitrogen supply was lower, from 188.4 to 352.6 kg N ha^{-1}, at an average 23% lower than that for the reference plots. Crop yields were not different between reference and pivot fertigated fields, although yields in drip-irrigated fields were smaller in some situations (Figure 5.6). Crop growth in subsurface drip fields was not always optimal, and greater expertise in the management of subsurface drip irrigation for extensive crops is essential before fertigation techniques can be successfully applied.

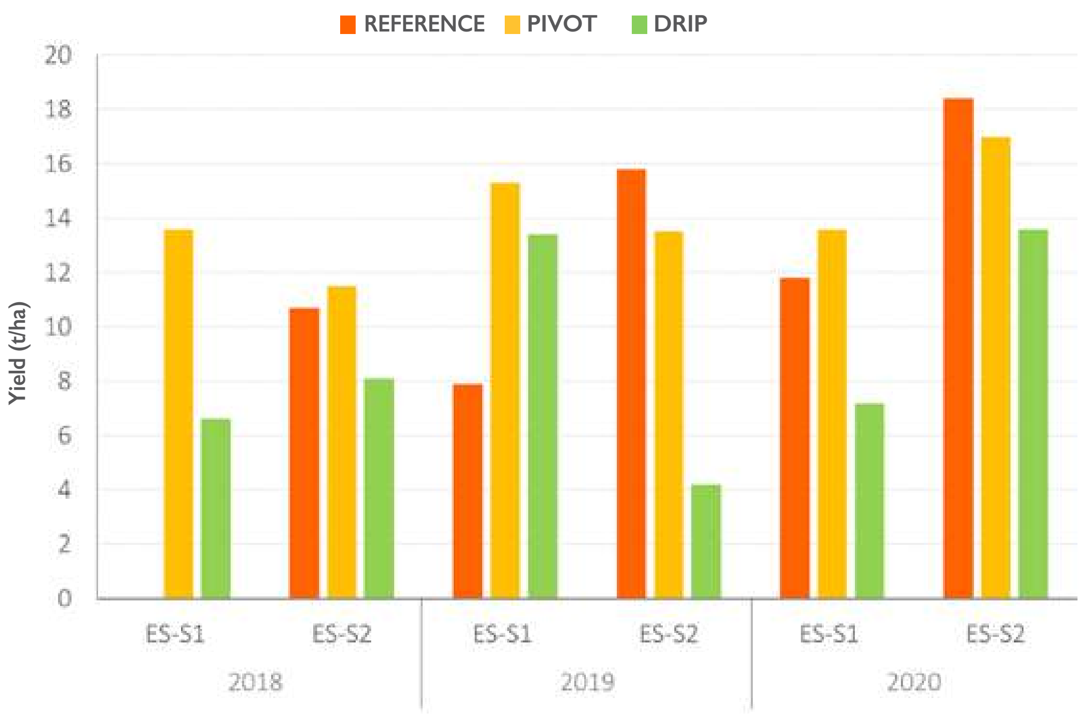


Figure 5.6. Maize yields in reference and fertigated fields during the three field seasons.

In the first campaign, nitrogen uptake by the crop was lower than in the other two campaigns due to the shorter crop cycles and ranged from 87.2 (ES-S2-D) to 187.8 kg N/ha (ES-S1-P). In the 2019 and 2020 seasons with longer cycle varieties, N extraction by the aboveground biomass reached an average value of 200 kg N/ha and was generally lower in subsurface drip irrigated plots (Table 5.7). Nitrogen use efficiency (NUE) was calculated as the ratio of N uptake (in the aboveground biomass) to N applied. The split of the N application rate adjusted to real crop demands with the fertigation techniques, in addition to the reduction of nutrient surpluses applied to the fields, was reflected in an increase in the efficiency of the use of N mainly in pivot systems. Thus, NUE in reference plots ranged between 0.31 and 0.72 with an average value of 0.52, and the highest NUE was obtained in pivot systems with an average value of 0.76 and ranging from 0.59 to 1.04. In drip irrigated fields, NUE (excluding ES-S1-D in 2020) slightly exceeded the values of reference fields (range 0.46-0.69) with an average value of 0.56, which is aligned with the lower crop yields obtained in subsurface drip irrigation in comparison to pivot irrigation at each site in the three seasons.

Table 5.7. N applied, N in the aboveground biomass (N uptake) and NUE in Spanish demonstration plots.

Site	N in base-dressing	N in side-dressing	Total N applied	N uptake		NUE N uptake/N applied	
	kg N/ha	kg N/ha	kg N/ha	kg N/ha			
				Average	±SE	Average	±SE
2018							
ES-S1-R	180.8	150.0	330.8	102.8	±9.7	0.31	±0.03
ES-S1-P	29.0	290.4	319.4	187.8	±8.6	0.59	±0.03
ES-S1-D	-	188.4	188.4	86.9	±9.4	0.47	±0.05
ES-S2-R	267.1	148.2	415.3	180.2	±4.1	0.43	±0.01
ES-S2-P	-	261.7	261.7	177.6	±19.9	0.68	±0.08
ES-S2-D	-	190.7	190.7	124.8	±9.9	0.63	±0.04
2019							
ES-S1-R	166.8	176.0	342.8	130.5	±6.7	0.38	±0.02
ES-S1-P	-	342.5	342.5	243.5	±25.1	0.71	±0.07
ES-S1-D	-	352.6	352.6	192.7	±5.6	0.56	±0.04
ES-S2-R	217.7	148.2	356.9	265.0	±18.6	0.72	±0.05
ES-S2-P	-	221.6	221.6	231.2	±10.4	1.04	±0.05
ES-S2-D	-	299.2	299.2	134.6	±5.8	0.45	±0.02
2020							
ES-S1-R	171.5	130.0	301.5	208.4	-	0.69	-
ES-S1-P	-	269.4	269.4	160.0	±8.8	0.59	±0.03
ES-S1-D	-	287.6	287.6	93.5	±3.9	0.33	±0.01
ES-S2-R	232.0	156.0	338.2	250.7	±7.8	0.65	±0.02
ES-S2-P	-	250.0	250.0	242.9	±14.3	0.97	±0.06
ES-S2-D	-	241.5	241.5	166.5	±8.8	0.69	±0.04

TKN: total Kjeldhal nitrogen, **TAN:** total ammoniacal nitrogen, **NUE:** nitrogen use efficiency.

5.5 LESSONS LEARNED AND TRANSFER TO OTHER FIELDS

The expertise obtained in the demonstration plots was transferred to two other farms where the fertigation technique was replicated in pivot and drip irrigation systems.

The pivot field was next to a pig farm, and it was possible to directly inject the slurry from the LF storage pond through a pipeline and avoid all the logistical difficulties faced in the demonstration plots due to road transport. In this plot of 54 ha, all the N needs for a *maize – wheat (1/2 plot) + pea (1/2 plot) – maize* rotation were applied with fertigation, with a maximum of 8 fertigation events of 19 hours for each crop in the rotation (Table 5.8), obtaining excellent yields and saving costs.

A drip transference field was also installed next to a fattening pig farm, but in this field, slurry needed to be filtered through both prototypes sequentially to obtain a liquid fraction adequate to be injected into the drip system. Two 30-m^3 storage tanks were installed on the farm to store the clean liquid fraction (DLF) for injection into the irrigation system. In 2019, only 49% of the N needs were applied using the pig slurry liquid fraction. The filtration and injection systems had to be adjusted, and various clogging problems affected filters and fertigation systems. In 2020, the entire crop N needs were met with pig slurry in 8 fertigation events (Table 5.8). However, maize lodged in both years, and the production yield was dramatically reduced. The problem was not associated with fertigation but with inadequate management of irrigation with inadequate irrigation timing and rates.

Table 5.8. Amount of N applied by fertigation in each of the crops of the transference plots, with the number of fertigation events and the percentage of crop N needs met by the slurry applied in the fertigation.

Site	Year	Area	Crop	N rate with fertigation	# Events	N needs covered
		ha		kg N/ha		%
Pivot	2019	54	Maize	170.0	6	100.0
	2019/20	27	Barley	116.5	5	100.0
	2020	27	Pea	93.2	4	100.0
	2020	27	Maize after pea	139.8	6	100.0
	2020	27	Maize after barley	209.7	7	100.0
Drip	2019	2.2	Maize short cycle	107.2	5	49.5
	2020	2.2	Maize	232.0	8	100.0

The results obtained in demonstration fields highlight the significant reduction in ammonia emissions when fertigation is introduced. Compared to the reference technique, the average reductions were 76% (±4% SE) with pivot irrigation and reached 90% (±3% SE) with subsurface drip irrigation. It should be noted that this result derives from a combination of factors. First, a reduction in the N dose applied was possible due to improved synchronization of N application to crop N needs with greater partitioning of the application of N through fertigation. On average, the rates of N applied were reduced by 29% for pivot (from 357.4 to 277.4 kg N/ha) and 25% for drip irrigation systems (from 357.4 to 261.5 kg N/ha) relative to N doses applied by farmers in reference fields and without jeopardizing crop production. Second, the pig slurry was diluted with water in every fertigation event. Third, the application of the slurry using subsurface drip irrigation or low-pressure systems in pivots with nozzles reduced drift and evaporation losses.

The fertigation technique was also able to increase the nitrogen use efficiency over that of traditional application methods (reference fields), mainly in the pivot systems.

Under the conditions of the two scenarios in which fertigation was transferred, a mixed farm-plot model allowed direct injection without the need for road transport, and sufficient slurry was available to meet the total N needs of the crops. This is the ideal situation for the success of this new fertilization practice. The road transport of the filtered slurry was one of the major bottlenecks in demonstration fields due to constraints on availability of this equipment during the fertilizing season and the necessity of perfectly clean conditions inside the tanks, which is more critical for drip irrigation systems.

In the pivot irrigation system, the particle size that needs to be filtered (500 μm) is not a limiting factor, and the use of a ramp that does not require a high investment is sufficient. Its handling is simple with low operating and maintenance costs and can be carried out by the farmer autonomously without permanent surveillance.

Fertigation in subsurface drip irrigation systems, although more efficient than pivot systems in reducing ammonia emissions, suffers additional drawbacks. First, it requires a second filtering step to achieve particle sizes of less than 100 μm in the liquid fraction and additional storage systems, which can limit its use. Second, the management of irrigation, which depends on the type of soil, needs to be more precise and requires high technical knowledge, as a favourable emergence or a good stand of the crop is critical to avoid lodging problems. Third, subsurface drip irrigation does not make possible the application of treatments against pests. One aspect to take into account for future work is the need for an in-depth analysis of the effect of the amount of small solids in the liquid fraction in fertigation management.

In all cases, it is necessary to know the volume and nitrogen concentration of the LF that is injected into the system to carry out good agronomic practices and adapt the application of N to the needs of the crop. If it is not possible to measure the amount of LF that is injected, in the case of the pivot, the ammonium concentration of the water applied in some fertigation events can be analysed, and the concentrations obtained can be multiplied by the water supplied by the irrigation system to estimate the doses of N applied.

In centralized management systems, good planning of logistical activities, including the need for filtered slurry, nitrogen richness of the slurry, separator yields and movement and availability of the transport equipment, is necessary for a successful application of the technique to meet the total crop requirements with slurry. However, with these premises, fertigation can contribute to improving slurry management in Aragon.

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6

FERTIGATION WITH DIGESTATE IN DEMONSTRATION FIELDS IN LOMBARDY (ITALY)

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6.1 INTRODUCTION

Livestock production in Lombardy, with a strong presence in the southeast of the region, is amongst the most intensive systems in Europe. As a result, large amounts of livestock effluents are generated. The nitrogen in these livestock effluents is estimated to be approximately 130,647 tons per year, 60% from cattle and dairy cows, 28% from pigs and 10% from poultry (ERSAF, 2011). Farmers tend to dispose of the effluents as rapidly and as close to the farm as possible since manure storage time is limited (from 4 to 6 months according to the type of manure) (ERSAF, 2011) and has significant costs in addition to the expenses of transport and spreading of manure. Nevertheless, the manure produced exceeds the crop needs. This can be explained by the livestock breeding system, which is characterized by the absence of grazing, and most of the protein feed is imported.

In close connection with livestock activity but also with the main energy crops (mainly maize and autumn-winter cereals), numerous plants for the production of electricity from biogas have been built in the last 20 years. Lombardy has the largest number of biogas plants and the largest installed capacity in Italy, more than 560 plants are powered by manure and vegetable biomass, with an average size of 680 kWe of installed power and most of them are directly managed by farmers.

Digestate is the by-product of this activity and has a valuable nutrient content. The nitrogen in the digestate is mainly in the form of ammoniacal nitrogen, which is very prone to volatilisation. Thus, although this product is an excellent fertiliser, it must be stored and applied in the field with techniques that limit emissions to the atmosphere. For this reason, the LIFE ARIMEDA project in Italy focused its activity on the use of digestate for fertigation as a suitable technique for reducing ammonia emissions.

6.2 FIELD TRIALS DESCRIPTION

The application of pivot and drip irrigation fertigation techniques using the liquid fraction of digestate after solid separation were evaluated and compared with traditional fertilization practices using the same irrigation systems at 3 farms (Figure 6.1):

- **Horti Padani (IT-S1)** farm in Cremona Province, equipped with a central pivot and biogas plants fed with livestock (pig) manure and biomass (corn silage, wheat, barley, sorghum, and by-products), was monitored in the 2018 and 2019 seasons.
- **Agriferr (IT-S2)** farm in Mantua Province, using drip irrigation with biogas plants fed with livestock manure (cattle and poultry) and biomass (corn silage, wheat, barley, sorghum, sugar beet, and by-products), was monitored in the 2018, 2019 and 2020 seasons.
- **La Maddalena (IT-S3)** farm in Brescia Province, equipped with a central pivot and biogas plants fed with poultry manure and biomass (corn silage, wheat, barley, sorghum, and by-products), was monitored in the 2020 season.

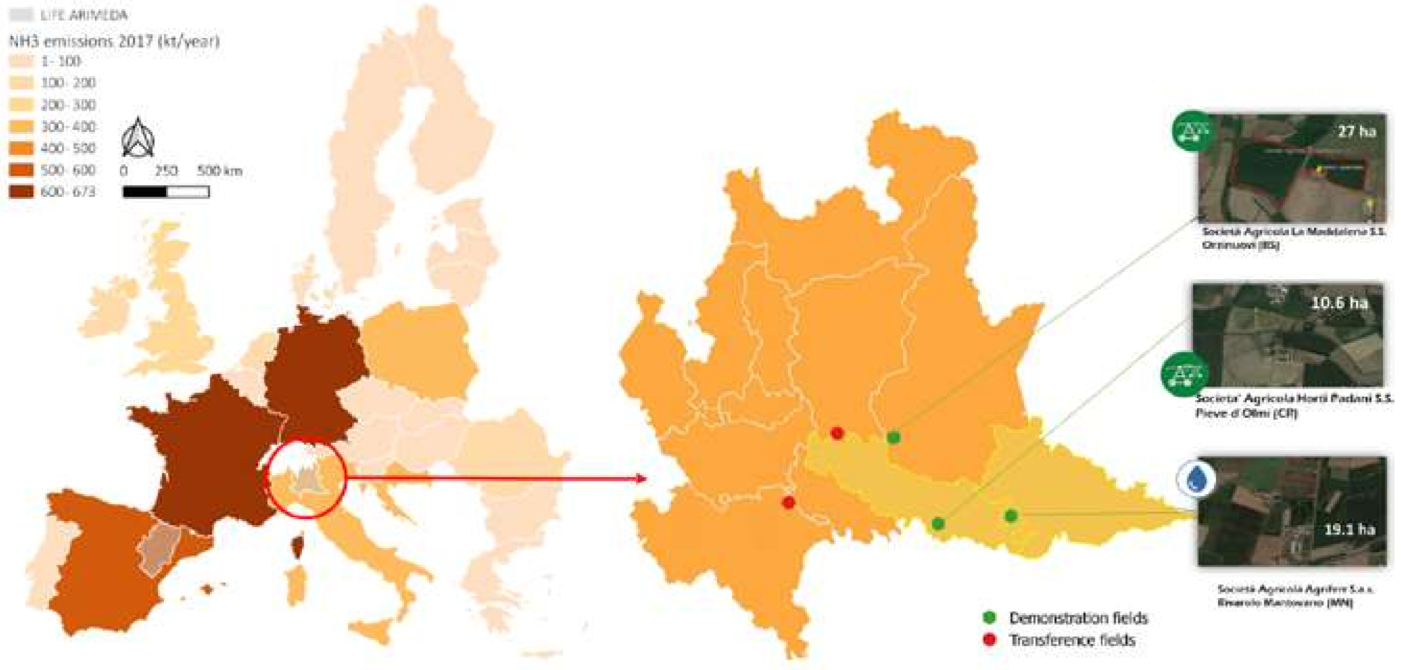

Figure 6.1. Locations of the three demonstration farms in Lombardy (Italy).

In all farms, the crop was silage maize sown after a winter cereal, and the fertilization techniques used are summarised in Table 6.1.

Table 6.1. Techniques used in the demonstration fields at the three farms in Lombardy (Italy).

	IT-S1	IT-S2	IT-S3
Irrigation system			
Fertigated fields	Pivot	Drip	Pivot
Reference fields	Pivot	Drip	Pivot
Base dressing techniques			
Fertigated fields	Direct incorporation	Direct incorporation	Shallow injection
Reference fields	Surface spreading and incorporation within 24 hours	Surface spreading and incorporation within 24 hours	Shallow injection
Field surface (ha)			
Fertigated fields	10.6	10.2 – 19.1	27.0
Reference fields	7.0-9.0	3.0 – 7.0	10.0
Monitoring period			
All fields	2018 and 2019	2018, 2019 and 2020	2020

6.2.1 AGRONOMIC MANAGEMENT AND FERTILIZING STRATEGY

Table 6.2 presents the main information about the trials at the demonstration farms; in all cases, the pre-sowing fertilisation and sowing were carried out from the beginning of June to the beginning of July, after the harvest of a winter cereal for silage.

Table 6.2. Main field operation dates on the three demonstration farms in Lombardy (Italy).

	Year	Pre-sowing fertilization	Sowing	Fertigation	Fertigation events	Digestate in fertigation (m^3/ha)
IT-S1	2018	12/07	15-17/06	20/07 - 09/08	6	75-85
	2019	13/06	18-21/06	25/07 - 12/08	4	74-85
IT-S2	2018	01-07/06	17/06-5/07	31/07 - 21/08	3	71-118
	2019	08/06	10-18/06	1/08, 12/08	2	86-230
	2020	26/05-3/06	1-6/06	15/07, 20/08	2	83-108
IT-S3	2020	1/06	16-19/06	27/07, 12/08	2	58-110

A summary of the nitrogen fertilisation applied in the different fields and years is reported in Table 6.3. Mineral fertilisation was applied in the reference fields only in 2020, while in the demonstrative fields, no mineral fertiliser was applied.

The total nitrogen supply was unequal among sites and within fields because the necessity of farm manure management did not reflect real crop requirements. Depending on the season and the adopted operations, the total nitrogen supply ranged from 461 to 942 kg N/ha in the reference fields and from 304 to 559 kg N/ha in the fertigated fields (Table 6.3).

Table 6.3. Nitrogen applied in the demonstration fields in Lombardy (Italy).

		Reference fields			Fertigated fields		
Farm	Year	Base dressing kg N/ha	Side dressing kg N/ha	Total kg N/ha	Base dressing kg N/ha	Side dressing kg N/ha	Total kg N/ha
IT-S1	2018	659	-	659	337	136	473
	2019	461	-	461	441	125	566
IT-S2	2018	464	-	464	329	43	372
	2019	942	-	942	466	45	511
	2020	511	94	605	482	55	537
IT-S3	2020	498	110	608	551	315	866

The weather conditions during the maize growing period were typical of the area. The average temperatures were 22-25 °C, and rainfall varied between 74 and 192 mm among the different farms and years. Average wind speed was 1-2 m/s.

6.2.2 DIGESTATE SOLID/LIQUID SEPARATION

The general scheme of the separation process was similar on each farm (Figure 6.2). The raw digestate (RD) was sent to the first step (PU1) of solid–liquid separation, consisting of a screw press, and the obtained liquid fraction (LF1) was sent to a tank from which it was pumped to the second separator. The second separator (PU2) consisted of a vibrating screen (IT-S1 and IT-S3) or a microfilter (IT-S2), and the liquid fraction (LF2) was collected in a second tank prior to being injected into the fertigation line. Tank 2 had a different volume on each farm, ranging between 7.5 m^3 (farm IT-S3) and 38 m^3 (farm IT-S1), according to the need for storing treated digestate before its field use.

For PU1, screw press separators with different screen sizes were installed on the three farms: farm IT-S1, 700-900 μm (SEPCOM Horizontal, WAMGROUP SpA, Ponte Motta/Cavezzo, MO, Italy); farm IT-S3, 800 μm (SEPCOM Horizontal, WAMGROUP SpA, Italy) and farm IT-S2, 500 μm (SM260 Mini, Cri-Man SpA, Correggio, RE, Italy).

For PU2, a vibrating screen (Image 6.1 a) was installed on farms IT-S1 and IT-S3 (all Acquafert srl, Cicognolo, CR, Italy), coupled to a system that cleaned the screen at regular intervals using a solution of sulfuric acid (50% v/v). In contrast, a microfilter (MFT500, SEPCOM, WAMGROUP SpA, Italy) was used at farm IT-S2, that in 2019 was substituted by a vibrating screen (Image 6.1 b). In farm IT-S1 and IT-S3 equipped with a center pivot irrigation system, the sieve size mounted on the vibrating screen was 200 and 500 μm respectively, which was sufficient because the size of the center pivot nozzles was at least 2 mm. By comparison, on the IT-S2 farm equipped with driplines (Typhoon plus by Netafim) the microfilter guaranteed the filtering of particles larger than 50 μm. These values were considered sufficient with respect to the recommended filtration sizes of 130–200 μm for drippers in the driplines used, as suggested by the manufacturer.

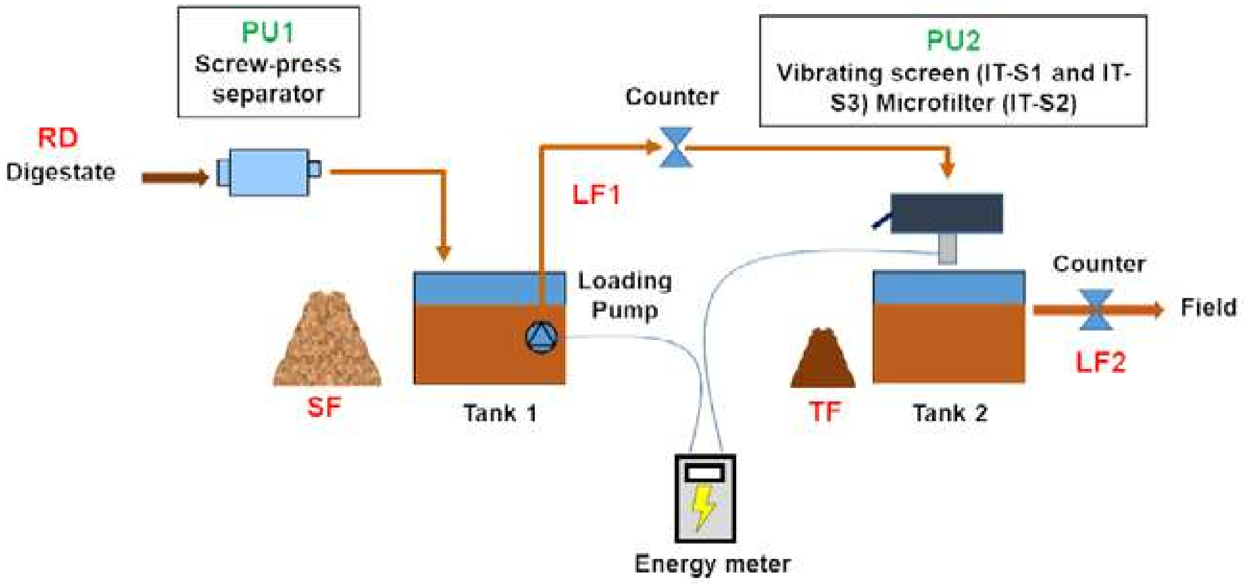

Figure 6.2. Flowchart of the solid-liquid separation systems on the farms in Lombardy (Italy).

The functioning of the separation systems was monitored at each fertigation event by recording digestate volumes and flow rates, manure characteristics, and electricity consumption. These data were used to evaluate system performance through the calculation of mass balances and separation efficiency indexes.

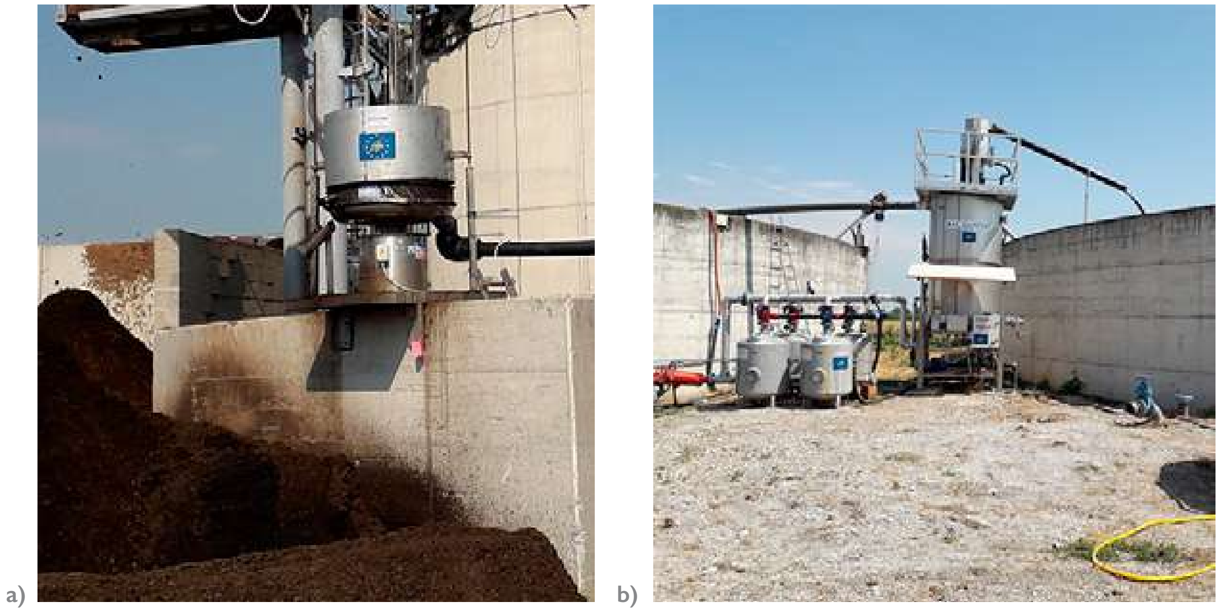
a) b)

Image 6.1. Vibrating screen (a) and microfilter (b) used for filtration of digestate in Lombardy (Italy).

The characteristics of the digestate that was injected in the irrigation season in each field and form each year is summarized in Table 6.3. After filtration, the concentrations of TAN and TKN in the digestate were still around or over 3.3 g/kg. The TKN content ranges from 4.5 to 6.1 g/kg and depends mainly on the feed of the anaerobic digester. The concentrations remained comparable to that of the digestates commonly used in the area, with a TAN/TKN ratio between 60% and 74%.

Table 6.4. Characteristics of the liquid fraction of the digestate after filtration in the demonstration sites in Italy. Mean values, standard deviations in brackets.

		TAN	TKN	pH	TS
Site	**Year**	g/kg	g/kg	kg N/ha	(% wb)
IT-S1	2018	3,6 (±0,5)	6,1 (±1,0)	8,0 (±0,1)	5,8 (±1,2)
	2019	3,5 (±0,1)	5,5 (±0,4)	8,2 (±0,1)	4,8 (±0,2)
IT-S2	2018	3,3 (±0,1)	4,5 (±0,1)	7,8 (±0,2)	3,9 (±0,2)
	2019	3,4 (±0,1)	4,9 (±0,2)	8,0 (±0,1)	4,3 (±0,2)
	2020	3,7 (±0,1)	5,1 (±0,1)	8,3 (±0,2)	4,4 (0,1)
IT-S3	2020	4,2 (±0,1)	6,1 (±0,4)	8,4 (±0,1)	4,8 (±0,3)

TAN: Total ammonium nitrogen; *TKN:* total Kjeldahl nitrogen; *TS:* Total solids; wb: wet basis.

According to the filtration strategies adopted, the filtered digestate showed values, comparable to those of the raw digestate, with a TS between 3.9% and 5.8%. The high content of TS after filtration is due to the increase of dissolved solids and fine solids after anaerobic digestion.

6.3 ENVIRONMENTAL MONITORING

Ammonia emissions

The data collected using ALPHA® samplers and processed with WindTrax enabled calculation of ammonia nitrogen emissions after pre-sowing applications and during fertigation. Although the doses of applied nitrogen were different between reference and fertigated fields and among the three years of testing, the positive effect of the innovative technique emerged when compared to the conventional methods practiced by farmers. The overall emissions in relation to the total nitrogen applied were lower in the fertigated fields than in the reference fields.

In IT-S1 (pivot irrigation system), ammonia emissions were monitored in 2018 and 2019. In both years, the emissions were lower when incorporation at base dressing and fertigation were used (Figure 6.3). In 2019, a very low amount of ammonia was emitted, probably due to the particular weather conditions in the days after application. The average emissions were 88 kg N-NH$_3$/ha for the reference field and 25 kg N-NH$_3$/ha for the fertigated field.

The results are also reflected in the percentage of total nitrogen emitted as ammonia with values of 14% and 5% for the reference and fertigated fields, respectively. It is interesting to note that the average reduction in emissions (64%) was almost constant between the two years, despite the huge difference in emissions between years within the same fertilization technique.

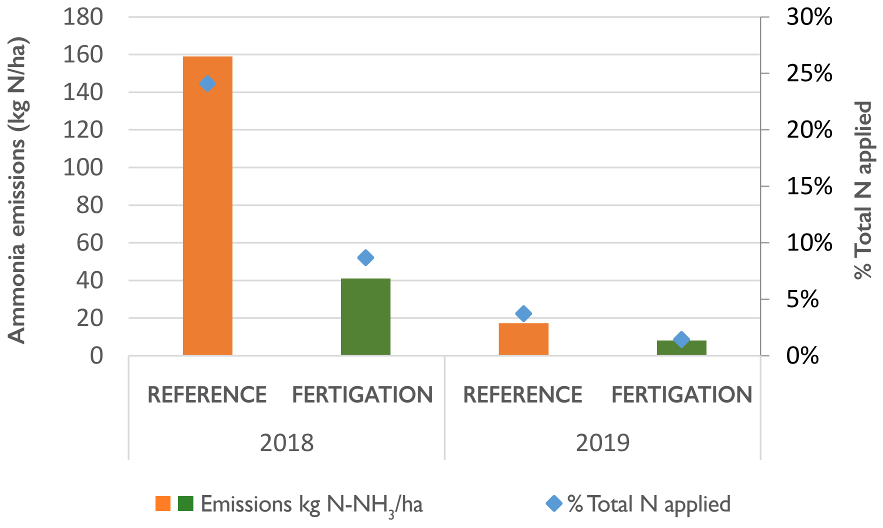

Figure 6.3. Ammonia emissions measured at Site IT-S1 in the reference field (in orange) and fertigated field (in green). Blue dots indicate the percentages of ammonia emitted relative to the total nitrogen applied.

For site IT-S2, the quantities of ammonia emitted from the reference and fertigated fields are reported in Figure 6.4. The reference field shows an average value of 59 kg N-NH$_3$/ha of ammonia released to the air over three years, while in the fertigated field, the combination of direct incorporation in base-dressing operations with fertigation reduced the ammonia emissions to an average of 12 kg N-NH$_3$/ha. The percentage of ammonia emitted relative to the total nitrogen applied was 9% on average for the reference fields and 3% for the fertigated fields. Thus, the reduction in ammonia emissions using incorporation at pre-sowing and fertigation can save 70% of the ammonia emissions on this farm.

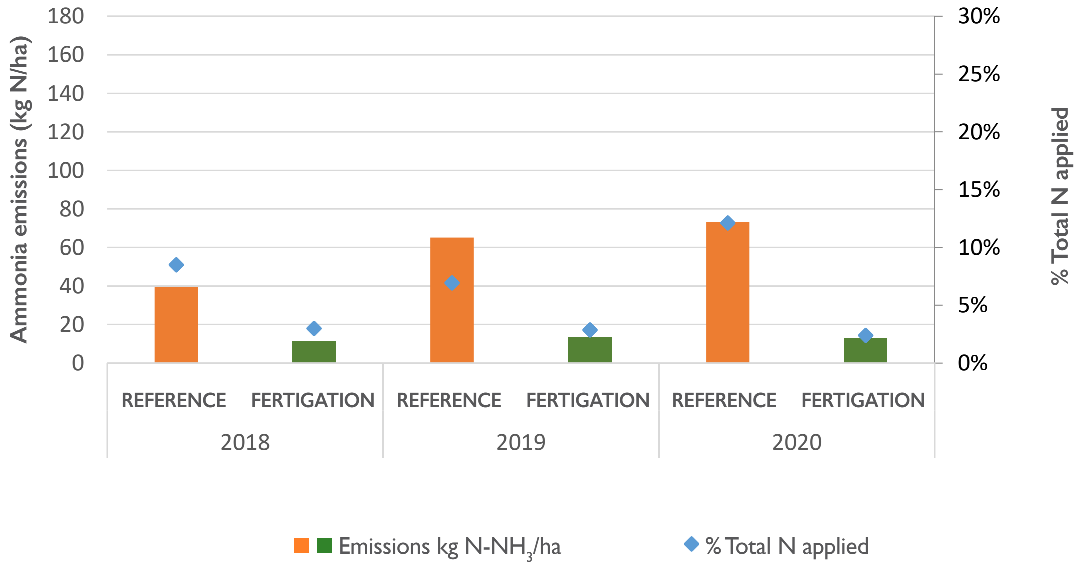

Figure 6.4. Ammonia emissions measured in the three years of monitoring at Site IT-S2 in the reference field (in orange) and fertigated field (in green). Blue dots indicate the percentages of ammonia emitted relative to the total nitrogen applied.

Finally, in IT-S3, the pre-sowing application of digestate was performed with shallow injection for both pivot reference and pivot-fertigated fields. Moreover, urea was also applied as side-dressing in the reference field. The absolute values of emissions were higher for the pivot-fertigated field due to the very high nitrogen dose applied. In fact, in terms of the percentage of nitrogen applied, emissions were similar in the fertigated field (Figure 6.5).

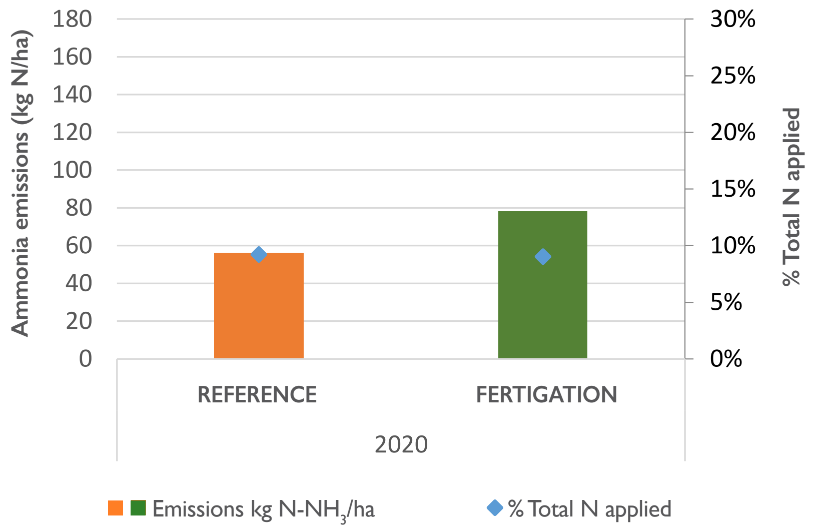

Figure 6.5. Ammonia emissions measured in the reference field (in orange) and fertigated field (in green) at Site IT-S3. Blue dots indicate the percentages of ammonia emitted relative to the total nitrogen applied.

From these results, it can be concluded that fertigation is a technique suitable for reducing ammonia emissions and that its effect can be enhanced by the use of a mitigation technique for base-dressing fertilisation.

Although suction cups were installed and monitored, in most cases, the soil was dry at 60 cm depth; therefore, it was not possible to obtain information about possible leaching. However, these results suggest that nitrates are maintained in the soil under these conditions and that eventual leaching might occur only when an intense rainfall event takes place.

6.4 AGRONOMIC MONITORING

In IT-S2, although there was variability among years and fields, yields in reference and fertigated fields were similar when averaged across the 3 years (Figure 6.6). This result is expected, as the high nitrogen doses applied by the farmer guaranteed crop growth, and the availability of nutrients was not a limiting factor.

The corresponding crop nitrogen uptake ranged from 165 to 198 kg/ha with an average of 183 kg/ha (198, 168 and 182 kg N/ha for the reference field and 165, 193 and 191 kg N/ha for the fertigated field in the three consecutive years).

Both the yields and the N uptake can be considered lower than the usual values for this crop in the area, but it must be considered that the maize was sown between the beginning of June and the beginning of July and that the growing season ranged from 93 to 125 days with an average of 113 days, shorter than usual.

In IT-S1, the yields were higher than those in IT-S2, especially in 2018 (Figure 6.7), although the growing season was slightly shorter (average 103 days). Additionally, at this site, the yields in the reference and fertigated fields were similar. Nitrogen crop uptake was 233 and 188 kg/ha for the reference field in 2018 and 2019 and 238 and 184 kg/ha, respectively, for the fertigated field.

In IT-S3, the yield in the reference field was 17.6 t of dry matter/ha, while that in the fertigated field was 15.6 t/ha, with corresponding nitrogen uptake values of 260 and 214 kg/ha, respectively. However, these differences might be attributed more to the field differences than to the application techniques.

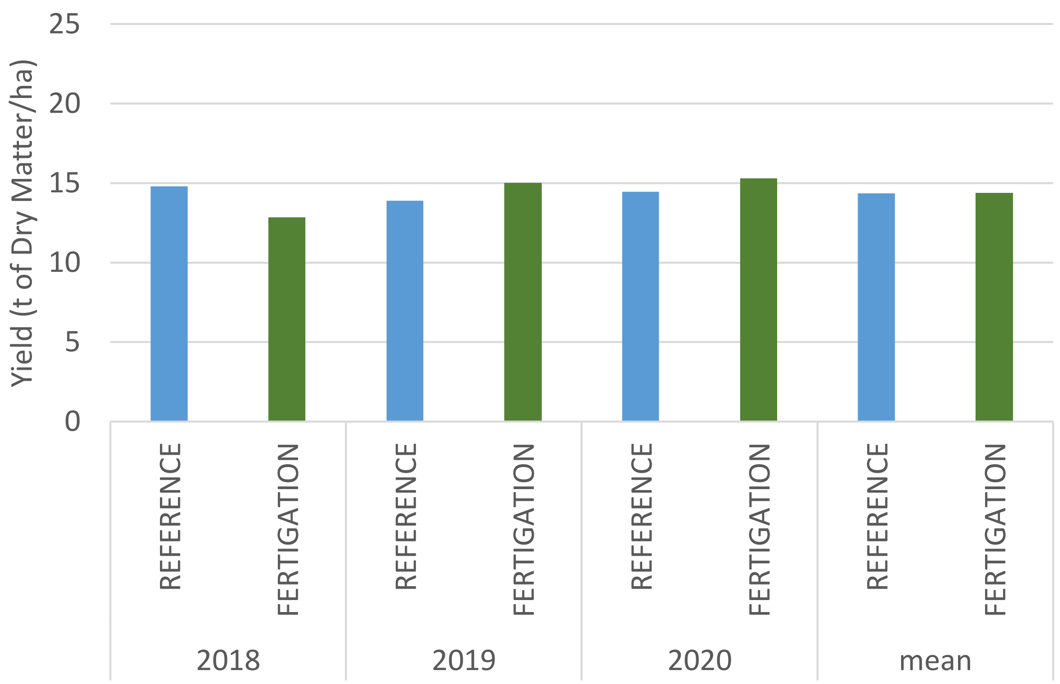

Figure 6.6. Maize (silage) yields obtained in the three years of monitoring in the drip reference (in blue) and drip-fertigated field (in green) at IT-S2.

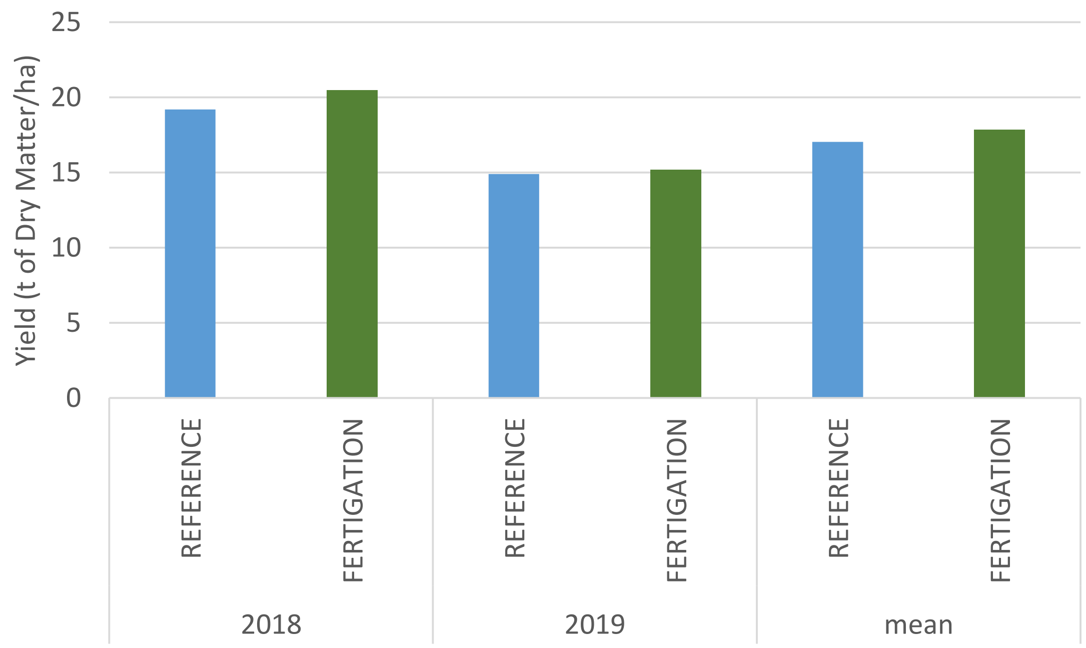

Figure 6.7. Maize (silage) yields obtained in the two years of monitoring in the reference (in blue) and fertigated (in green) fields at IT-S1.

Although a statistical comparison of NUE is outside the aim of this work, some indications can be obtained from our results. First, due to the relevant amount of nitrogen applied, the NUE values obtained are low. However, they are consistent with experience in the same area. Second, most of the differences in NUE are due to the variation in nitrogen application among fields. Due to operational constraints and difficulties in controlling the doses with the equipment used by the farmers, the total nitrogen applied varied greatly (Table 6.3). Therefore, the results obtained should only be considered a general indication of the achievement possible with fertigation.

Figures 6.8 and 6.9 report the NUE values at IT-S2 and IT-S1, respectively. In IT-S2, the NUE in the fertigation fields was slightly higher than that in the reference fields (average of 39% in the fertigated field and 30% in the reference field), but this average was affected by a very low NUE in 2019 for the reference field due to an overapplication of nitrogen. Additionally, at IT-S1, the average NUE was higher for the fertigated field but with contrasting results in the two years. Finally, at IT-S3, the NUE in the fertigated field was 25%, much lower than that in the reference field (43%), but in this case, 40% more nitrogen was applied in the fertigated field.

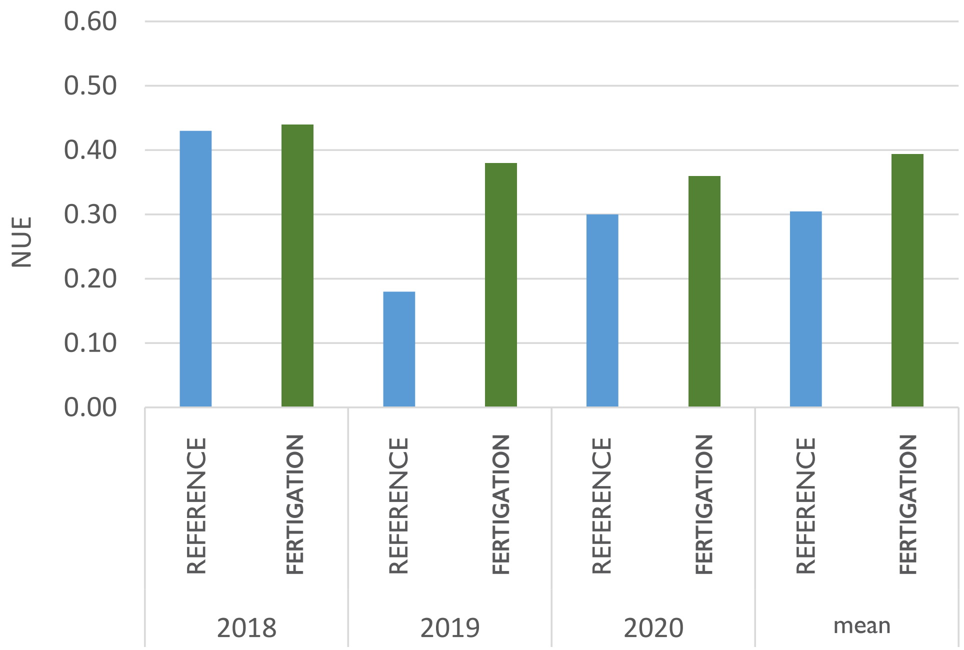

Figure 6.8. NUE calculated as the ratio of the nitrogen uptake to the nitrogen applied in the three years of monitoring in the reference (in blue) and fertigated (in green) fields at IT-S2.

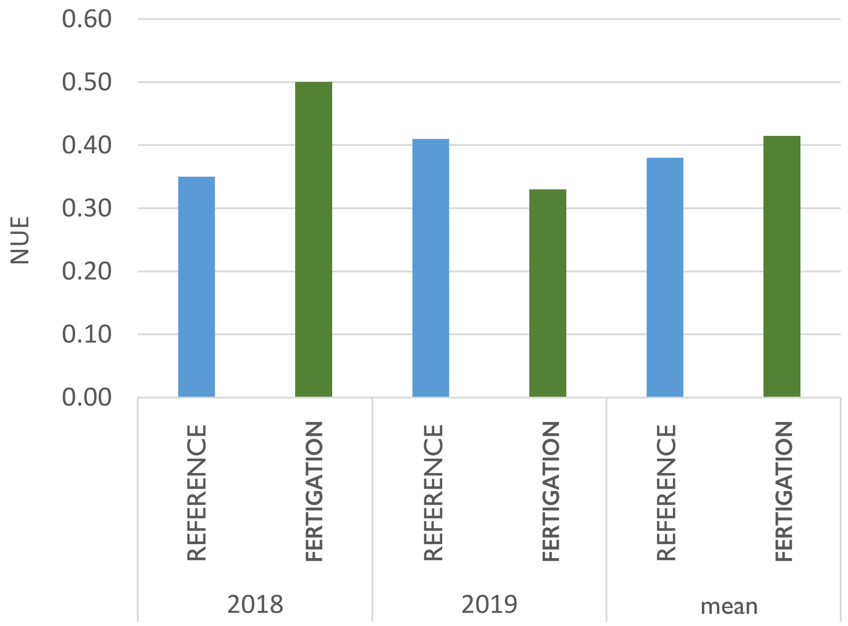

Figure 6.9. NUE calculated as the ratio of the nitrogen uptake to the nitrogen applied in the two years of monitoring in the reference (in blue) and fertigated (in green) fields at IT-S1.

6.5 LESSONS LEARNED

Some of the parameters estimated in the demonstration plots were also assessed on three other farms where the fertigation technique was replicated.

Drip irrigation was applied on two of the farms, while the third farm was the same one that was monitored for ammonia emissions in 2020. The main figures are reported in Table 6.4.

Tabla 6.4. Fertigation performed in the transference plots in Lombardy (Italy).

Site	Year	Area	Crop	N rate with fertigation	# Fertigation events
		ha		kg N/ha	
Drip 1	2019	2.0	maize (1st crop)	53	3
	2020	2.0	maize (2nd crop)	49	3
Drip 2	2019	2.5	maize (2nd crop)	27	2
	2020	2.5	maize (1st crop)	110	3*
Pivot	2019	30.0	maize (2nd crop)	101	3

*one event with mineral fertiliser

Image 6.2. Filtration system installed to supply the digestate to the drip irrigation in the Drip 1 farm in Lombardy(Italy).

The Drip 1 farm is located in Pavia Province, and the distance from the other farms was too high for transportation; therefore, a filtration system was installed (Image 6.2 and 6.4). After the screw press separator was installed on the farm, the liquid fraction was passed through a vibrating screen with a mesh size of 100 microns and then through a sand filter.

The transference field of the Drip 2 farm is located in the province of Bergamo, close to a centralised treatment plant collecting slurry from nearby livestock farms. The first year, the slurry was obtained from the treatment plant, but there were some residues of solids interfering with the correct functioning of the system; therefore, in 2020, the filtered digestate was transported from the IT-S2 farm with a truck (Image 6.3). The filtered digestate was unloaded in containers to supply the injection pump installed in the field. Additionally, in this case, however, some suspended solids were still present in the storage; therefore, the fertigation was limited in terms of digestate volume, and some mineral fertiliser was distributed with the drip system to supply the required dose of nitrogen.

Image 6.3. The filtered digestate in 2020 was transported by truck from IT-S2 to Drip 2 transference field in Lombardy (Italy).

Image 6.4. The storage and pumping station for the Drip 1 transference field in Lombardy (Italy).

In all the farms and years, the yields obtained with fertigation were similar and highlighted the possibility of increasing the nitrogen efficiency with this technique.

The results obtained in the demonstration fields and confirmed in the transference fields highlight the significant reduction in ammonia emissions when fertigation is introduced, without decreased yields. Compared to the reference technique, the reductions were greater than 60% with pivot irrigation, and 90% reductions were achieved with subsurface drip irrigation.

It should be noted that this result derives from a combination of factors. In particular, if a quota of manure is maintained to be distributed in pre-sowing, the distribution technique used becomes fundamental for the overall result. From Figure 6.10, it can be seen how distributing 50% of the effluent pre-sowing with slurry tank and splash plate and the other 50% with fertigation can mitigate ammonia emissions, but the obtainable reductions compared to the reference technique are relatively low (37-40%).

Incorporating the entire dose of effluent in pre-sowing was effective, allowing emissions to be reduced by 60-67%. This range was lower than expected, probably due to the high dose applied at a single time and the incomplete ground coverage after incorporation. It must also be taken into account that the incorporation was carried out in June and therefore under high temperature conditions, enhancing ammonia emissions.

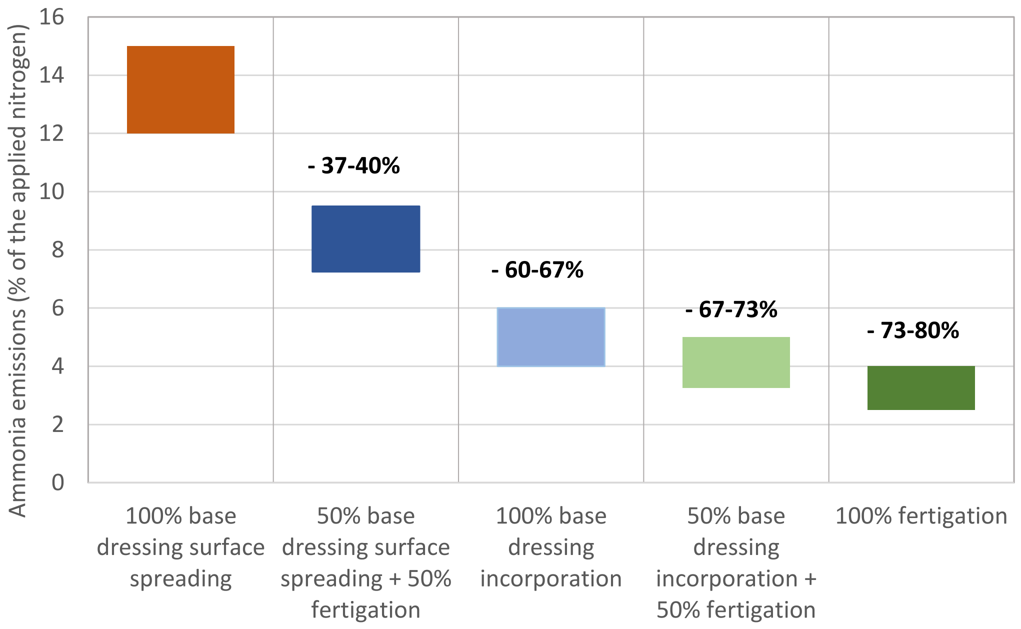

Figure 6.10. Range of ammonia emissions expected with different application techniques and sharing of the application between base-dressing and side-dressing.

The greatest containment of emissions is achieved by exclusive use of fertigation to distribute the effluent. However, under Italian conditions, this solution is not always feasible, especially when maize is sown after a winter cereal, with an irrigation season of limited duration. In any case, even distributing 50% of the nitrogen in pre-sowing with adequate techniques and 50% with fertigation allows ammonia emission reduction of 70% in comparison to the reference system.

Considering the possibility of increasing nitrogen efficiency, expressed as the ratio between nitrogen removed and supplied to the crop (NUE), the fertigation technique confirmed the expectations, although in Italy, the increase in the NUE with respect to the reference system did not exceed 50%. This is for two reasons. The first concerns the overall excessive supply of nitrogen to the crop, based on normal agricultural practice, which was not fully utilized by the crop. A second reason concerns the composition of the digestate used in the tests carried out. The quantity of organic nitrogen present in this product was 30-35%, even after the filtration system was used for fertigation. This implies that this share of nitrogen must first be mineralized in the soil before being used by the plants. The mineralization process occurs slowly; therefore, this nitrogen share is not completely used during the short growing season. It has been estimated that, using an appropriate dose of nutrients and the correct application technique for base-dressing combined with fertigation at side-dressing, the NUE can exceed that of the reference system by 40%.

In any case, the solution to be adopted on an individual farm must be designed in relation to the characteristics of the product to be used (slurry or digestate) and the irrigation system used (drip or low-pressure sprinkling).

Special attention must be paid to the transportation of filtered digestate or slurry, as the operation can contaminate the product and, in some cases, cause the aggregation of solids, which can complicate the subsequent distribution, especially when drip irrigation is used.

To obtain the desired agronomic and environmental results, fertilization management must be careful and carried out in the appropriate manner to make the best use of the specific equipment for this operation.

The areas involved can vary from 2 ha to 10 ha in a single block or be sectorized for dripline fertigation and may extend to 60 ha for pivot fertigation. When sizing a digestate separation system to be used with fertigation, the priority is to ensure the necessary removal of solids to avoid obstructions in the irrigation system. Analysing the characteristics of the separation systems tested in the project, it was possible to note the following:

- the dripline requires more thorough filtration; in fact, the drippers allow the passage of particles smaller than 200 µm.
- the pivot, featuring a nozzle size of 2 mm, allows filtration with a larger mesh, up to 500 µm.

By adopting this type of separation, it has been observed that high contents of solids remain in the liquid fraction but always with particle sizes below the obstruction limits of the drippers and nozzles. Another aspect to consider to carry out efficient fertigation is the maintenance of an adequate dilution ratio compatible with cultivation needs. The dilution ratio can vary from 3% to 10% for fertigation with a drip line and from 5% to 20% for fertigation with a pivot.

In the demonstration fields, the practices adopted have demonstrated managerial advantages in relation to:

- the improvement of timely irrigation, particularly in small plots
- the punctual distribution of water and nutrients during the vegetative period
- the effective enhancement of the digestate and less use of chemical fertiliser
- the possibility of distributing digestate over a longer period of time

On the other hand, some aspects can be considered weaknesses such as:

- the requirement for dedicated human resources
- the need to provide for the automation of operations to make the technique more efficient

It is therefore evident how the virtuous management of digestate coupled with correct management of the water resource, in addition to reducing ammonia emissions, can contribute to the improvement of the agronomic conditions typical of the Po Valley.

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7

A LIFE CYCLE ASSESSMENT OF FERTIGATION IN MEDITERRANEAN AREAS

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7.1 INTRODUCTION AND METHODOLOGY

Life cycle assessment (LCA) has been used to estimate the environmental impacts of maize production systems, following the ISO 14040/44 methodology (ISO 14040, 2006) and the EPD guidelines developed for "Arable Crops" (Environdec, 2014).

7.1.1 GOAL OF THE STUDY AND SELECTION OF FUNCTIONAL UNIT

The goal of this study is to evaluate the environmental impact of maize cultivation considering different irrigation and fertigation techniques. For this purpose, maize cultivation trials were carried out in northern Italy (Lombardy region, provinces of Cremona and Mantua) and in northeastern Spain (Aragon, in the regions of Cinco Villas and La Litera).

A functional unit (FU) is defined as a quantified performance of a product system to be used as a reference unit in an LCA (ISO 14040, 2006). Although different functional units, such as the area of the plot, can be used, mass-based FU is widely used for LCA of agricultural systems (Fedele et al., 2014; Notarnicola et al., 2015).

In this study, two different FUs were selected:

> - 1 ton of dry matter of chopped maize biomass for the Italian scenarios where cultivation is dedicated to the production of silage maize.
> - 1 ton of maize grain (at commercial moisture) for the Spanish scenarios in which the cultivation purpose is the production of grain.

Image 7.1. Pivot irrigation system used for fertigation with the liquid fraction of digestate in Lombardy (Italy).

7.1.2 DESCRIPTION OF CULTIVATION PRACTICES

Standardized scenarios were constructed to represent the usual practices in Aragon (Spain) and Lombardy (Italy) and do not correspond to any specific demonstrative field. Two different fertigation techniques, pivot (Image 7.1) and drip irrigation (Image 7.2), were tested in each area, and seven scenarios were analysed (Table 7.1):

- Four scenarios in Italy: one reference scenario (IT-PR) with pivot irrigation, one fertigation scenario with pivot irrigation and fertigation (IT-PF) and a reference with drip irrigation (IT-DR) compared to a drip-irrigated fertigation scenario (IT-DF).
- Three scenarios in Spain: one reference (ES-R) and two fertigation scenarios in which irrigation took place with a pivot and fertigation (ES-PF) or with drip irrigation and fertigation (ES-DF). In these three scenarios, water was collectively managed by an irrigation community.

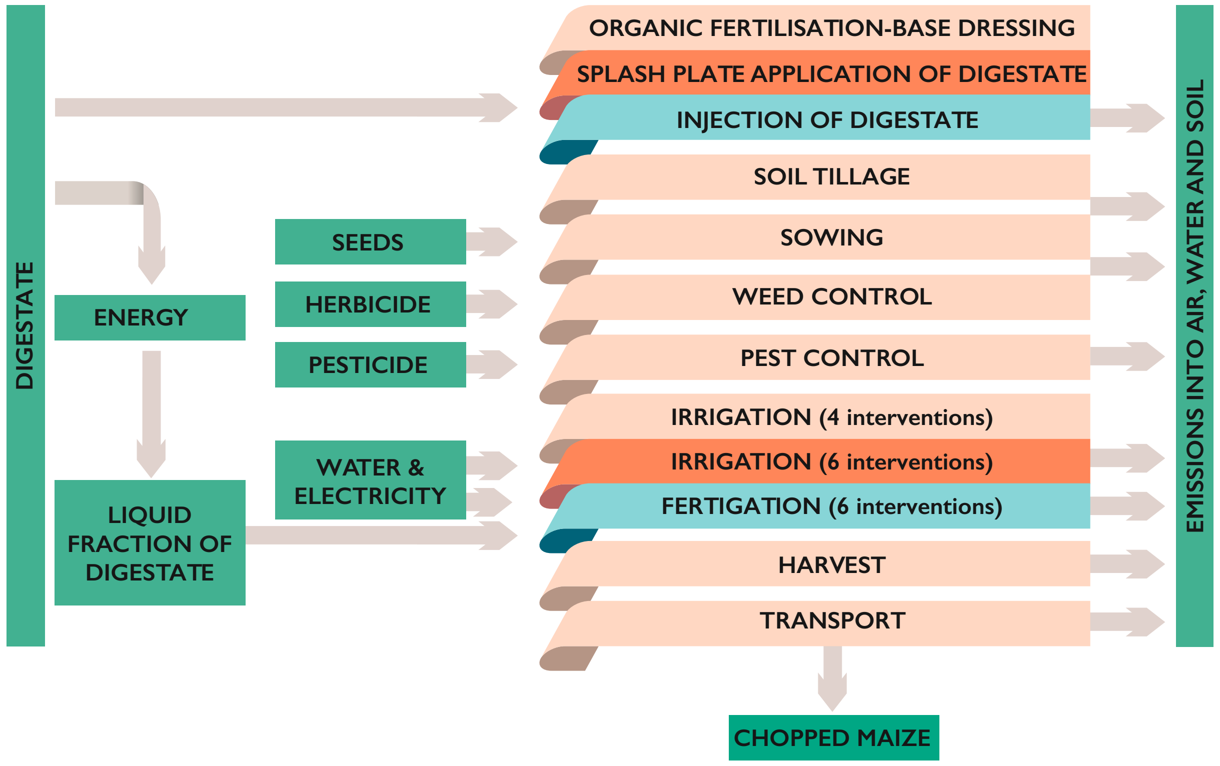
Table 7.1. Agricultural scenarios considered in LCA of the LIFE ARIMEDA project.

Country	Pre-sowing fertilisation	Side-dressing	Irrigation system	Fertigation	Scenario
Italy	Digestate/surface distribution		Pivot	No	IT-PR
	Digestate/injection	Liquid fraction Digestate/fertigation	Pivot	Yes	IT-PF
	Digestate/surface distribution		Drip irrigation	No	IT-DR
	Digestate/injection	Liquid fraction Digestate/fertigation	Drip irrigation	Yes	IT-DF
Spain	Pig slurry/surface distribution	Synthetic N- surface distribution	Centralized irrigation system	No	ES-R
	No N fertilization, only P	Fertigation with the liquid fraction of pig slurry	Pivot centralized irrigation system	Yes	ES-PF
	No N fertilization, only P	Fertigation with the liquid fraction of pig slurry	Subsurface drip irrigation centralized irrigation system	Yes	ES-DF

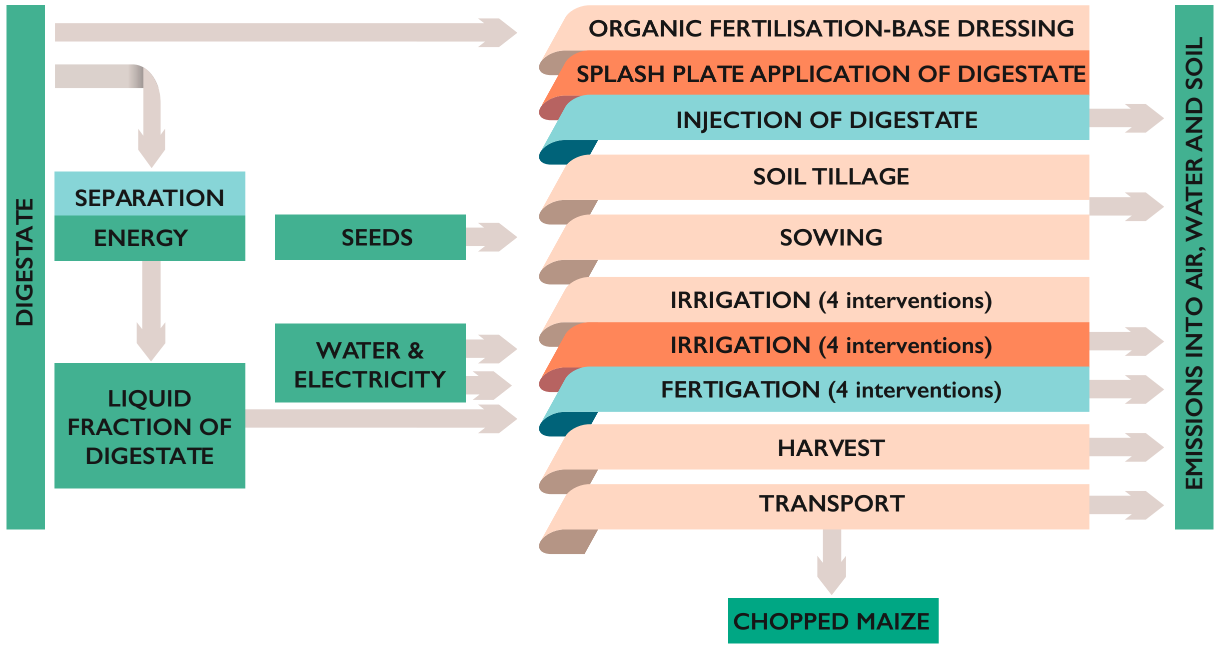
7.1.3 SYSTEM BOUNDARY

A "from cradle to farm gate" perspective was adopted. The system boundaries include all the operations from the application of organic fertiliser and soil tillage until the harvesting and transport of the harvested biomass, chopped maize in Italy (Figure 7.1) and maize grain in Spain (Figure 7.2). The following activities were included: raw material extraction (e.g., fossil fuels), manufacture of agricultural inputs (e.g., seeds, fertilisers, pesticides and agricultural machines), production of energy (e.g., electricity used for irrigation), use of agricultural inputs (fertiliser emissions, pesticide emissions, diesel fuel emissions and tire abrasion emissions), maintenance and final disposal of machines and supply of inputs to the farm.

FERTIGATION WITH PIVOT



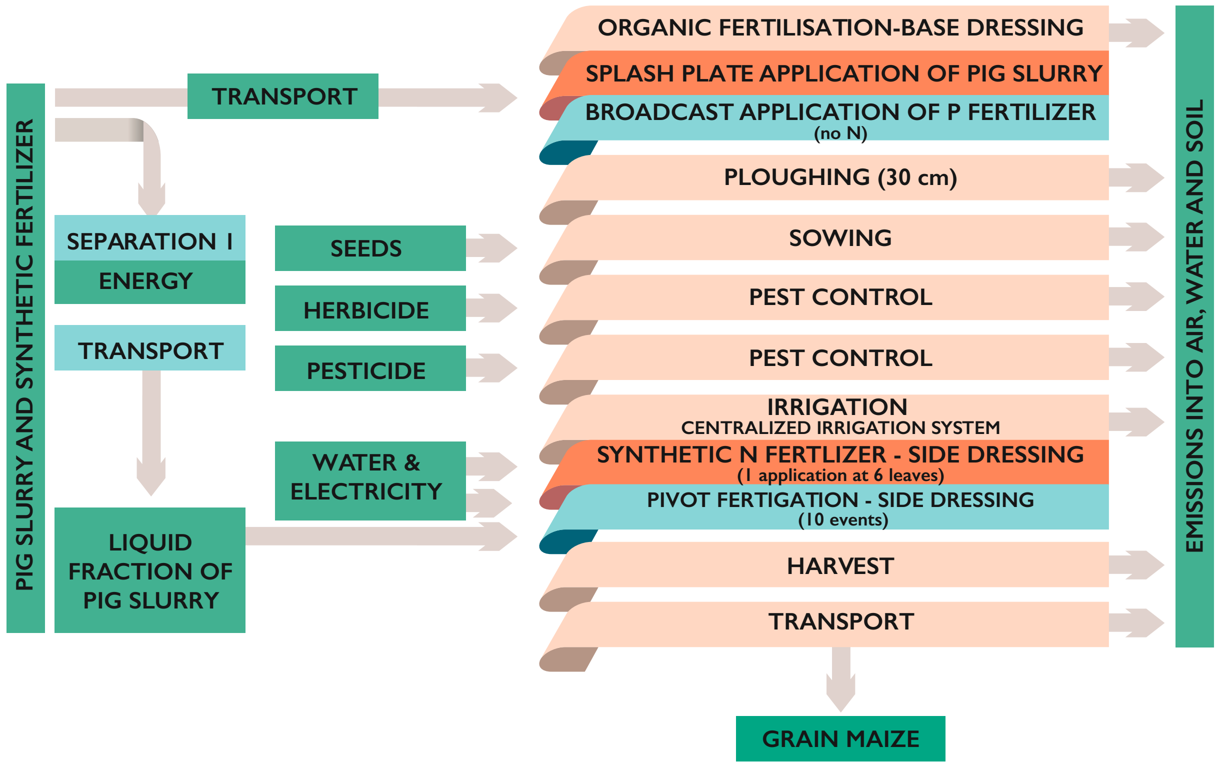
FERTIGATION WITH DRIP IRRIGATION



🟩 Inputs/outputs shared by the two scenarios
▨ Operations in common
🟧 Specific operations for the reference scenarios
🟦 Specific operations for the fertigation scenarios

Figure 7.1. System boundary for the two cultivation practices in Italy.

FERTIGATION WITH PIVOT



FERTIGATION WITH SUBSURFACE DRIP IRRIGATION

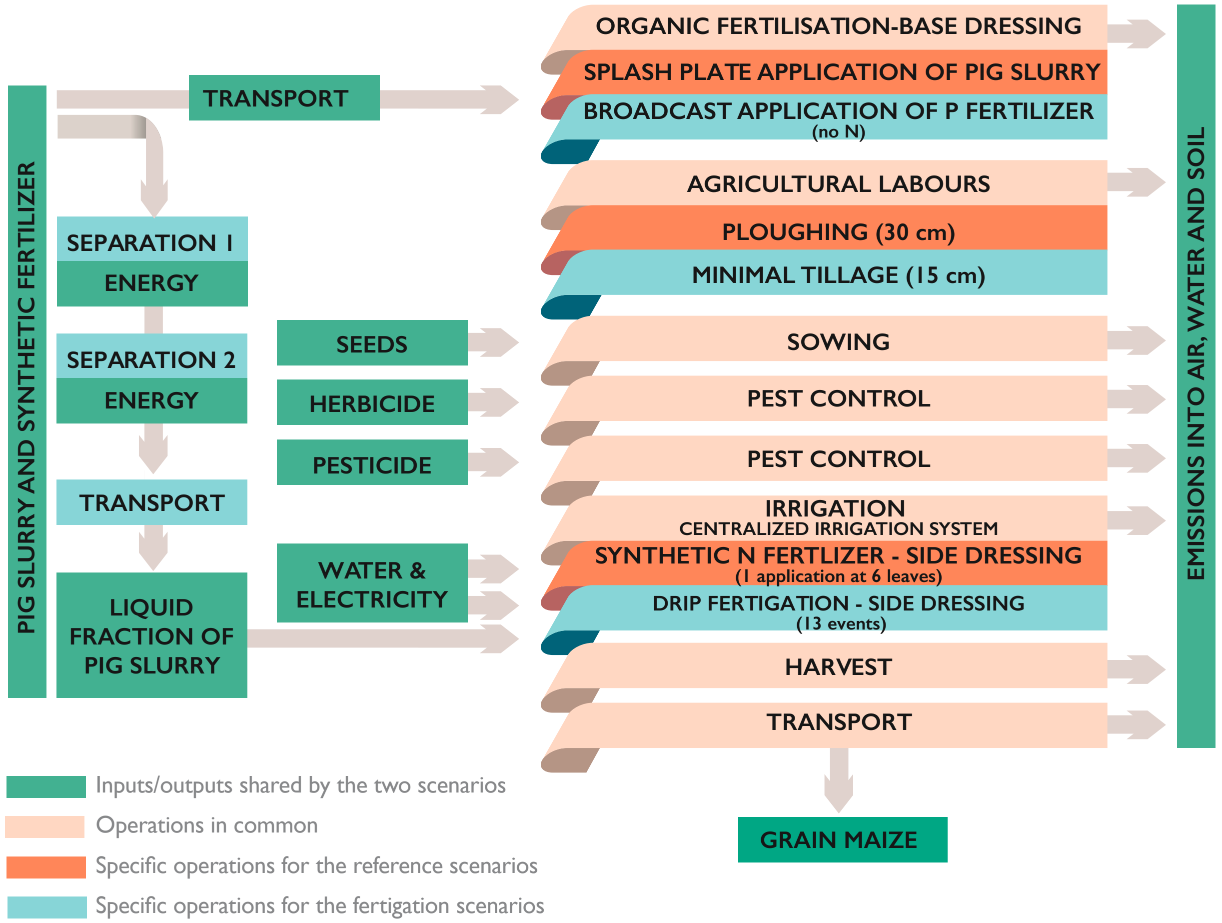


Figure 7.2. System boundary for the two cultivation practices in Spain.

Regarding the treatment of organic fertilisers (digestate in Italy and pig slurry in Spain), in addition to the electricity consumed, the materials needed for prototype manufacturing were taken into account. Finally, no environmental load was considered for the organic fertiliser used because it is a waste product of livestock activity.

Considering that the goal of this LCA is comparative (i.e., to assess the impact of variation due to the different techniques – irrigation vs. fertigation), the impacts of pivot and drip system manufacturing were not included. This exclusion slightly affects the absolute results, but because the use of pivots and drip irrigation is the same in the reference and fertigation scenarios, it does not influence the relative comparison or the general conclusions.

It was assumed that in the two study regions, cereal crops have been grown for many years (> 30 years). Consequently, the soil carbon content was supposed to be in equilibrium, and therefore, no changes in soil organic carbon were considered (Environdec, 2014).

7.1.4 INVENTORY DATA COLLECTION

The Life Cycle Analysis Inventory (LCAI) was built using both primary and secondary data. Primary data are directly collected by surveys, field measurements and farmer interviews, while secondary data are estimated using emission models or retrieved from the literature and/or databases.

Primary data about the cultivation techniques, the sequences of the field operations, and the amounts of the various production factors used (e.g., seeds, fuels, fertilisers, pesticides, electricity) were collected during the different field trials. Information on the machinery (tractors, operating machines and combine harvesters), such as mass, power, working time and working capacity, was retrieved from surveys at the farms.

Concerning the emissions related to fertilization, the emissions of NH_3 were measured by passive samplers (CEH ALPHA® samplers) and evaluated with WindTrax software, as reported in Chapter 4. For the Italian scenarios, the emissions considered were 3%, 5% and 12%, while those for the Spanish scenarios were 3%, 8% and 25% of the amounts of N applied for the drip fertigation, pivot fertigation and reference scenarios, respectively. Emissions of other N compounds (N_2O, NO_3^-) were assessed according to the model proposed by Brentrup et al. (2000). This model is based on the nitrogen balance between (i) supply from the application of fertilisers, N released from crop residue mineralisation, and atmospheric N deposition; and (ii) N removal related to the nitrogen content in the harvested biomass. NO_3^-) leaching was assessed considering soil characteristics, rainfall and the nitrogen available in the soil after ammonia volatilization, denitrification and crop removal.

Phosphate emissions were calculated following Prahsun (2006) and Nemecek and Kägi (2007); in more detail, two different phosphorus emissions into water were considered:

- leaching into groundwater assessed using a factor of 0.070 kg P ·ha^{1} ·year^{-1}
- runoff to surface water evaluated considering 0.175 kg P ·ha^{-1} ·year^{1} as the emission factor

Due to a lack of data on the fraction of soil eroded, phosphate emissions through erosion to surface waters were not included.

The emissions of active ingredients related to the application of pesticides were considered according to the PCR for arable crops (Environdec, 2014) (100% released into the soil).

Background data about the production of seeds, diesel fuel, fertilisers, pesticides, tractors and agricultural machines were retrieved from Ecoinvent® Database v.3.6.

7.1.5 LIFE CYCLE IMPACT ASSESSMENT (LCIA)

The environmental impacts were estimated using the composite method recommended by the International Reference Life Cycle Data System (ILCD) (Wolf et al., 2012). The following impact categories were considered: climate change (CC), ozone depletion (OD), particulate matter (PM), human toxicity with carcinogenic effects (HTc), human toxicity with no carcinogenic effects (HTnoc), photochemical ozone formation (POF), terrestrial acidification (TA), terrestrial eutrophication (TE), freshwater eutrophication (FE), marine eutrophication (ME), freshwater ecotoxicity (FEx), and mineral and fossil resource depletion (MFRD).

7.2 RESULTS

7.2.1 LIFE CYCLE ANALYSIS OF FERTIGATION WITH DIGESTATE IN ITALY

The contribution analysis for the Italian scenarios is reported in Table 7.2. The differences in impacts between the reference scenarios and the fertigation scenarios are presented in Figure 7.3.

The analysis of the contributions shows similar trends among all the scenarios evaluated even when there are some differences between the scenarios. In particular, the main difference involves the presence of the separators in the fertigated pivot (IT-PF) and drip scenarios (IT-DF). The manufacture of the separators mainly affects human toxicity through a carcinogenic effect (HTc) with 16-19% of the total impact, freshwater ecotoxicity (FEx) with 3 to 13% of the total impact and mineral and fossil resource depletion with 6-8% of the total impact.

In addition, with regard to freshwater ecotoxicity (FEx) in pivot systems (IT-PR and IT-PF), pesticide-derived emissions represent by far the main share of the impact, ranging between 81-78%, while in drip irrigation (IT-DR and IT-DF), the main contributors to the FEx impact category are related to irrigation/fertigation (i.e., electricity, pumps and separators). In fact, in drip irrigation, the manufacturing of the irrigation pump used for drip irrigation plays a relevant role in FEx (43-35%) and human toxicity with carcinogenic effects (approximately 9%).

Table 7.2. Absolute environmental impacts for the Italian scenarios (expressed for 1 ton of dry biomass).

Impact category	Units	IT-PR	IT-PF	IT-DR	IT-DF
Climate change (CC)	kg CO_2 eq	201.0	171.9	219.6	194.1
Ozone depletion (OD)	kg CFC-11	9.11×10^{-6}	9.44×10^{-6}	1.10×10^{-5}	1.14×10^{-5}
Human toxicity, non-cancer effects (HT-noc)	CTUh	7.43×10^{-5}	7.55×10^{-5}	5.88×10^{-5}	5.91×10^{-5}
Human toxicity, cancer effects (HT-c)	CTUh	2.40×10^{-6}	2.88×10^{-6}	3.15×10^{-6}	3.90×10^{-6}
Particulate matter (PM)	kg PM2.5	0.297	0.111	0.299	0.081
Photochemical ozone formation (POF)	kg NMVOC eq	0.492	0.494	0.477	0.477
Acidification (TA)	molc H^+ eq	12.49	4.04	12.53	2.56
Terrestrial eutrophication (TE)	molc N eq	55.42	17.62	55.40	10.82
Freshwater eutrophication (FE)	g P eq	42.12	42.74	49.95	50.94
Marine eutrophication (ME)	kg N eq	10.96	5.98	10.95	6.38
Freshwater ecotoxicity (FEx)	CTUe	3626	3811	1152	1409
Mineral and fossil resource depletion (MFRD)	g Sb eq	1.50	1.72	1.54	1.80

CFC: Chlorofluorocarbons; **CTUh:** Comparative Toxic Unit for human; **PM2.5:** Particulate matter (<2.5 μm); **NMVOC:** Non-methane volatile organic compounds; **CTUe:** Comparative toxic unit for aquatic ecotoxicity.

In addition, the contributions analysis shows that:

> • The mechanisation of field operations is responsible for the main share of the ozone depletion (OD) environmental impact. The impact of pivots (IT-PR, IT-PF) contributes approximately 74%, while the impact is less in drip irrigation at 43% and 41% for IT-DR and IT-DF, respectively. Field operations are also the main hotspots in human toxicity with no carcinogenic effect (over 90% in pivot scenarios and 81-83% in drip scenarios), photochemical ozone formation (approximately 90% in pivots, approximately 76-78% in drip irrigation), and mineral and fossil resource depletion (86-83% in pivot scenarios and 79-73% in drip scenarios). Finally, field operations are also relevant in human toxicity with carcinogenic effects (69-56% in pivots and 42-33% in drip scenarios).
>
> • The consumption of electricity, in general, exerts greater impacts in drip irrigation (both IT-DR and IT-DF) than in pivot irrigation. In pivot scenarios (IT-PF and IT-PR),

it never exceeds 15% in any of the evaluated categories except for ozone depletion (approximately 20% in both scenarios), while in drip irrigation (IT-DR and IT-DF), it is the main factor affecting ozone depletion (56-58%) and is relevant in human toxicity with carcinogenic effects (47-40%), freshwater eutrophication (approximately 25% for both scenarios), freshwater ecotoxicity (33-29%) and climate change (22-23%).

- For all the scenarios, the emissions of N and P compounds are the main factors responsible for climate change (approximately 60-70%), mainly due to the emission of nitrous oxide; particulate matter (from 60 to 90%); terrestrial acidification (80-96%); terrestrial eutrophication (83-96%); and freshwater eutrophication (78-65%), mainly due to ammonia emissions. Finally, marine eutrophication (not less than 95%) was mainly associated with nitrate leaching. Although these emissions are mainly responsible for particulate matter, terrestrial acidification and freshwater eutrophication in both the reference and fertigation scenarios, in the fertigation scenarios, the reduction in ammonia emissions related to the adoption of fertigation can be realised with a lower relative contribution.

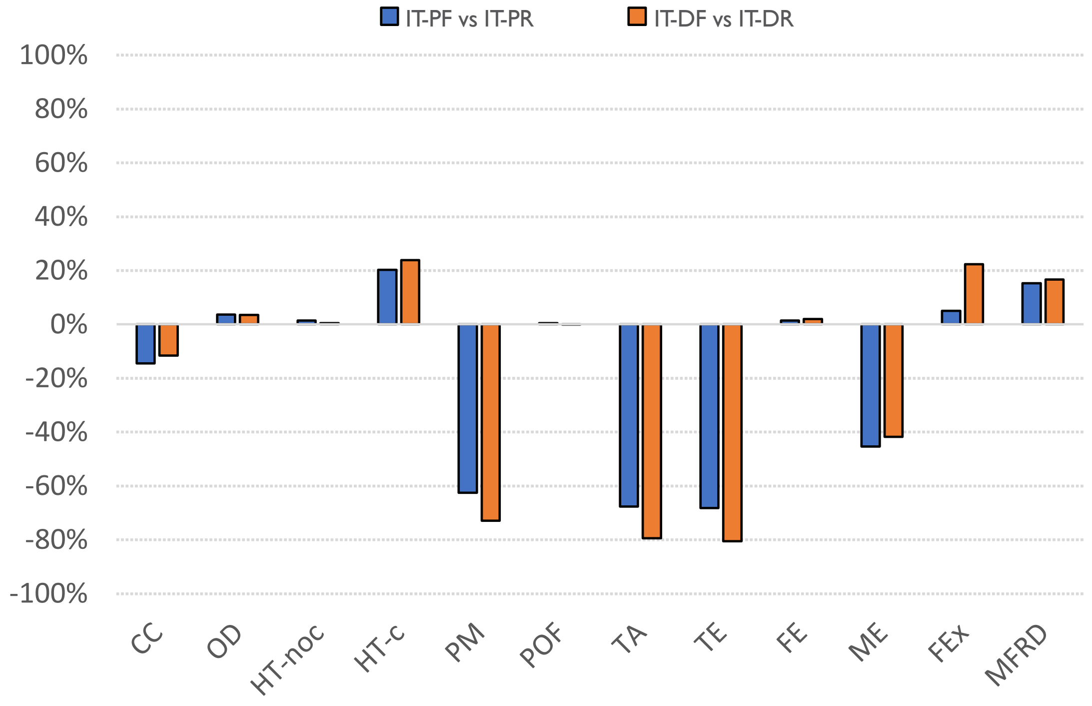


Figure 7.3. Differences in impacts between fertigation and reference scenarios with digestate in Italy.

Comparing the reference scenario with the corresponding fertigation scenario, the results of the comparison are not unequivocal: there is not a best scenario that outperforms the others in all the evaluated impact categories (Figure 7.3). However, the effects of fertigation in the various impact categories evaluated can be highlighted. For pivot systems, the fertigation scenario (IT-PF) performs better than the reference scenario (IT-PR) for 5 of the 12 evaluated impact categories. Higher impact reductions are achieved for the impact categories most affected by ammonia emissions (particulate matter, 62.5%; terrestrial acidification, 67.7%; and terrestrial eutrophication, 68.8%). For the remaining 7 impact categories, there are increases in impacts ranging from 0.5 to 20%, and higher impact increments occur for those impacts where the role of the separator and electricity for fertigation is most relevant (human toxicity with carcinogenic effects and mineral and fossil resource depletion). Similar conclusions can be drawn by comparing IT-DR and IT-DP except for freshwater ecotoxicity, where the increase in impact related to the use of the separator in the adoption of fertigation is higher. However, it should be noted that this is a relative value, and the absolute impact increments of the two scenarios are similar.

7.2.2 LIFE CYCLE ANALYSIS OF FERTIGATION WITH SLURRY IN SPAIN

The Spanish scenarios are compared in Figure 7.4. The contribution analysis shows results similar to those for the Italian scenarios. In particular, emission of N and P compounds is the main factor responsible in all the scenarios for particulate matter, terrestrial acidification, terrestrial eutrophication, freshwater eutrophication (due to ammonia emissions), marine eutrophication (due to nitrate leaching) and climate change (due to nitrous oxide). The contribution of ammonia emissions is higher in the reference scenario and decreases in the two fertigation scenarios as a result of the application of fertigation. The shares of the impacts related to the manufacturing of the separator exceed 10% for three impact categories in the case of pivot irrigation (human

Image 7.2. Drip irrigation system used for fertigation with the liquid fraction of pig slurry in Cinco Villas (Aragon, Spain).

toxicity with carcinogenic effects, freshwater ecotoxicity and mineral and fossil resource depletion) and for five (toxicity related impact categories, PM and MFRD) in the case of drip irrigation.

The contribution of the separator, related to the material consumed for its manufacturing, is higher in the ES-DF, where drip irrigation is used for irrigation and fertigation. This higher contribution is due to the need for two separators working sequentially for fertigation in drip irrigation.

The two fertigation scenarios allow a better adjustment of the amount of nitrogen applied and the replacement of N synthetic fertilisers that leads to main benefits in climate change, human toxicity with carcinogenic effects, freshwater ecotoxicity, and mineral and fossil resource depletion, which are those impact categories where the relative impacts due to the N fertiliser consumption are higher (13.7%, 14.6%, 30.4% and 14.9%, respectively).

Regarding the relative comparisons among the different scenarios, it can be stressed that:

- for 8 of the 12 evaluated impact categories, the reference scenario (ES-R) shows the highest impact. The impact reduction achieved by the fertigation scenarios ranged from 2-10% for photochemical ozone formation and climate change to 68-89% for those impacts deeply affected by ammonia emissions (i.e., particulate matter, terrestrial acidification and terrestrial eutrophication). For climate change, the impact reduction (approximately 10% for the two fertigation scenarios) is related to the lower emission of N_2O. For particulate matter, terrestrial acidification and terrestrial eutrophication, between the two fertigation scenarios, higher impact reductions are achieved for drip irrigation (ES-DF) because of a higher reduction in ammonia emissions than in pivot irrigation.

- for the remaining 4 impact categories (human toxicity with carcinogenic effects, freshwater eutrophication, freshwater ecotoxicity and mineral and fossil resource depletion), fertigation scenarios show higher effects than the reference scenario with greater impacts for drip fertigation in the 4 impact categories. The increases in impacts in fertigation scenarios over those in the reference scenario are considerable (> +70%) for human toxicity with carcinogenic effects, freshwater eutrophication and mineral and fossil resource depletion (almost completely related to the consumption of steel in the production of the separation and injection equipment used for fertigation). The increases are smaller (approximately 6.5%) for freshwater eutrophication.

- between the two fertigation scenarios, drip irrigation performs better for those impact categories (i.e., climate change, ozone depletion, human toxicity with no carcinogenic effects, particulate matter, terrestrial acidification and terrestrial eutrophication), where the reference (ES-R) is the worst scenario. In contrast, except for marine eutrophication, drip irrigation shows higher impacts than pivot irrigation for the remaining impact categories (human toxicity with carcinogenic effects, freshwater eutrophication, freshwater ecotoxicity and mineral and fossil resource depletion), where fertigation is the worst scenario.

The comparison between the reference scenario and the fertigation scenario highlights tradeoffs among the various impact categories evaluated. Fertigation solutions considerably improve the environmental performance due to the effects related to ammonia emissions and the replacement of mineral fertilisers but involve non-negligible increases in human toxicity with carcinogenic effects, freshwater ecotoxicity and mineral and fossil resource depletion.

Table 7.3. Absolute environmental impacts for the Spanish scenarios (expressed for 1 ton of maize grain at commercial moisture, 14%).

Impact category	Units	ES-R	ES-P	ES-D
Climate change (CC)	kg CO_2 eq	235.2	211.1	210.2
Ozone depletion (OD)	kg CFC-11	2.24×10^{-05}	1.71×10^{-05}	1.58×10^{-05}
Human toxicity, non-cancer effects (HT-noc)	CTUh	1.05×10^{-04}	9.46×10^{-05}	$9,32 \times 10^{-05}$
Human toxicity, cancer effects (HT-c)	CTUh	5.99×10^{-06}	1.07×10^{-05}	1.30×10^{-05}
Particulate matter (PM)	kg PM2.5	0.590	0.203	0.131
Photochemical ozone formation (POF)	kg NMVOC eq	0.609	0.601	0.557
Acidification (TA)	molc H^+	21.98	6.21	2.88
Terrestrial eutrophication (TE)	molc N eq	96.52	25.61	10.80
Freshwater eutrophication (FE)	g P eq	97.56	103.60	103.96
Marine eutrophication (ME)	kg N eq	2.56	1.37	2.06
Freshwater ecotoxicity (FEx)	CTUe	2366	4195	4199
Mineral and fossil resource depletion (MFRD)	g Sb eq	3.627	6.433	6.697

CFC: Chlorofluorocarbons; **CTUh:** Comparative Toxic Unit for human; **PM2.5:** Particulate matter (<2.5 μm); **NMVOC:** Non-methane volatile organic compounds; **CTUe:** Comparative toxic unit for aquatic ecotoxicity.

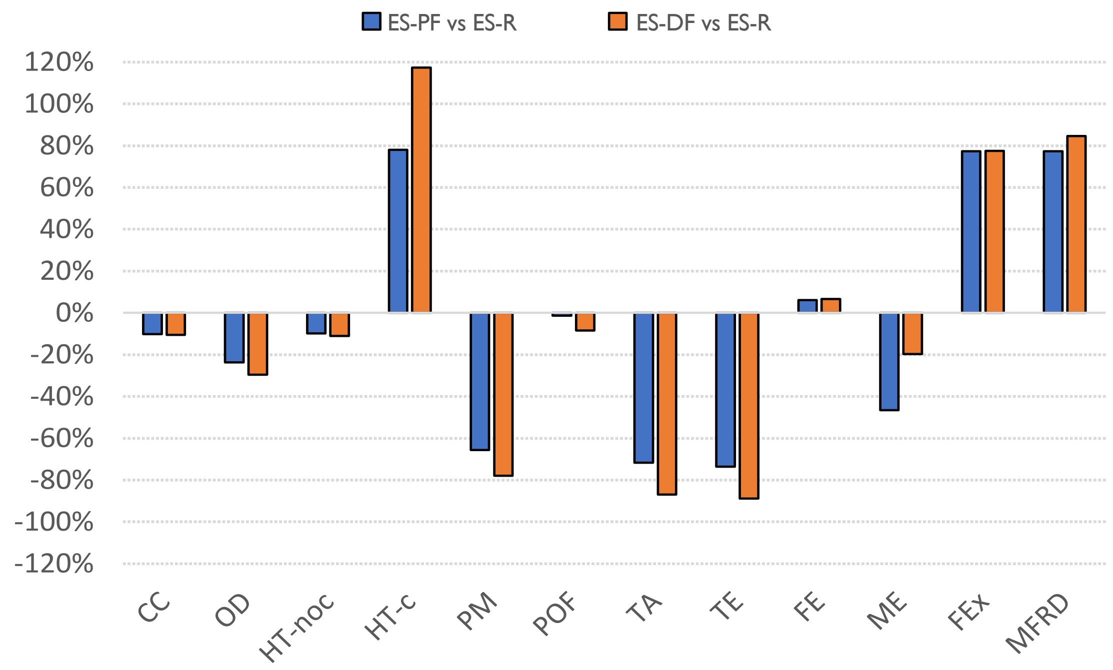


Figure 7.4. Differences in impacts between fertigation and reference scenarios with pig slurry in Spain.

7.3 CONCLUSIONS

Ammonia emissions are deeply affected by digestate and slurry application techniques; consequently, acidification, terrestrial eutrophication and particulate matter emissions are the impact categories that show greater differences between the two scenarios.

As expected, the reduction in ammonia losses entails a significant reduction in the environmental impacts associated with this pollutant. Although climate change (carbon footprint) is the best-known impact indicator, reductions in particulate formation, soil acidification and some of the different types of eutrophication are noteworthy for a context such as that of the Po Valley in Lombardy (Italy) and Ebro Valley in Aragon (Spain).

The outcomes of this LCA can be useful not only for technicians, farmers and their associations for the identification of the most effective fertigation solutions but also for policy-makers and regional officials involved in the definition of the CAP subsidies framework. Without reliable information about the environmental performance of various fertigation techniques, it will not be possible to drive the application of organic fertilisers towards more sustainable manure management.

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8

ECONOMIC ANALYSYS OF FERTIGATION IN DIFFERENT SCENARIOS

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8.1 INTRODUCTION

There is no market, or reference cost to quantify the economic value of digestate and slurry as fertilizer for the crops, neither for the products (solid fraction and liquid fraction) obtained after a solid-liquid separation process (Leip et al., 2019). The value of these products in the agricultural system depends on the casuistry at the local level, on supply and demand, on the presence of companies specialized in the management of these by-products as fertilizers, on the market prices of synthetic fertilizers and other sociological factors. The relation between livestock and agricultural farmers and the management model also has a decisive influence on the economic analysis. While in regions such as Aragon the specialization of the agricultural and livestock sectors has evolved towards industrialized type models favouring a disconnection between the two activities, the proliferation of anaerobic digestion plants in regions such as Lombardy has promoted a mixed model combining anaerobic digestion facilities with large agricultural areas linked to the application of the produced digestate as cropland fertilizer.


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The value of manure is usually estimated, comparatively when applied at agronomic doses, based on its ability to replace mineral fertilizers in terms of fertilizer units. Generally, only the N content is taken into account, less frequently the P and K contents are also considered, and rarely the content of other micronutrients or the contribution of organic matter to soil fertility. These types of benefits are difficult to translate into economic terms, as involve complex analytics and indirect effects on soil quality that are difficult to quantify, but that have repercussions on crop productivity.

The cost analysis of the fertigation of extensive crops (Image 8.1) with liquid fraction (LF) of slurry or digestate can be divided into three processes: solid-liquid separation on the farm, transportation of the LF (by pipes or with tanks) and fertigation in the agricultural plot. In the case of fields far from livestock farms or anaerobic digestion plants, in addition to transportation, it will be necessary to implement field LF storage infrastructures with capacity to allow a good management.

Image 8.1. Fertigation in pivot. Demonstration field of LIFE ARIMEDA Project (La Melusa, ES).

The most favourable situation, from an economic point of view, occurs when a farm has irrigated crop fields in the surroundings, since both transport and storage infrastructure are avoided.

The cost of fertigation depends on different factors all of them determining, namely the N concentration of the product, the land surface cultivated, the type of irrigation system and the distance between the field and the plot (Table 8.1).

The analysis is performed in specific hypothetical cases and focus on the effect that the different factors may have on the variability of the fertigation costs. This cost analysis focuses on the techniques demonstrated during 3 years in the ARIMEDA project. In Aragon, fertigation was evaluated with the LF of pig slurry transported by tanker and in Italy with digestate from anaerobic digestion plants and injected directly into the irrigation networks of the farms.

Table 8.1. Factors that influence the cost of fertigation.

FACTOR	ECONOMIC EFFECT
N concentration of slurry and digestate	This is a determining factor, since the reference unit in the economic analysis is the cost of 1 kg N applied in the field. A higher concentration will mean a lower volume of LF to manage and therefore lower separation, transport and fertigation costs.
Cultivation surface	The scale effect derived from the land surface that is managed from a single injection point (fertigation). The larger the surface, the lower the impact of investment costs in storage and LF injection equipment.
Distance between the farm and the cultivation plots	Transport costs have a relevant relative weight in the total cost of kg N managed in the form of LF, in addition to other impacts such as those derived from CO_2 emissions. The distance and the configuration of the irrigation system will determine the possibility of direct injection from storage in the farm or biogas plant or the need for road transport. The latter will significantly increase management costs and labour hours.
Type of crop	Crops with a higher demand for N, such as maize, or the possibility of carrying out double crops, result in lower relative investment costs.
Type of irrigation infrastructure	The type of irrigation, sprinkler irrigation (pivot) or drip irrigation, affects greatly the separation costs on the farm, since the separation costs are higher the greater the restriction of the size of solid particles that the irrigation system admits to avoid obstructions in nozzles or drippers. Restrictions considered are 250-500 µm for sprinkler/pivot irrigation and 100-200 µm for drip systems.

8.2 FERTIGATION WITH PIG SLURRY IN ARAGON

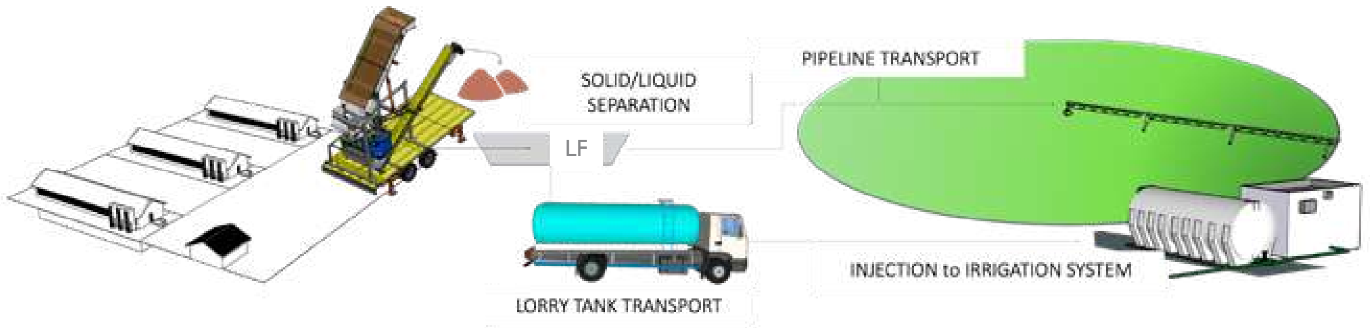

Figure 8.1. Diagram of the different processes for fertigation with pig slurry in Aragon (ES).

8.2.1 SOLID/LIQUID SEPARATION

Two case studies are proposed to obtain liquid fractions suitable for fertigation in pivot and drip irrigation. The study is based on the separation systems used in the LIFE ARIMEDA project (Figure 8.1). For fertigation with pivot, only a first stage of mechanical separation is necessary to eliminate particles larger than 250 µm, in drip irrigation a second separation process working in line with the previous one is necessary to reduce the size of particles in the LF from 250 µm at 100 µm. Table 8.2 shows the costs for each fertigation system:

Table 8.2. Cost analysis for different mechanical solid/liquid separations for pig slurry.

		PIVOT 1st separation	DRIP 1st + 2nd separation	
START DATA	Particle size	250 µm	100 µm	Units
	Slurry LF volume	15,000	15,000	m^3/year
	Total N concentration in LF	2.5	2.5	kg Nt/m^3
	Separation flow	10	10	m^3/h
	Running time	1,500	1,500	h/year
	Power separation equipment	12.25	21.35	kW
	Personal cost	15	15	€/h
	Energy cost	0.15	0.15	€/kWh
	Equipment depreciation	10	10	years
	Infrastructure depreciation	25	25	years
	Annual maintenance costs	4%	4%	% Eq. inv.
	Workforce	0.5	1.0	h/day
INVESTMENT COSTS (fixed)	**Investment costs**			
	Separation equipment	40,000	72,000	€
	LF Storage	8,000	16,000	€
	Total	**48,000**	**88,000**	**€**
	Investment depreciation			
	Separation equipment	4,000	7,200	€/year
	LF Storage	320	640	€/year
	Total	**4,320**	**7,840**	**€/year**
OPERATING COSTS (variable)	**Operating costs**	1,600	2,880	€/year
	Labour cost	1,406	3,038	€/year
	Energy costs	2,756	5,209	€/year
	Total	**5,763**	**11,128**	**€/year**
LF TOTAL COST	**Annual cost**	**10,083**	**18,968**	**€/year**
	Per m^3 separated LF	**0.67**	**1.26**	**€/m^3**
	Per Kg N in LF	**0.28**	**0.51**	**€/kg N**

- **CASE 1:** 250 µm – LF suitable for its use in pivot or sprinkler irrigation
- **CASE 2:** 100 µm – LF suitable for its use in drip irrigation

The volume of LF considered for this analysis is 15,000 m^3 /year with a nitrogen concentration of 2.5 kg/m^3, which would provide 37,500 kg N, enough fertilizer units for an agricultural area of 140 ha of maize applying a dose of 280 kg N/ha. These values are only indicative and it would be necessary to carry out a detailed study of the actual fertilization needs of each scenario based on the expected productions, the type of crop and the contributions from other sources such as the soil, irrigation water or previous leguminous crops.

In this analysis, the use of mechanical separation equipment, without using chemical additives (coagulants and/or flocculants), has been considered, with systems similar to those used in the demonstration plots of the LIFE ARIMEDA project. The separation prototypes used ramp pressing and filtration systems (for 1st separation) and vibratory systems (for 2nd separation) that provided adequate separation for the needs of the irrigation systems used in the tests.

The costs of separation are estimated between 0.69 €/ LF m^3 in the case of pivots (one separation) and 1.26 €/ LF m^3 for drip irrigation. Depreciation of equipment is the highest contribution to the cost (42%) followed by the cost of energy (27%) (Figure 8.2).

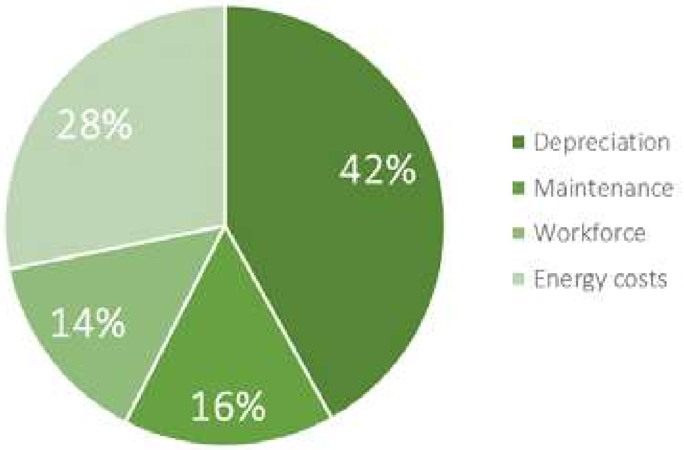

Figure 8.2. Distribution of the cost of solid/liquid separation process of pig slurry for fertigation using mechanical separation systems (without chemical additives).

In the case study proposed, the concentration of N in the slurry influences the cost of separation, (as he higher this concentration, the smaller the volume of slurry to handle), in both the amortization of the initial investment and the operational costs. Figure 8.3 shows that values can range between 0.15 and 0.71 €/kg N for pivot fertigation and between 0.26 and 1.30 €/kg N for drip fertigation, considering a range of N concentration between 1.0 and 5.0 kg N/m^3.

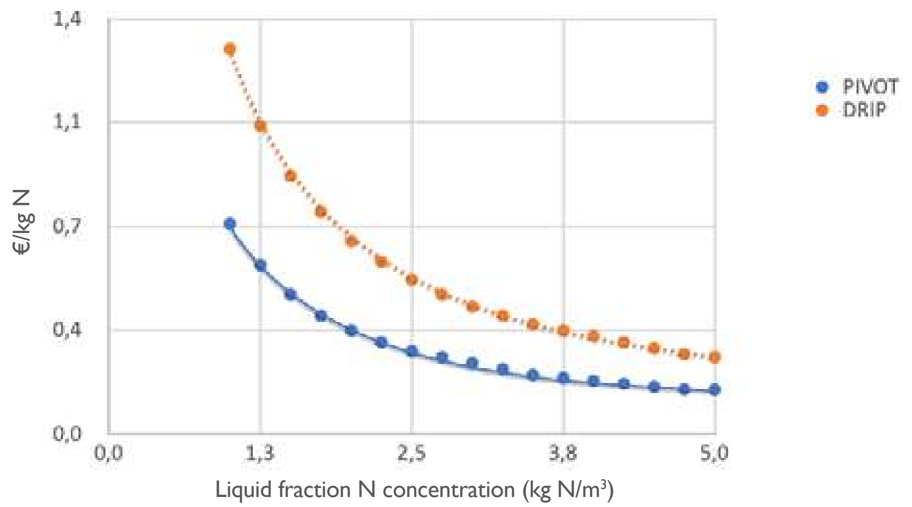

Figure 8.3. Cost of solid/liquid separation of slurry for use in fertigation.

8.2.2 TRANSPORTATION

To analyse the costs of transportation by tanker in those scenarios in which the injection cannot be made directly from the farm storage, the following data have been considered:

- Transport service with 20 m^3 capacity tanker or truck: 70 €/h
- Charging time: 5 min
- Downloading time: 5 min
- Average speed: farm exit, road and plot entrance: 60 km/h

In this study, the transport distance, and the nitrogen concentration of LF significantly affected the costs. Very low concentrations of N (<1.8 kg N/m^3) greatly penalize transport costs and the differences in cost, due to the distance travelled, are reduced with increasing N concentration (Figure 8.4).

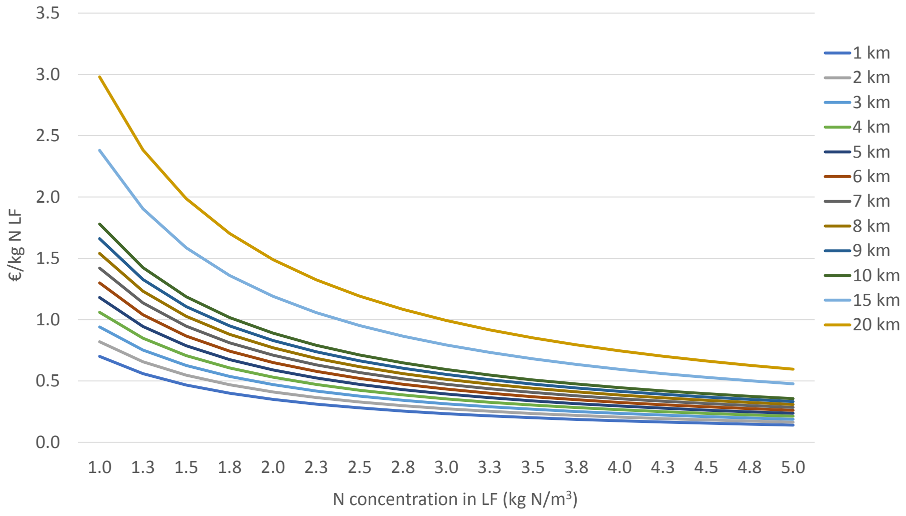

Figure 8.4. Tanker transport costs of the liquid fraction of the slurry (€/kg N) depending on the farm-plot distance (km).

8.2.3 APPLICATION OF FERTIGATION IN THE FIELD

To analyse in detail the cost of injecting the liquid fraction into the irrigation system and based on the experience of the LIFE ARIMEDA project, 3 possible scenarios have been considered: pivot fertigation in plots of 10 and 50 ha and drip fertigation in plots of 10 ha (Table 8.3).

Table 8.3. Cost analysis of liquid fraction injection in pivot and drip irrigation systems.

		PIVOT	PIVOT	DRIP	UNITS
START DATA	Surface	10	50	10	ha
	N dose	250	250	250	kg N/year
	N concentration in LF	2.5	2.5	2.5	kg N/m^3
	Injection flow	10	30	10	m^3/h
	Injected volume	1,000	5,000	1,000	m^3
	Running time	100	167	100	h/year
	Injection pump power	2.20	7.75	2.20	kW
	Personal cost	15	15	15	€/h
	Energy cost	0.15	0.15	0.15	€/kWh
	Equipment depreciation period	10	10	10	years
	Infrastructure depreciation period	25	25	25	years
	Annual maintenance costs	4%	4%	4%	% Eq. invest.
	Workforce	1	1	1	h/day
INVESTMENT COSTS (fixed)	**Investment costs**				
	Injection equipment	5,700	11,700	6,200	€
	LF Storage	8,000	16,000	8,000	€
	Total	13,700	27,700	14,200	€
	Annual investment cost				
	Injection equipment	570	1,170	620	€/year
	LF Storage	320	640	320	€/year
	Total	890	1,810	940	€/year
OPERATING COSTS (variable)	Maintenance	228	468	523	€/year
	Labour cost	188	313	188	€/year
	Energy cost	33	194	33	€/year
	Total	449	975	744	€/year
TOTAL COST	**Annual cost**	**1,339**	**2,785**	**1,684**	**€/year**
	Per separate m^3	**1.34**	**0.56**	**1.68**	**€/m^3**
	Per kg N in LF	**0.54**	**0.22**	**0.67**	**€/kg N**

In the cost of fertigation in the field, the plot surface and the LF nitrogen concentration are the variables that determine the cost. For instance, for an average concentrations of 2.5 kg N/m^3 of LF the cost of injection can range from 0.18 €/m^3 in pivots of 50 ha to 0.54 €/m^3 in plots of 10 ha. The effect of nitrogen concentration on injection costs is much greater in large plots than in smaller plots, mainly due to investment in equipment and storage that directly depend on the volume of liquid fraction to be managed (Figure 8.5).

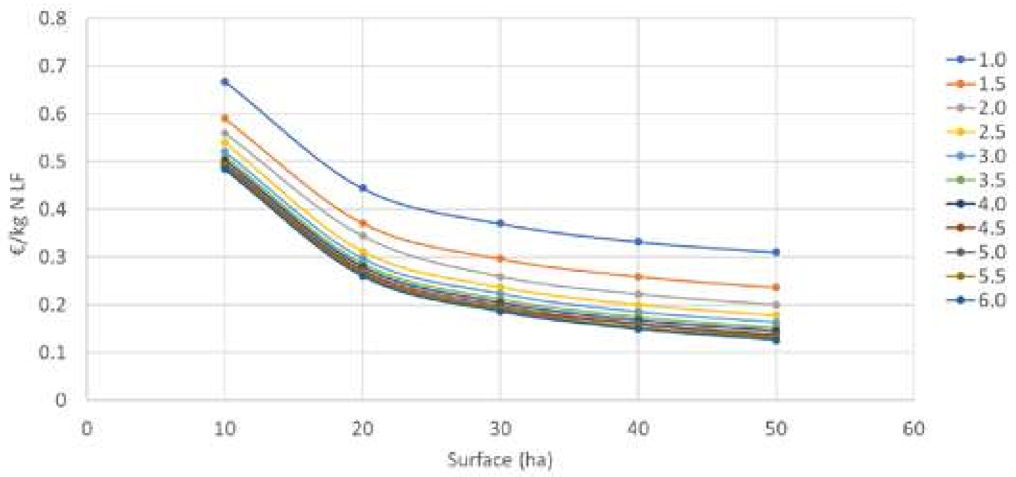

Figure 8.5. Cost of fertigation with pivot depending on the surface of the plot and the concentration of N in the slurry liquid fraction.

8.2.4 COST ANALYSIS OF FERTIGATION - TOTAL COST

Applying the premises detailed in the previous sections, Tables 8.4 and 8.5 detail the cost for the use of fertigation in different agricultural scenarios based on the cost of transport with a 20 m^3 tank and the slurry LF nitrogen concentration.

Table 8.4. Cost analysis (€/kg N and €/ha) of fertigation in a 30-ha pivot. Rate: 250 kg N/ha.

N concentration in LF (kg N/m^3)	Farm-plot distance (km)			
	0 (no transport)	3	5	10
COSTS PER FERTILIZER UNIT (€/kg N)				
1.0	1.08	2.02	2.26	2.86
1.5	0.77	1.39	1.55	1.95
2.0	0.61	1.08	1.20	1.50
2.5	0.52	0.89	0.99	1.23
3.0	0.46	0.78	0.86	1.06
3.5	0.41	0.68	0.75	0.92
4.0	0.38	0.62	0.68	0.83
4.5	0.36	0.57	0.62	0.75
5.0	0.40	0.53	0.58	0.70
COSTS PER AGRICULTURAL AREA (€/ha)				
1.0	270	505	565	715
1.5	192	348	388	488
2.0	152	270	300	375
2.5	129	223	247	307
3.0	116	194	214	264
3.5	103	170	187	230
4.0	96	155	170	207
4.5	90	142	155	188
5.0	86	133	145	175

The results obtained show that the costs of applying fertigation in drip irrigation practically double those of fertigation in pivot systems. This is fundamentally due to the repercussion of the separation costs that require a greater investment in equipment and storage capacity and higher operating costs. The modifications in the implanted irrigation systems require low-cost investments aside from the injection and storage equipment since they are limited to the change of low-pressure nozzles (pivot) and the installation of additional filters in the case of drip irrigation.

If the animal farmer assumes the costs for separation and transport and the agricultural farmer was willing to pay up to 75%, in order to have a saving of 25%, of the cost of mineral fertilization, pivot fertigation would be economically feasible when tank transport is not necessary, with transport up to 5 km if the concentration of N in the LF is ≥1.5 kg N/m^3 or up to 10 km if the concentration of N is ≥2 kg N/m^3 (used cost of mineral fertilisers: €1/kg N). In the case of drip fertigation, viability would be achieved without transport with a concentration of N in the LF ≥1.5 kg N/m^3, with transport up to 5 km if the concentration is 2.5 kg N/m^3 and up to 10 km with concentrations ≥3.0 kg N/m^3.

Table 8.5. Cost analysis (€/kg N and €/ha) of fertigation in a 10-ha drip irrigated plot. Rate: 250 kg N/ha.

N concentration in LF (kg N/m^3)	Farm-plot distance (km)			
	0 (no transport)	3	5	10
COSTS PER FERTILIZER UNIT (€/kg N)				
1.0	2.11	3.05	3.29	3.89
1.5	1.60	2.23	2.39	2.79
2.0	1.35	1.82	1.94	2.24
2.5	1.19	1.57	1.66	1.90
3.0	1.09	1.40	1,48	1,68
3.5	1.02	1.29	1.36	1.53
4.0	0.97	1.21	1.27	1.42
4.5	0.92	1.13	1.18	1.32
5.0	0.89	1.08	1.13	1.25
COSTS PER AGRICULTURAL AREA (€/ha)				
1.0	528	763	823	973
1.5	400	557	597	697
2.0	338	455	485	560
2.5	298	392	416	476
3.0	273	351	371	421
3.5	255	322	339	382
4.0	243	301	316	354
4.5	230	282	296	329
5.0	223	270	282	312

8.3 FERTIGATION WITH DIGESTATE IN LOMBARDY

The cost analysis carried out in Lombardy for the application of fertigation with the liquid fraction of the digestate has two peculiarities with respect to the scenarios proposed in Aragon within the framework of the project:

> **1.** In the mixed model farm with biogas plant – agricultural plots, the transport considered is always by pipeline, injecting the liquid fraction directly from its storage in the anaerobic digestion plant or in the farm into the irrigation network.
>
> **2.** Drip irrigation systems are superficial. They are installed and removed before and after each campaign to be able to carry out the necessary agricultural work on the plot.

Two study cases have been analysed that can serve as a reference to evaluate the variability and cost ranges of implementing fertigation with digestate in extensive crops with drip and pivot irrigation.

CASE STUDY 1: Cost analysis of fertigation with the liquid fraction of digestate in a drip irrigation system.

The following information has been used for the analysis:

- Digestate liquid fraction N concentration: 5 kg/m^3
- Applied dose: 200 kg N/ha
- Managed volume: 40 m^3/ha
- Cost of electricity consumption: 0.4183 €/m^3, or 16.73€/ha (based on an average consumption of 2.35 kWh/m^3)
- Labour cost: 13.56€/ha (based on 13.56 €/h and 1.00 h/ha)
- Operation cost (including reagents): 0.50 €/m^3 or 20.00 €/ha
- Injection flow: 3 m^3/h.

The analysis shows that, under these conditions, the cost of fertigation ranges from 136 €/ha on farms with agricultural areas of 100 ha to 912 €/ha on plots of 10 ha (Figure 8.6). This high cost in small plots surface is directly related to the amortization of the investment cost in solid/liquid separation systems.

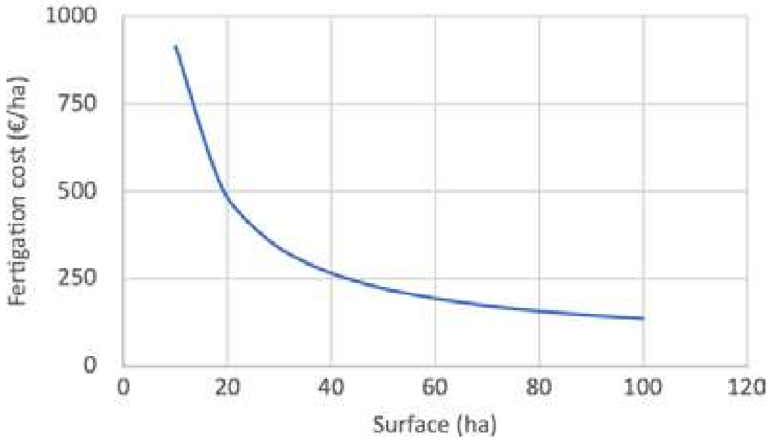

Figure 8.6. Cost analysis of drip fertigation with digestate LF depending on the managed agricultural area.

CASE STUDY 2: Cost analysis of fertigation with the liquid fraction of digestate in pivot

The following information has been used for the analysis:

- N concentration in the digestate liquid fraction: 5 kg/m^3
- Applied dose: 200 kg N/ha
- Managed volume: 40 m^3/ha
- Cost of electricity consumption: 0.4183€/m^3 or 16.73 €/ha (based on a consumption of 2.35 kWh/m^3)
- Labour cost: 9.49€/ha (based on 13.56 €/h and 0.70 h/ha)
- Operation cost (including reagents): 0.50 €/m^3 – 20.00 €/ha
- Injection flow: 5 m^3/h.

The analysis shows that the cost of fertigation ranges from 99 €/ha on farms with agricultural areas of 150 ha to 577 €/ha on plots of 10 ha (Figure 8.7). This high cost in small surfaces is directly related to the amortization of the investment in solid/liquid separation systems. For pivot the cost per hectare in large farms (around 100 ha) is similar to those of drip irrigation, but the scale effect of the land surface is less important in pivots; for example, for a 30 ha plot, the cost barely exceeds 300 €/ha.

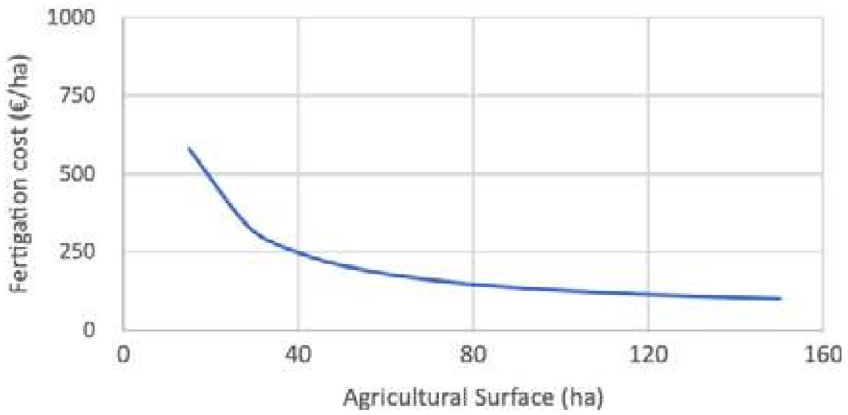

Figure 8.7. Analysis of the costs of fertigation in pivot with the digestate LF depending on the managed agricultural area.

The analysis of the distribution of costs in each of the fertigation systems evidences the leading role that the amortization of solid/liquid separation systems has in the analysis, especially in drip irrigation systems (Figure 8.8).

Image 8.2. Detail of surface drip irrigation in a demonstration plot of the LIFE ARIMEDA Project (Lombardy, IT).

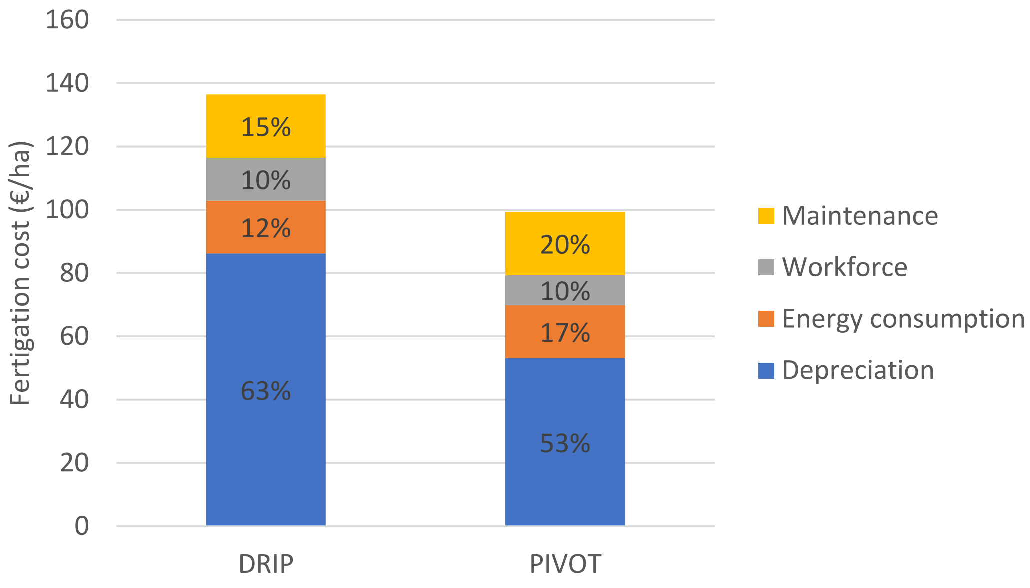

Figure 8.8. Distribution of costs when using fertigation with digestate LF for drip a pivot irrigation system.

The digestate application cost results 0.50 €/kg N for pivot and 0.68 €/kg/N for drip irrigation, when the dose applied is 200 kg N/ha with a digestate concentration of 5 kg/m^3 and the area covered with fertigation is 150 ha (pivot) or 100 ha (drip). A reduction of the area covered increase the incidence of investment costs. The cost of 0.75 €/ha (75% of the cost of mineral fertiliser) is reached when the area is around 80 ha for pivot and 90 ha for drip irrigation systems. It has to be pointed out how the distribution costs are generally lower than a traditional application system (slurry tanker).

8.4 ECONOMIC VALUE OF FERTIGATION

The price of synthetic nitrogen fertilizers is highly dependent on the price of energy, especially natural gas. This dependency is due to the high energy consumption of the Haber-Bosch process used in their manufacturing. The current situation in the market for synthetic and mineral fertilizers, in which the cost of energy has sharply rise, constitutes a favourable opportunity for fertilizers of organic origin, such as digestate or slurry. The creation of a stable market that allows the use of organic fertilizers with efficient technologies can represent important savings for farmers. In addition, this management system is aligned with the circular economy strategy and with the objectives of reducing ammonia and greenhouse gas emissions set by the European Union in the environmental and agricultural policies (CAP) developed in recent years.

It is important to note that direct injection into the irrigation system, as has been implemented and analysed in Lombardy, eliminating road transport, allows a much more efficient management and with greater potential for scaling. The mixed farm plot model with this configuration represents a very favourable scenario for the application of this technique.

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9

SOCIAL PERCEPTION OF THE IMPACT OF AGRICULTURAL ACTIVITY RELATED TO MANURE AND DIGESTATE MANAGEMENT AND THE APPLICATION OF SUSTAINABLE PRACTICES SUCH AS FERTIGATION

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9.1 INTRODUCTION

In the agricultural sector, the adoption of technologies and techniques that help mitigate ammonia emissions derived from the use of organic fertilizers (as livestock manures), such as fertigation, can generate important benefits in the value chain of the food produced and, consequently, promote the use of good practices in the management of slurry and digestate from anaerobic digestion facilities. However, this goal can only be successfully achieved if farmers are fully aware of the benefits to be derived from the application of these technologies and fully join this global effort, otherwise it will fail. The environmental sustainability of production systems is not a sufficient incentive on its own and the profit margins of livestock and agricultural production systems must be taken into account when proposing alternative management techniques to the usual ones. The solutions, methods and approaches developed by the LIFE ARIMEDA project have proven to be suitable for adoption by private investments. However, farmers often show resistance to change and the adoption of innovations in their management practices; acceptance of new techniques and their use is often delayed, such is the case for manure management alternatives. A solution to this problem could be the implementation of specific information and training campaigns in combination with political instruments and economic incentives to foster the image and production of farms that are climate and environmental friendly (Image 9.1 and 9.2).

In order to successfully transfer practices such as fertigation as a sustainable technique for the management of slurry and digestate, it is crucial to know the perception of the sector directly involved in these activities and to understand how farmers (potential users of this practice) identify the main facilitators and barriers for its implementation, as well as to what degree they perceive that this technique can be interesting and attractive for their activity.

Within the framework of the LIFE ARIMEDA project, a survey has been prepared, with the support and collaboration of the University of Zaragoza, in which the perception of farmers in the regions of Aragon and Lombardy is evaluated using 48 indicators, 24 facilitators and 24 barriers to the implementation of fertigation with the liquid fraction of slurry and digestate respectively (Table 9.1). The indicators were scored on a scale of 0 to 5 from least to greatest importance of the indicator according to the perception of the respondent. The 48 indicators were grouped according to 5 criteria: 1. economic, 2. political, strategic and legislative, 3. social, 4. technological and 5. environmental.

The indicators were outlined in collaboration with the technicians of the sector and the resulting survey was distributed in Aragon through the Irrigation Communities of Bardenas (Cinco Villas) and the Canal de Aragón and Cataluña (La Litera) and in Lombardy through the Regional Breeders Association of Lombardy (ARAL). The analysis of the social perception was carried out from the information data provided by the questionnaire answers, which was answered by 39 respondents, 25 in Aragon and 14 in Italy.

Table 9.1. Facilitators and barriers included in the social study carried out within the framework of the LIFE ARIMEDA project.

Criteria	FACILITATORS Favorable aspects that facilitate and can promote the use of fertigation techniques with the liquid fraction of slurry
Economy	**F1** Reduce fertilization costs and increase the profit margin for the farmer
	F2 The mixed livestock-agriculture model has economic advantages (costs and efficiency)
	F3 A mixed livestock-agriculture system allows the creation of new service models (opportunities for new businesses).
	F4 Insufficient public support: Insufficient financial funds to carry out a bid for the substitution of synthetic fertilizers
Policy/ Strategy/ Legislation	**F5** They help the development of the sector by promoting innovation
	F6 They are a support to a regional strategy of transition towards a sustainable socio-economic and environmental model
	F7 Fertigation is of strategic interest in areas with a high concentration of livestock
	F8 The sector shares Europe's strategic interest in reducing the consumption of mineral fertilizers
Social	**F9** They improve the social perception of the agricultural and livestock sector as an activity in rural areas
	F10 Contribute to innovation and change towards sustainable slurry management practices
	F11 They are of interest because they are measures that respond to environmental social expectations and demands
	F12 They are of interest because it contributes to the sector complying with the obligations and requirements of current regulations
	F13 The mixed livestock-agriculture system allows the creation of new, more technical jobs linked to new companies
Technology	**F14** They are an opportunity to replace synthetic fertilizer with slurry
	F15 A solid fraction rich in phosphorus and organic matter is obtained that can be easily recovered
	F16 Nitrogen losses to the atmosphere decrease and the fertilizer value of the slurry increases
	F17 They extend the times of application to the field increasing their competitiveness in the market as a fertilizer product
	F18 Facilitate slurry management in settings where the plots are next to the farm
Environmental	**F19** They reduce the odors generated in the management and application of slurry to the field
	F20 Decrease emissions of ammonia into the atmosphere harmful to health (compared to the usual fertilization practices with slurry)
	F21 They do not increase the risk of nitrate washing into water courses
	F22 They make it possible to reduce the amount of mineral fertilizer that is applied in irrigation systems, replacing it with slurry and reducing the impacts associated with excess fertilization
	F23 Improve nutrient recycling in production chains (efficient reuse of slurry at local and regional level)
	F24 They contribute to the reduction of road transport when the plots are next to the farm

Criteria	BARRIERS Aspects that hinder the use of fertigation techniques with the liquid fraction of slurry
Economy	**B1** They need a prior investment in equipment: separators, storage and injection system
	B2 The separation and the fertigation system requires follow-up and maintenance operations
	B3 To apply fertigation in drip systems it is usually necessary to invest in the installation of irrigation since it is a rare system in extensive crops
	B4 There is direct competition between slurry fertilization and the market for the production and marketing of mineral fertilizers
	B5 There is disconnection between agriculture and livestock with a great growth of livestock farms in the territory
	B6 There is a lack of companies with R + D + i capacity in the sector
Policy/ Strategy/ Legislation	**B7** Lack of a regional strategy for the transition to a sustainable agro-livestock model due to short-range policies without a strategic territorial vision
	B8 There are polarized positions and interests between the intensification and specialization of livestock and the development of sustainable strategies in the agricultural and livestock sector
	B9 There is a differentiated regulation in the use of organic and synthetic fertilizers that discriminates the fertilization with slurry versus mineral fertilization
	B10 The sector does not know in depth the regulations on the use of slurry
	B11 There is no interest on the part of the sector to know the regulations to introduce new innovative techniques in the management of slurry and manure. The main motivation is the implications in the collection of the CAP
Social	**B12** The social impacts of slurry management are not taken into account when making investments and innovations in the agricultural sector
	B13 Society perceives greater risks in the use of slurry as fertilizer than in the use of mineral fertilizers
	B14 Lack of professionalization of the sector
Technology	**B15** Insufficient progress in technologies for the recovery of slurry as fertilizers
	B16 Fertigation with slurry may require transport and additional storage on the farm or plot
	B17 Fertigation with slurry in drip systems has as an added difficulty the correct management of irrigation in extensive crops
	B18 There is a lack of knowledge of the nutrient content of the slurry (fertilizer value)
	B19 It is difficult to control the doses applied in fertigation
	B20 Technical manpower is needed for the application of fertigation (separation, fertilizer plan and logistics).
Environmental	**B21** Lack of vision of the resources of the environment as an opportunity
	B22 Lack of knowledge of the potential biosanitary risks derived from the use of slurry in fertigation
	B23 Lack of knowledge of the environmental effect of emerging pollutants such as antibiotics and sanitary products used in livestock
	B24 Risk of impact on the quality of soils and water

9.2 THE STUDY IN ARAGON (SPAIN)

In Aragon, the survey was distributed mainly in two rural areas where irrigated agriculture and intensive livestock play a very important role in the local economy, Cinco Villas and La Litera.

The average profile of the respondent is a male between 24 and 67 years of age (average 50 years), with secondary or university studies and whose main activity is agriculture. Among those surveyed, farmers who manage agricultural areas between 0 and 200 hectares predominate (Figure 9.1) and for most of them the use of slurry as organic fertilizer is not unknown, applying it regularly or, at least, occasionally in their fields.

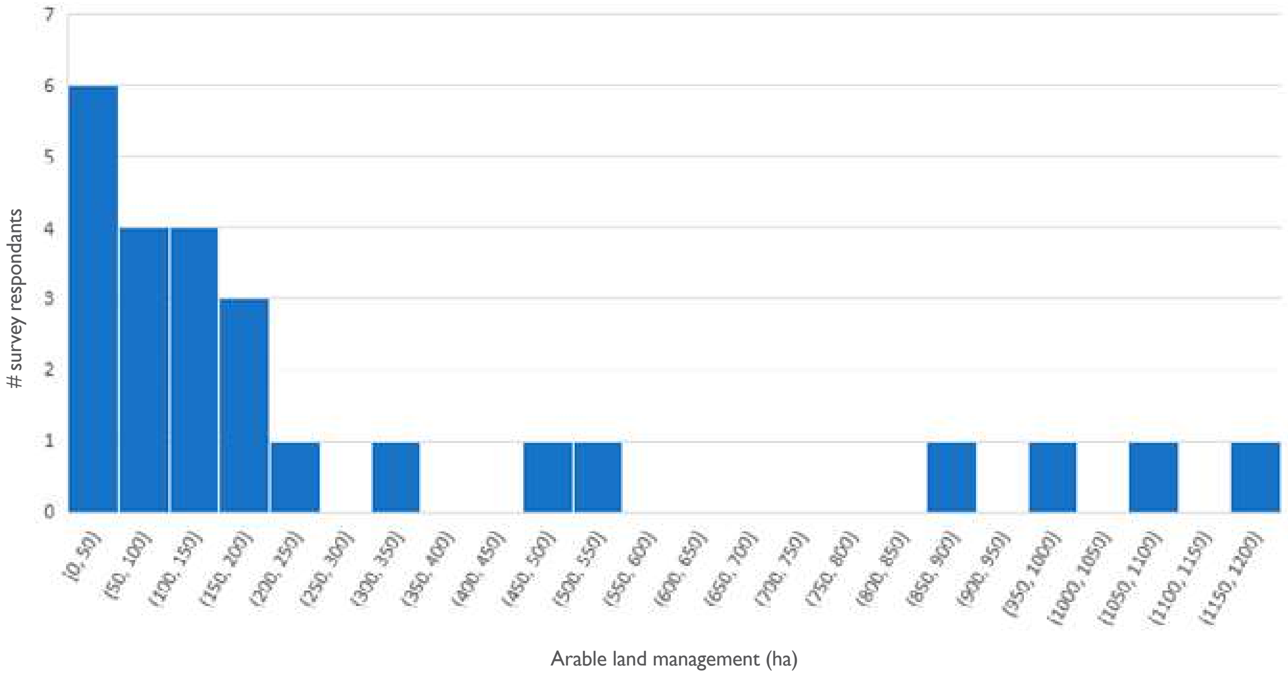

Figure 9.1. Distribution of the number of respondents according to the size of agricultural area they manage as farmers in Aragon.

It has been observed that in the case of La Litera the use of fertigation with both mineral fertilizer and slurry is more widespread than in Cinco Villas and 83% of those surveyed had irrigation systems with pivot or lateral machines (rangers).

From the results of the surveys, the following conclusions were drawn regarding the indicators proposed as possible facilitators in the promotion of fertigation with the liquid fraction of slurry (Figure 9.2):

> **1.** The three most highly valued aspects are the economic advantages of the mixed livestock-agriculture model, the strategic interest of fertigation in areas with high livestock concentration and the more efficient use of the nutrients in the slurry at the local and regional level, recycling the available resources within the productive chain. The reduction in road transport when the plots are next to the farm, as well as the reduction of fertilization costs and the extension of the times of application to the field, are also valued very positively.
>
> **2.** The incentives valued to a lesser extent are those related to the alignment of the strategies with European policies, the application of good practices to help improve the social perception of agricultural and livestock activity and the reduction of odors.
>
> **3.** Social indicators are those that have the least weight in general terms when acting as catalysts for the use of sustainable agricultural practices such as fertigation.

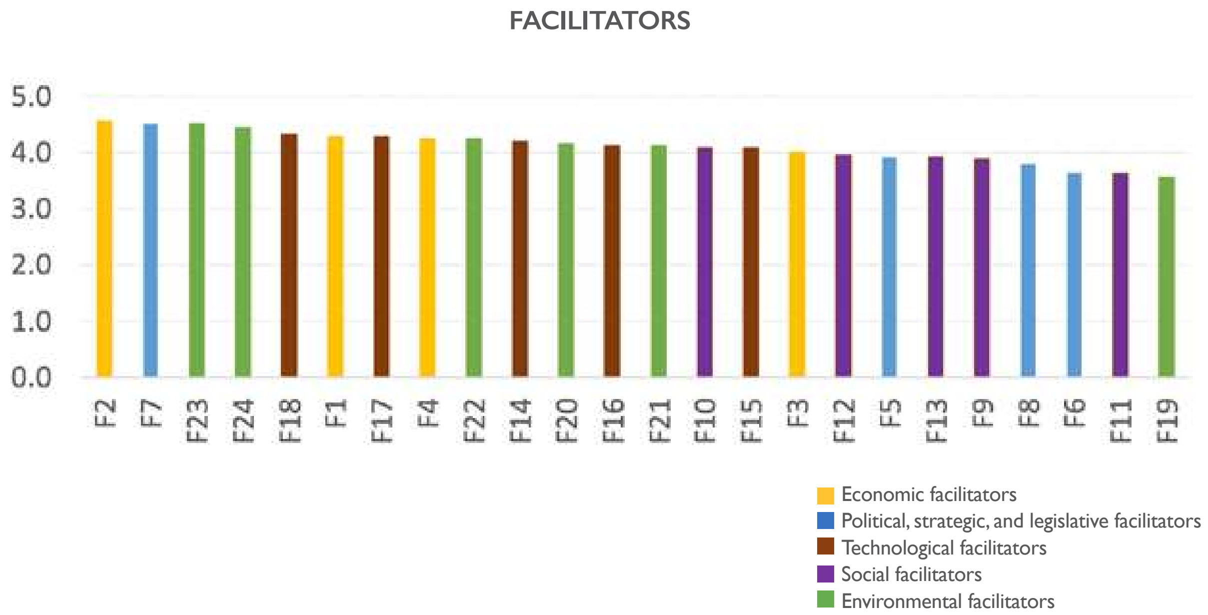

Figure 9.2. Assessment (0-5) of the facilitators that could promote the application of fertigation with the liquid fraction of slurry in Aragon (Spain). The codes correspond to the indicators listed in table 9.1.

Regarding the main barriers that hinder the use of fertigation in the conditions studied by the LIFE ARIMEDA project (Figure 9.3):

> **1.** Respondents consider that the main barriers are in the investments that are necessary for solid/liquid separators and injection systems or even in the irrigation system itself when using drip, especially in small farms.
>
> **2.** The non-existence of companies with innovation capacity in the sector, the operation and maintenance costs of the systems and the transport needs when the plot is not next to the farm are also perceived as important aspects to take into account.
>
> **3.** The drip irrigation system is the one identified as the most difficult to apply in Aragon at the moment.
>
> **4.** In the social aspects, farmers perceive as a barrier that society perceives greater risks in the use of slurry as fertilizer than in the use of mineral fertilizers, which is also reflected in the legislative sphere with the existence of a differentiated regulation in the use of both fertilizers.
>
> **5.** The barriers that cause less concern are the difficulty to control the application rates and the risk of impact on the quality of the soils and water, as well as the ignorance of potential biosanitary risks and the competition in the market between organic and inorganic fertilizers.

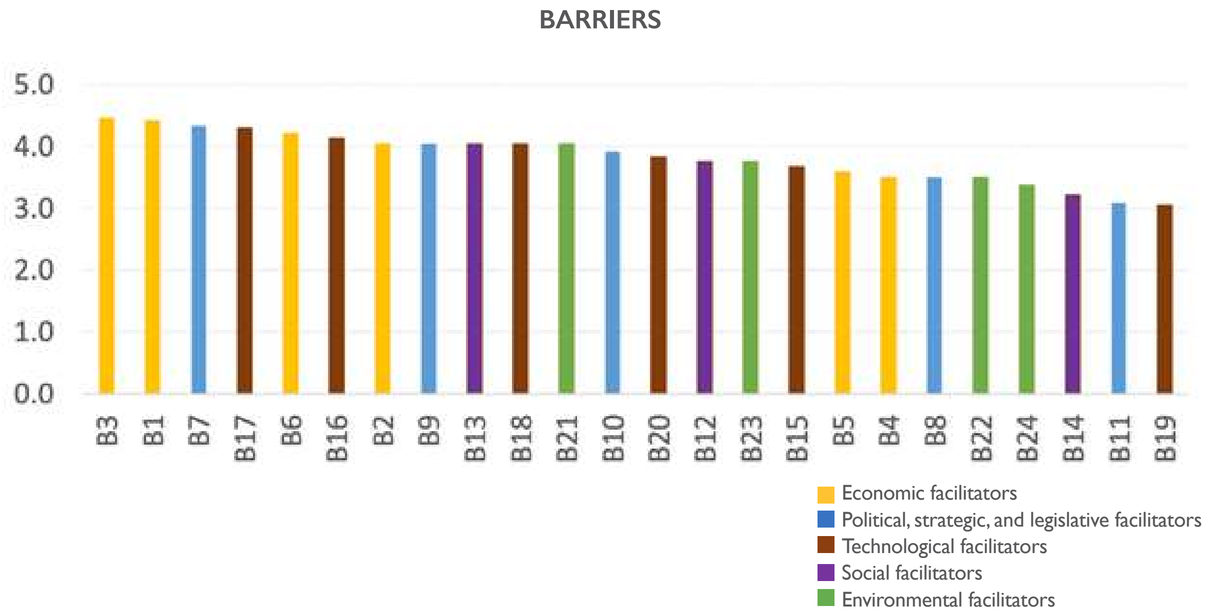

Figure 9.3. Assessment (0-5) of the barriers that hinder the use of fertigation techniques with the liquid fraction of slurry in Aragon (Spain). The codes correspond to the indicators listed in table 9.1.

The study carried out in Aragon showed that techniques such as fertigation are perceived by farmers as an opportunity, as stated by 80% of those surveyed in this region. However, it was repeatedly insisted that the lack of a clear regulation in the use of these practices, the restrictions on the use of organic fertilizers that prevent taking advantage of all the benefits of this technique and the absence of a firm strategy on the part of the Administration promoting its implementation are very important conditioning factors to take into account when analysing its application potential in the study areas. Only 20% consider fertigation a necessity and it is not perceived in any case as a risk by farmers.

Image 9.1. Field visit at the La Melusa farm in Tamarite de Litera (Aragon, Spain).

9.3 THE STUDY IN LOMBARDY (ITALY)

In Lombardy the survey was distributed through the Regional Breeders Association of Lombardy. In this region, the mixed farm-plant anaerobic digestion-agricultural plot model is widespread.

The average profile of the respondent was men between 27 and 61 years old, the average was 46 years old, with secondary or university studies and whose activity is mainly carried out as a livestock farmer with agricultural land. Among the respondents, farmers who manage agricultural areas of between 155 and 205 hectares predominate (Figure 9.4), areas greater than those managed by farmers in Aragon, and for whom the use of slurry or digestated as organic fertilizer is the usual practice. The use of fertigation is less widespread and it is very little used with the liquid fraction of the digestate.

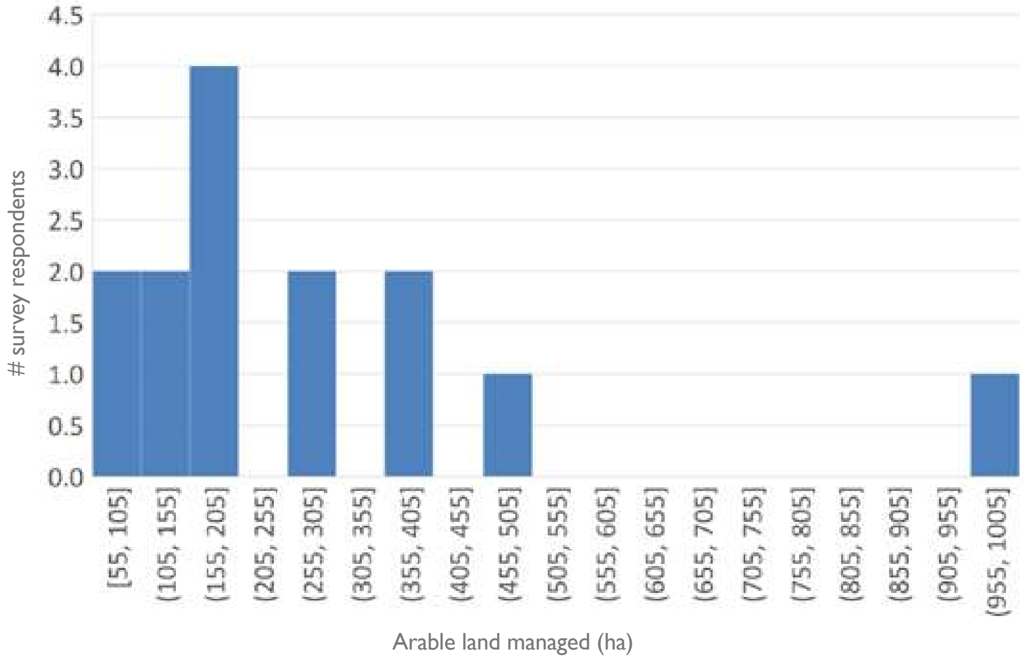

Figure 9.4. Distribution of the number of respondents according to the agricultural area they manage as farmers in Lombardy.

The following conclusions were drawn from the results of the surveys regarding the possible aspects that may contribute to promoting the use of fertigation with the liquid fraction of the digestate in Lombardy (Figure 9.5)::

1. As in the case of Aragon, the economic advantages of the mixed farm-plot model is the main incentive for the implementation of techniques such as fertigation.

2. The ease of handling and distribution of the digestate, allowing the mineral fertilizer to be substituted also at side-dressing, is the second aspect that the respondents have valued more positively.

3. Indicators of a social nature are those that are less valued in general terms as useful tools to promote and extend the use of fertigation.

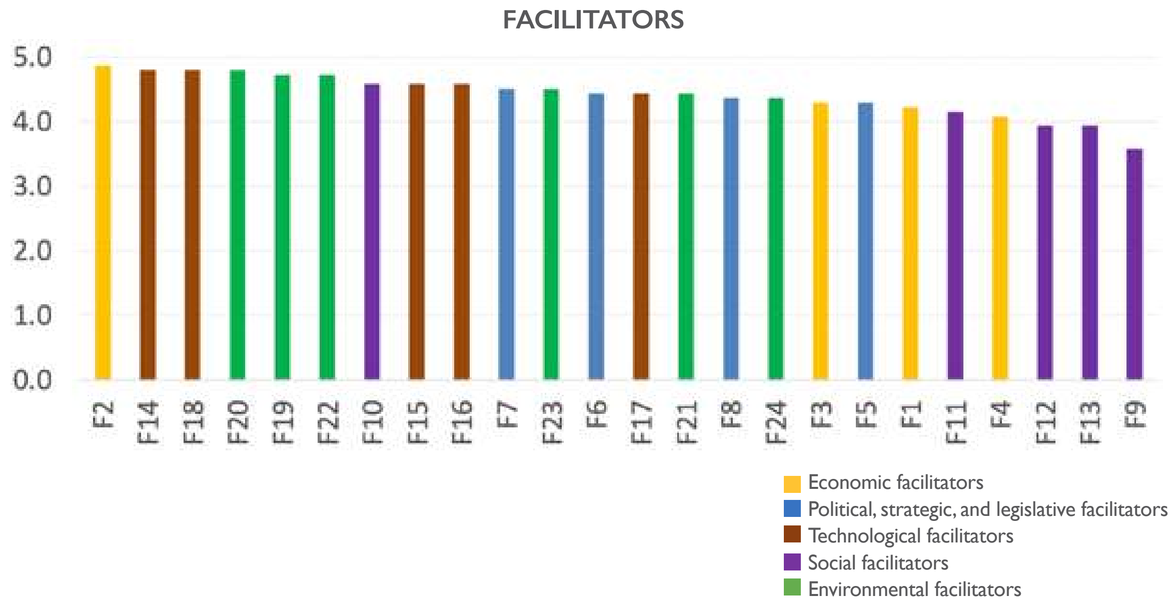

Figure 9.5. Assessment (0-5) of the facilitators that favour the application of fertigation with the liquid fraction of digested in Lombardy (Italy). The codes correspond to the indicators listed in table 9.1

Regarding the aspects that hinder the use of fertigation techniques with the liquid fraction of slurry (Figure 9.6):

1. The operations of separation and maintenance of fertigation systems are identified as the main barrier to their use, closely followed by the lack of professionalization of the sector, the lack of knowledge of the fertilizer value of the digestate and the needs of technical personnel for planning and proper execution of fertigation.

2. Social indicators linked to social perception about the use of organic fertilizers, regulatory restrictions or direct competition with mineral fertilizers are perceived in Italy as weaker barriers than in the case of Aragon. They are less important determinants when considering the use of fertigation.

3. The environmental aspects of the use of this practice still to be evaluated, such as possible biosanitary risks, emerging contaminants such as antibiotics and sanitary products or the possible impact on the quality of soil and water are perceived as important issues to take into account, although they are not the most decisive.

Image 9.2. Field visit and transfer day in Lombardy (Italy).

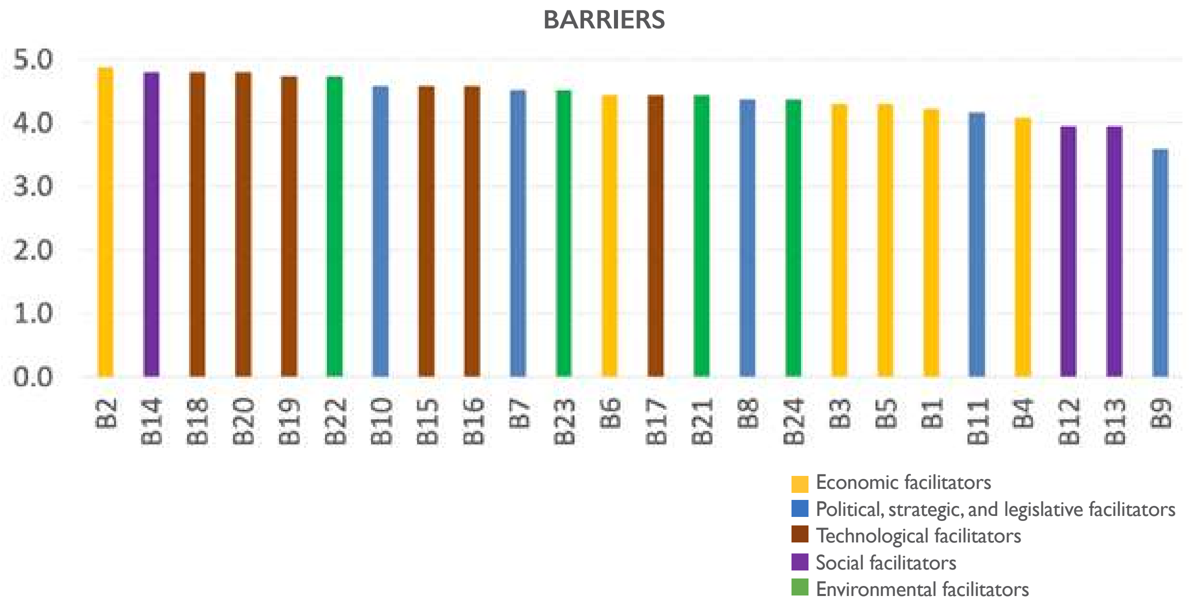

Figure 9.6. Assessment (0-5) of the barriers that hinder the use of fertigation techniques with the liquid digested fraction in Lombardy (Italy). The codes correspond to the indicators listed in table 9.1.

In Lombardy, the fertigation technique is also considered, according to this study, as a clear opportunity for the sector according to 79% of those surveyed, and it is identified as a need by half of the participants. In this region, respondents also expressed their dissatisfaction with the lack of support for regulatory measures that favor and promote the use of organic fertilizers versus synthetic ones.

LIFE ARIMEDA PROJECT

Ammonia emission reduction in Mediterranean agriculture with innovative slurry fertigation techniques

LIFE Programme Environment and Resource Efficiency

DURATION: 01/09/2017 – 30/09/2021

PROJECT BUDGET: 2,608,324 €

EU CONTRIBUTION: 1,522,293 € (59.11%)

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