

OPTIMIZING LINEAR MOVE IRRIGATION SYSTEMS FOR PRECISION LIVESTOCK EFFLUENT APPLICATION IN MAIZE CULTIVATION

OPTIMISATION DES SYSTÈMES D'IRRIGATION À RAMPE FRONTALE POUR L'ÉPANDAGE DE PRÉCISION D'EFFLUENTS D'ÉLEVAGE EN CULTURE DE MAÏS

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ABSTRACT

The optimization of fertilization systems plays a key role in improving nutrient distribution efficiency and reducing environmental impacts in agricultural practices. Agriculture is widely acknowledged as a major source of diffuse pollution of surface and groundwater, largely due to the application of synthetic fertilizers and livestock effluents. It also represents a significant contributor to atmospheric emissions, with livestock operations being the primary source of ammonia emissions, linked to acidification and particulate matter formation, as well as methane and nitrous oxide. Consequently, implementing effluent application techniques that maximize nutrient efficiency while reducing atmospheric emissions has become imperative. In this context, the present study addresses the optimization of a linear move irrigation system fitted with an articulated boom for fertilization in actively growing maize to maximize immediate nutrient uptake. The main objective was to evaluate the feasibility and efficiency of substituting synthetic fertilizers entirely with adequately treated bovine livestock effluents applied as top-dressing. The field trial, carried out on a commercial farm in the Polesine area (Veneto Plain, Italy), included a detailed assessment of effluent distribution uniformity to ensure consistent and sustainable nutrient application. In particular, the trial involved the study of a new distribution system to replace the existing one, which consisted of simple drop pipes with plate emitters characterized by poor application uniformity. The study revealed that distribution uniformity was suboptimal due to severe nozzle clogging and pressure losses along the distribution line. To improve distribution uniformity, it was first necessary to modify the nozzles. In this regard, nozzles were designed that could be directly attached to the individual drop hoses without modifying the machine, thereby keeping costs low for farmers. The nozzles consist of an external PP (polypropylene) body containing a perforated PVC (Polyvinyl chloride) cylinder; the diameter of the orifice determines the nozzle flow rate.

In addition, four pressure gauges were installed at regular intervals to monitor pressure variations along the line. Furthermore, to further reduce the risk of clogging caused by plant material and small stones, the slurry was homogenized as much as possible through an initial mixing step in the tank before being pumped into the distribution line. Following modifications to the emitters, the coefficient of variation (CV), which represents the standard deviation relative to the mean and is used to evaluate distribution uniformity, improved from 43% to 11%. Moreover, thanks to the implemented modifications, pressure along the entire line was found to be uniform, taking into account head losses due to the line length. Finally, nozzle clogging was reduced by approximately 70–80%, thereby also decreasing the time required by the farmer for machine maintenance. Overall, these measures resulted in a more efficient and robust system, ensuring uniform slurry distribution while substantially reducing clogging and maintenance requirements. The results of this study demonstrate that precision fertigation using treated bovine livestock effluents applied through a linear move irrigation system represents a technically feasible and environmentally sustainable alternative to conventional synthetic fertilization in maize cultivation. The improvement in distribution uniformity achieved through relatively simple system modifications highlights the importance of proper system design and maintenance when applying organic effluents.

Keywords: Optimization of fertilization systems; Agricultural practices; Effluent application techniques; Nozzle flow rate; Organic effluents.

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RÉSUMÉ

L'optimisation des systèmes de fertilisation joue un rôle essentiel dans l'amélioration de l'efficacité de la répartition des éléments nutritifs et la réduction des impacts environnementaux des pratiques agricoles. L'agriculture est largement reconnue comme une source majeure de pollution diffuse des eaux de surface et souterraines, en grande partie en raison de l'application d'engrais de synthèse et d'effluents d'élevage. Elle contribue également de façon importante aux émissions atmosphériques, les activités d'élevage constituant la principale source d'émissions d'ammoniac, associées à l'acidification et à la formation de particules, ainsi que d'émissions de méthane et de protoxyde d'azote. Il est donc devenu indispensable de mettre en œuvre des techniques d'épandage des effluents qui maximisent l'efficacité des éléments nutritifs tout en réduisant les émissions atmosphériques. Dans ce contexte, la présente étude porte sur l'optimisation d'un système d'irrigation à rampe frontale muni d'un bras articulé pour fertiliser le maïs en pleine croissance et maximiser l'absorption immédiate des éléments nutritifs. L'objectif principal consistait à évaluer la faisabilité et l'efficacité du remplacement intégral des engrais de synthèse par des effluents bovins convenablement traités et appliqués en fertilisation de couverture. L'essai au champ, mené dans une exploitation commerciale de la région du Polesine, dans la plaine de Vénétie en Italie, comprenait une évaluation détaillée de l'uniformité de répartition des effluents afin de garantir une application homogène et durable des éléments nutritifs. L'essai portait notamment sur un nouveau système de distribution destiné à remplacer le dispositif existant, constitué de simples tuyaux de descente équipés de diffuseurs à plaque et caractérisé par une faible uniformité d'application. L'étude a révélé que cette uniformité était insuffisante en raison d'un colmatage important des buses et de pertes de pression le long de la conduite de distribution. Pour améliorer l'uniformité de répartition, il a d'abord été nécessaire de modifier les buses. Des buses pouvant être fixées directement sur chaque tuyau de descente, sans modification de la machine, ont ainsi été conçues, ce qui a permis de limiter les coûts pour les agriculteurs. Elles se composent d'un corps extérieur en PP (polypropylène) contenant un cylindre perforé en PVC (polychlorure de vinyle) ; le diamètre de l'orifice détermine le débit de la buse.

En outre, quatre manomètres ont été installés à intervalles réguliers afin de surveiller les variations de pression le long de la conduite. Pour réduire davantage le risque de colmatage causé par des débris végétaux et de petites pierres, le lisier a été homogénéisé autant que possible par un premier mélange dans la cuve avant son pompage dans la conduite de distribution. Après modification des émetteurs, le coefficient de variation (CV), qui représente l'écart-type rapporté à la moyenne et sert à évaluer l'uniformité de répartition, est passé de 43 % à 11 %. De plus, grâce aux modifications mises en œuvre, la pression s'est révélée uniforme sur toute la longueur de la conduite, compte tenu des pertes de charge dues à sa longueur. Enfin, le colmatage des buses a diminué d'environ 70 à 80 %, ce qui a également réduit le temps consacré par l'agriculteur à l'entretien de la machine. Dans l'ensemble, ces mesures ont permis d'obtenir un système plus efficace et plus robuste, assurant une répartition uniforme du lisier tout en réduisant sensiblement le colmatage et les besoins d'entretien. Les résultats de cette étude montrent que la fertigation de précision au moyen d'effluents bovins traités, appliqués par un système d'irrigation à rampe frontale, constitue une solution de remplacement techniquement réalisable et écologiquement durable par rapport à la fertilisation de synthèse conventionnelle en culture de maïs. L'amélioration de l'uniformité de répartition obtenue grâce à des modifications relativement simples du système souligne l'importance d'une conception et d'un entretien appropriés lors de l'application d'effluents organiques.

Mots clés : Optimisation des systèmes de fertilisation; Pratiques agricoles; Techniques d'épandage des effluents; Débit de la buse; Effluents organiques.

Introduction

Water is the most critical natural resource on Earth, yet only 0.3% of the total freshwater available is accessible at the surface in rivers and lakes. Global freshwater consumption is dominated by agriculture, which accounts for 70% of total use worldwide and 54% in Italy (ISTAT, 2022). At the same time, the agricultural sector is widely recognized as the primary source of diffuse pollution in

both surface and groundwater bodies, mainly through the application of fertilisers, slurries, and livestock effluents (GeSEFFE Project, 2020). This dual role — as the largest consumer of water and a major contributor to its pollution — places agriculture at the centre of current debates on environmental sustainability and resource management.

Water insecurity is further exacerbated by climate change, which increases the frequency and intensity of extreme meteorological events such as droughts and floods, while the progressive reduction of soil permeability due to urbanisation diminishes the natural water absorption capacity of ecosystems. These dynamics collectively threaten food security, public health, and economic stability, urging governments to adopt adaptive and mitigation strategies (Ceretta et al., 2022). In this context, improving irrigation efficiency becomes essential for ensuring future food production. Irrigation technologies range from gravity-based methods to pressurised systems, among which micro-irrigation achieves distribution efficiency of 90–95% and sprinkler irrigation reaches 70–80% under optimal conditions (Bortolini, 2022; Capra et al., 2023). The most advanced approach is represented by Precision Irrigation (PI), a component of Precision Agriculture (PA), which maximises Water Use Efficiency (WUE) through the spatial and temporal optimisation of water application. This is achieved by integrating real-time soil moisture sensors — including Ground Penetrating Radar (GPR), Electromagnetic Induction (EMI), and Electrical Resistivity Profilers — with remote sensing of canopy radiative temperature for the dynamic detection of crop water stress and variable-rate application (Castrignanò, 2015; Gargano, 2024).

Alongside water management, the rational use of livestock effluents represents a key component of sustainable agricultural systems. More than 70% of the nitrogen and phosphorus ingested by animals is excreted and retained in effluents, making their agronomic valorisation fundamental to closing nutrient cycles and reducing dependence on synthetic fertilisers, whose prices have risen by nearly 11% in recent years due to energy costs and global market pressures (MBF Group, 2025). Proper effluent management — encompassing adequately sized storage, solid-liquid separation, and the surface application of treated liquid fractions through innovative distribution systems such as pivot and linear articulated booms — allows in-crop nutrient delivery, increases nitrogen use efficiency, and reduces both atmospheric emissions and nitrate leaching into water bodies (GeSEFFE Project, 2020; Mantovi et al., 2022; Pignagnoli, 2025). The regulatory framework governing these practices, particularly the Nitrates Directive (91/676/EEC), establishes nitrogen application limits differentiated by territorial vulnerability, requiring the adoption of good agronomic practices to ensure environmentally sound and efficient fertilisation.

In light of these considerations, the integration of precision irrigation technologies with the sustainable agronomic use of livestock effluents emerges as a coherent and complementary strategy for addressing the dual challenge of water scarcity and nutrient management in modern agriculture. The present study aims to investigate this integrated approach, evaluating its potential to enhance crop productivity, reduce environmental impact, and improve the long-term sustainability of agricultural systems.

Materials and methods

Trial area

The experimental area is located in the Veneto region (northern Italy), which, although falling within the Mediterranean climatic belt, presents distinctive characteristics primarily due to its position at mid-latitudes, in a transitional zone between the central European area — dominated by western atmospheric circulation and Atlantic Ocean influence — and the southern European area, characterised by subtropical anticyclones and Mediterranean Sea dynamics.

The field under study is situated in the municipality of Trecenta, in the Province of Rovigo. It belongs to the farm's landholding and is located approximately 370 metres from the farm headquarters. The plot has a rectangular shape, with the longer side — corresponding to the direction of tillage

operations — oriented in a north-south direction. The total surface area covers 9.40 hectares and the terrain is essentially flat, with a slight slope toward a drainage canal located to the north.

Soil texture analysis was carried out through sampling across different areas of the plot, revealing spatial variability in soil composition. Samples collected from the central and most extensive portions of the field showed a clay-loam texture, while a sample taken from a transitional zone presented a sandy clay-loam texture. A further sample, collected from the northern edge of the plot, exhibited a loam texture. This textural heterogeneity reflects the typical pedological variability observed in the alluvial plain soils of the Po Valley and should be considered in the design and management of both irrigation and fertilisation strategies.

Irrigation System Description

The experimental field is equipped with a pivoting linear system (also known as a "racetrack" or hippodrome configuration), capable of operating both in pivot mode and in linear front-advance mode. The system comprises a pumping unit, a mobile tower with a guidance system, lateral spans, a distribution apparatus, and drive wheels with an advancement mechanism. Irrigation water is drawn and pressurised by an electric pump located adjacent to the supply ditch, powered by a photovoltaic system. The pump is positioned approximately 130 metres from the main water source and 80 metres from the livestock effluent storage tanks, in order to minimise hydraulic resistance and facilitate connection to the slurry storage infrastructure. A buried 160 mm diameter PVC pipeline conveys water to a T-junction installed in a manhole located 220 metres from the pump. This junction, equipped with guillotine valves, enables the alternating supply of two adjacent fields — one to the south and one to the north of the manhole. From each valve, a PVC pipeline of equal diameter leads to the central point of each field, running alongside the lane used by the mobile tower. At each central point, a hydrant connects the underground pipeline to the surface supply hose, which consists of a polyethylene (PE) tube with an outer diameter of 140 mm and a length of approximately 230 metres. One supply hose is installed per field, and each is attached to the mobile tower, which drags the PE tubing along its path during irrigation operations.

The mobile tower has a pyramidal structure made of galvanised steel, composed of four angle irons and a series of L-shaped transverse elements connected at the corners with bolts, providing structural stability. The tower is supported by circular-section tubulars joining the four corners and is mounted on four drive wheels enabling linear movement. A central feed pipe connects the supply hose at the bottom to the lateral span pipeline at the top via a rotating joint. A generator set with an internal combustion engine, producing 16 kW, is mounted on the tower structure to supply electrical power to the control panel, the wheel motors, the automatic nozzle switching system, and the booster pump.

The lateral spans are connected to the mobile tower through the rotating joint and reach a total height of approximately 4 metres, consisting of two 60-metre spans. Each span is composed of 6-metre galvanised steel tubes with a diameter of 140 mm, coupled with flanged joints and bolts, and reinforced with tie rods and galvanised steel carpentry. The spans are connected by articulated sleeves, and at each junction a truss structure — supported by two wheels — bears the load of the entire span assembly. The system terminates with a 10-metre suspended, modular boom arm, at the end of which a long-range sprinkler with a flow rate of 386 L min⁻¹ and a throw of 30 metres is installed, supplied by a booster pump operating at 4.4 bar. The total steel structure length is 130 metres and, including the terminal sprinkler, irrigates a strip of approximately 160 metres. The distribution apparatus operates at approximately 2 bar with a theoretical flow rate of approximately 90,000 L h⁻¹.

The distribution system consists of static and rotating low-pressure sprinklers, mounted inverted on drop tubes made of plastic material and stabilised by 25 mm diameter galvanised steel tubing. Sprinkler configuration varies according to position and operating mode: 180° sprayers with reduced flow rates are installed near the metallic structural elements, while 360° sprayers are positioned within the spans. Hydraulic valves regulate nozzle operation during pivot mode. In linear mode, all sprayers

in the first span are active, while half of those in the second span are closed; in pivot mode, this configuration is reversed. The advancement system is sequential, with timed and scaled start-stop cycles governed by the control panel, which monitors misalignment sensors located at the span joints to coordinate movement across all spans. Maximum theoretical advance speed is 3.4 metres per minute, equivalent to approximately 200 m h⁻¹. Motor power ranges from 0.6 to 1 HP depending on the required advancement speed.

Liquid Effluent Distribution System

The liquid effluent distribution system operates independently from the irrigation circuit, utilising a horizontal chopper pump ("Doda" model) equipped with a rotating blade and fixed counter-blade mechanism designed to reduce fibrous components present in bovine effluent and improve flow conditions. The pump is driven by the power take-off of a 74 kW tractor and draws directly from the slurry storage tank. The effluent is conveyed through the same underground pipeline network used for irrigation, with the electric irrigation pump isolated by a dedicated valve. Separation between the fertilisation and irrigation lines is achieved via a T-fitting installed downstream of the rotating joint: through a system of valves, the span pipeline is closed and the PVC slurry conduit is opened.

The effluent distribution pipeline is integrated within the structural framework of the hippodrome system spans. Pipe diameter decreases progressively with distance from the inlet, reflecting the reduction in flow rate along the line. Immediately after the T-fitting and the subsequent bend, the diameter is reduced from 140 to 100 mm. The subsequent pipeline consists of 6-metre UPVC tubes anchored to the structure with chains or harness fittings. For the first 54 metres — approximately corresponding to the length of the first span — the pipe diameter is 90 mm; over the following 54 metres the diameter reduces to 75 mm, and over the final 24 metres it further decreases to 63 mm. This progressive diameter reduction ensures continuity of operating pressure as flow rate decreases along the line.

Drop tubes consisting of 25 mm diameter rubber hoses are connected to the UPVC pipeline via saddle clamps at 3-metre intervals, bringing the distributor to approximately one metre above the ground surface. Each distributor consists of a PVC valve — for manual shut-off in case of blockage — and a circular conical stainless steel deflector plate, which produces a broadcast distribution pattern with a diameter of approximately three metres, consistent with the spacing between drop tube positions.

Crop Management

The preceding crop in the experimental field was second-crop maize, harvested as silage on 5 November 2024. Following harvest, soil conditions were suboptimal due to abundant rainfall, with high moisture content and localised waterlogging. To restore suitable seedbed conditions, targeted soil aeration operations were carried out in addition to standard tillage practices. Specifically, subsoiling was performed on 20 November, followed by shallow eco-ploughing at approximately 15 cm depth on 25 November. In spring, a rotary harrow pass and subsequent Cambridge roller consolidation were performed on 7 and 15 April, respectively, to refine the seedbed and improve capillary water retention. Maize (*Zea mays* L.) was sown on 29 April using a six-row precision planter at 75 cm row spacing. At sowing, a localised application of monoammonium phosphate (NP 12-52) at 130 kg ha⁻¹ was performed, together with a pyrethroid soil insecticide (Tefluthrin-based). Early post-emergence herbicide treatment was carried out on 3 May. Inter-row cultivation was performed on 29 May at the six-to-seven leaf stage. Nitrogen top-dressing was applied differentially across the field: granular urea (46% N) at 300 kg ha⁻¹ was used in the areas not covered by the linear irrigation system, while liquid bovine effluent — previously separated from the solid fraction — was distributed via the articulated boom system in the remaining areas. Harvest took place on 31 August and 1 September using a Claas Lexion 7700 combine harvester equipped with an 8-row header and Fieldview data acquisition technology.