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Linear programming for regulation-compliant digestate disposal in Spanish biogas plants

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Resumen

La digestión anaerobia convierte materias orgánicas en biogás y un digerido rico en nutrientes cuya aplicación al suelo devuelve nutrientes a los cultivos próximos. La asignación de lotes de digerido a parcelas elegibles está condicionada por los Reales Decretos 1051/2022 y 47/2022, por marcos autonómicos como el Decreto 153/2019 de Cataluña, y por la demanda de nutrientes y el estado del suelo, generando un problema de planificación con numerosas restricciones. Este trabajo formula un modelo de programación lineal sobre un horizonte de 12 meses que asigna digerido entero o separado a parcelas priorizando las más próximas a la planta, sujeto a límites de nitrógeno, metales pesados y salinidad. El modelo se resuelve mensualmente en un esquema de horizonte deslizante estabilizado por una penalización sobre los cambios en las decisiones comprometidas. En un escenario sintético de 2 000 parcelas, se cumplen todos los umbrales normativos y la planta obtiene un plan mensual de aplicación recalculable ante cambios normativos.

Palabras clave: Sistemas logísticos complejos, Sistemas inteligentes de apoyo a la decisión en fabricación, Modelado y toma de decisiones en sistemas complejos, Optimización y control de sistemas en red a gran escala, Planificación y control de la producción.

Linear Programming for Regulation-Compliant Digestate Disposal in Spanish Biogas Plants

Abstract

Anaerobic digestion converts organic feedstocks into biogas and a nutrient-rich digestate whose land application closes the nitrogen loop and offsets part of nearby croplands' synthetic-fertilizer demand. Allocating digestate batches to eligible parcels is constrained by Spanish Royal Decrees 1051/2022 and 47/2022, by autonomous-community frameworks such as Catalonia's Decree 153/2019, and by crop nutrient demand and soil status, yielding a large constrained planning problem. This work formulates a linear programming model over a 12-month horizon with monthly time steps that allocates whole or separated digestate to parcels, prioritising those closest to the plant, subject to nitrogen, heavy-metal and salinity limits. The model is re-solved every month within a rolling-horizon scheme stabilised by a penalty on changes to previously committed decisions. On a synthetic scenario of 2,000 parcels, all regulatory thresholds are met and the plant obtains a monthly application plan that can be recomputed as regulations change.

Keywords: Complex logistic systems, Intelligent decision support systems in manufacturing, Modelling and decision making in complex systems, Optimization and control of large-scale network systems, Production planning and control.

1. Introduction

Anaerobic digestion (AD) converts organic feedstocks (livestock manure, agro-industrial waste and the organic fraction of municipal solid waste) into biogas (typically 50–70 % CH_4 and 30–50 % CO_2) and a nutrient-rich digestate (European Biogas Association, 2023). Unlike most industrial by-

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products, digestate retains agronomic value: because biogas consists mainly of CH_4 and CO_2, the mineral elements N, P and K present in the feedstocks are largely conserved in the digestate (European Biogas Association, 2023). Digestate can therefore replace part of the synthetic nitrogen applied to cropland, lowering fertilization costs and returning nutrients to the soil. Figure 1 illustrates the complete management cycle: organic feedstocks enter the digester; the resulting digestate is stored and, where a separator is available, split into a liquid fraction and a solid fraction; whether separated or used as whole digestate, each fraction is then distributed to nearby agricultural parcels, returning nutrients to the land. The biogas co-produced during digestion is upgraded to biomethane and injected into the gas network, closing the energy loop.

The scale of this resource is now substantial and continues to grow. Europe already hosts more than 19 000 biogas and 1 400 biomethane plants (Asociación Española de Biocircularidad, 2025), and approximately 73 % of their digestate output reaches agricultural land as a biofertilizer (European Biogas Association, 2023). With production projected to rise from 31 Mt of dry matter (DM) per year in 2022 to 177 Mt DM/year by 2050 (Table 1), systematic management of digestate allocation is needed for both environmental compliance and day-to-day plant operation.

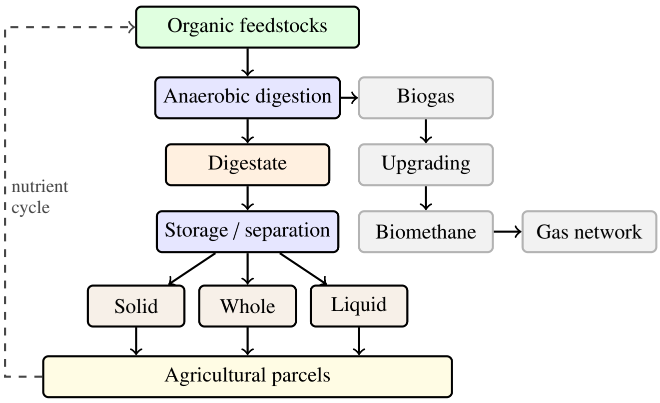

Figure 1: Digestate and biogas management cycle in an anaerobic digestion facility.

Table 1: Projected European digestate production up to 2050 (European Biogas Association, 2023).

	2022	2030	2050
Total digestate (Mt DM/year)	31	75	177

Deciding which parcel receives which digestate fraction, in what quantity and month, is highly constrained. Nutrient and heavy-metal composition must be matched to each crop's nitrogen demand without exceeding the thresholds of a layered regulatory framework: in Spain, national decrees, nitrate-vulnerable-zone action programmes and autonomous-community rules each impose binding caps on application rates, seasonal windows and soil-quality limits. The nitrogen fraction is of particular concern, since the higher ammonium-to-organic-nitrogen ratio of digestate raises short-term efficacy but also the leaching risk if timing and dose are not controlled (European Biogas Association, 2023). Slope, soil saturation and ban periods further narrow the feasible window, making manual scheduling of a plant serving thousands of dispersed parcels a complex task.

Quantitative approaches for biomass and organic waste supply chains have been reviewed by Pantet et al. (2026), who identify linear programming (LP) as a recurrent modelling choice when allocation decisions are continuous and constraints are linear. Despite this body of work, no published model integrates the full three-tier stack of Spanish nutrient regulations at individual parcel resolution. This paper formulates an LP model that enforces national, nitrate-vulnerable-zone and autonomous-community constraints simultaneously, handles whole, solid and liquid digestate fractions in a unified formulation, and embeds the model in a rolling-horizon scheme that re-optimises a full 12-month plan each month while stabilising previously committed allocations. The model is tested on a synthetic dataset of 2 000 parcels. Section 2 reviews the regulatory framework. Sections 3–5 present the formulation and solution approach. Section 6 reports the case study and Section 7 concludes.

2. Regulatory framework

At each facility the digestate co-produced with biogas can reach tens of thousands of tonnes per year (European Biogas Association, 2023). Its land application is governed by three regulatory tiers, described in the following subsections: national decrees, nitrate-vulnerable-zone action programmes, and autonomous-community rules.

2.1. National level

At the national level, Royal Decree 1051/2022 (Government of Spain, 2022a) sets minimum good agricultural practices for nutrient application, including closed periods, buffer distances to watercourses, slope and saturated-soil restrictions, mandatory fertilization plans, and heavy metal thresholds for soils and applied materials (Annex IV of RD 1051/2022).

2.2. Nitrate-vulnerable zones

Nitrate-vulnerable zones (NVZs) are areas designated under EU Directive 91/676/EEC as at risk of nitrate pollution from agricultural sources. Royal Decree 47/2022 (Government of Spain, 2022b) establishes the autonomous-community action programmes for these zones, which cap organic nitrogen loading at 170 kg N ha^{-1} yr^{-1}.

2.3. Regional frameworks

Autonomous communities have the authority to define additional agronomic fertilizer limits on top of the national baseline, and in many cases this legislation is recent or still being developed. Catalonia's Decree 153/2019 (Government of Catalonia, 2019), for example, sets total nitrogen limits by crop type (Annex 5) that can be more restrictive than the national 170 kg N/ha cap; the model parameterises these per parcel and crop type.

3. Problem statement

The allocation task is a large-scale agricultural nutrient management problem: digestate batches produced at the plant must be matched to eligible parcels over time while complying with crop nutrient demand, soil status and the regulatory windows described in Section 2. In practice, parcel geometry, area and declared crop can be retrieved from public registries such as SIGPAC (*Sistema de Información Geográfica de Parcelas Agrícolas*). Nutrient and heavy-metal concentrations of each digestate fraction (whole, solid or liquid) are measured monthly in the laboratory and enter the model as parameters. These measurements characterise the digestate product, not the soil nutrient state: compliance limits are expressed as applied dose per hectare, so rainfall-driven soil changes do not alter the enforced limits, and application on saturated soils is in any case barred by RD 1051/2022.

4. Mathematical model

The allocation model is a linear program (LP) with a 12-month planning horizon discretised in monthly time steps. The horizon spans a full year because the nitrogen cap is annual and the digestate that accumulates during the summer ban requires foresight over the whole year. The monthly time step matches the coordination granularity with farmers; short-term weather variability is absorbed at the daily operational layer and through the monthly re-optimisation (Section 5). Because the horizon usually crosses the calendar boundary, two calendar years are indexed simultaneously to allow per-year nitrogen accounting against the running calendar limit.

4.1. Sets and indices

Time.

- $t \in T$: months in the planning horizon, $|T| = 12$.
- $y \in Y$: calendar years intersected by the horizon, $|Y| \leq 2$.
- $T_y \subseteq T$: months belonging to year y.
- $T^F \subseteq T$: months with a country-wide application ban.
- $T_c^F \subseteq T$: months in which application is forbidden on crop c.
- $T_p^C \subseteq T$: months in the crop calendar of parcel p (harvest month and growing period) in which application is prohibited.

Plant.

- $d \in D$: digestate types (whole, solid, or liquid fraction).
- $s \in S$: storage tanks.
- $D_s \subseteq D$: digestates compatible with tank s.

Parcels and crops.

- $p \in P$: agricultural parcels.
- $c \in C$: crops.
- $P_c \subseteq P$: parcels declared with crop c.
- $P^-, P^+ \subseteq P$: parcels with soil pH below 7 and at or above 7, respectively.

Substances.

- $m \in M = \{N_{org}, N_{am}, P, K\}$: nutrients.
- $h \in H = \{Cd, Cu, Ni, Pb, Hg, Zn, Cr(VI), As\}$: heavy metals.
- $q \in Q = M \cup H$: tracked substances.

4.2. Parameters

Plant.

- ρ_d: density of digestate d (ton/m^3).
- η_d: dry-matter fraction of digestate d.
- κ_{dq}: concentration of substance q in digestate d (% of DM for $q \in M$, mg/kg of DM for $q \in H$).
- γ_d: electrical conductivity of digestate d (dS/m).
- G_{dt}: generation of digestate d in month t (ton).
- I_s^{INI}: initial inventory of tank s (m^3).
- I_s^{MIN}, I_s^{MAX}: lower and upper capacity of tank s (m^3).

Parcels.

- A_p: area of parcel p (ha).
- $\ell_p = d_{\max}/(d_p + 0.1)$: proximity score of parcel p, where d_p is the road distance (km) from the plant to parcel p and $d_{\max} = \max_{p \in P} d_p$. The mapping is strictly decreasing in d_p, so the term ℓ_p enters the objective (18) with a negative sign to prioritise nearby parcels; the +0.1 offset prevents exponential growth when $d_p \approx 0$.
- $\pi_p \in \{0, 1\}$: operator-assigned priority indicator. Parcels with $\pi_p = 1$ receive an additional unit of objective reward on top of the proximity score ℓ_p, directing the model to serve them preferentially; parcels with $\pi_p = 0$ compete for digestate based on proximity only.
- H_{ph}^{INI}: initial soil concentration of heavy metal h in parcel p (mg/kg).
- γ_p^{INI}: initial soil electrical conductivity in parcel p (dS/m).
- A_{pd}^{INI}: amount of digestate d already applied to parcel p in the running calendar year prior to the current run (ton).

Regulatory thresholds.

- N_p^{MAX}: annual nitrogen cap on parcel p (kg N/ha); equals 170 in nitrate-vulnerable zones, the fertilization-plan crop demand otherwise.
- γ_p^{MAX}: salinity cap on parcel p (dS/m).
- M_h^-, M_h^+: national maximum soil concentration of heavy metal h in low- and high-pH parcels (mg/kg).
- B_h: national maximum yearly contribution of heavy metal h to soil (g/ha).
- θ_h^-, θ_h^+, β_h: regional analogues of M_h^-, M_h^+, B_h enforced in autonomous communities with stricter limits.
- $\alpha \in (0, 1]$: compliance margin on the nitrogen cap ($\alpha = 1$ in the case study).

Soil physics constants.

- $\Sigma_{\text{HM}} = 1{,}762{,}750$ kg/ha: effective soil mass per hectare for heavy-metal dilution. Computed from a bulk density of about 1.41 g/cm^3 integrated over the top 25 cm (the EU-standard depth for organic amendments), yielding 3,525,500 kg/ha, then halved by a factor of 0.5 as a safety margin against non-uniform vertical distribution of heavy metals in agricultural soils.
- $\Sigma_{\text{EC}} = 3{,}525.5$ t/ha: soil mass per hectare for electrical-conductivity mixing, equal to the full top-25 cm mass in tonnes; no safety factor is applied because salinity changes mix proportionally with the applied volume.

4.3. Decision variables

Application.

- $x_{dpt} \geq 0$: amount of digestate d applied to parcel p in month t (ton).
- $X^{\text{tot}}_{dt} \geq 0$: total amount of digestate d applied in month t (ton).
- $X^{\text{year}}_{ydp} \geq 0$: amount of digestate d applied to parcel p in calendar year y including the carry-in A^{INI}_{pd} for the running year (ton).

Storage.

- $I_{st} \geq I^{\text{MIN}}_s$: inventory of tank s at the end of month t (m^3), bounded above by the soft capacity constraint (2).
- $\sigma_s \geq 0$: slack on the upper capacity of tank s (m^3); a positive σ_s is the volume of digestate that cannot be stored and must be removed through external disposal, penalised by w^S in the objective (19).

Substance contributions.

- $C_{qp} \geq 0$: cumulative contribution of substance q to parcel p over the horizon (kg/ha for nutrients, mg/ha for heavy metals).
- $C^{\text{year}}_{yqp} \geq 0$: contribution of substance q to parcel p within calendar year y (same units as C_{qp}).

End-of-horizon soil state.

- $H^{\text{fin}}_{ph} \geq 0$: soil concentration of heavy metal h in parcel p at the end of the horizon (mg/kg).
- $\gamma^{\text{fin}}_p \geq 0$: soil electrical conductivity in parcel p at the end of the horizon (dS/m).

4.4. Constraints

The mass balance for each tank equates the end-of-month inventory to the previous level, plus the volumes generated during the month, minus the volumes of compatible digestates withdrawn for field application:

$$I_{st} = I_{s,t-1} + \sum_{d \in D_s} \frac{G_{dt} - X^{\text{tot}}_{dt}}{\rho_d} \quad \forall\, s, t, \tag{1}$$

In (1), $I_{s,t_0-1} \equiv I^{\text{INI}}_s$ at the first month t_0 of the horizon. The inventory must respect each tank capacity, a bound softened by the slack σ_s so that an unavoidable surplus during the closed season is absorbed at a penalty rather than rendering the plan infeasible:

$$I_{st} \leq I^{\text{MAX}}_s + \sigma_s \quad \forall\, s, t. \tag{2}$$

Monthly and yearly aggregates of the application variable are defined by

$$X^{\text{tot}}_{dt} = \sum_{p \in P} x_{dpt} \quad \forall\, d, t, \tag{3}$$

$$X^{\text{year}}_{ydp} = \begin{cases} A^{\text{INI}}_{pd} + \sum_{t \in T_{y_1}} x_{dpt} & \text{if } y = y_1, \\ \sum_{t \in T_y} x_{dpt} & \text{if } y > y_1, \end{cases} \quad \forall\, y, d, p, \tag{4}$$

where $y_1 \in Y$ is the first calendar year of the horizon. The term A^{INI}_{pd} accounts for the amount already applied before the current run, and is added only in year y_1 because the annual nitrogen cap is computed from the start of that calendar year, not from the planning horizon start.

Each gross ton applied carries $1000\,\eta_d$ kg of dry matter, in which the mass fraction of substance q is κ_{dq}. Dividing by the parcel area yields the per-hectare contribution over the horizon and per calendar year:

$$C_{qp} = \frac{1000}{A_p} \sum_{d \in D} \sum_{t \in T} \eta_d\, \kappa_{dq}\, x_{dpt} \quad \forall\, q, p, \tag{5}$$

$$C^{\text{year}}_{yqp} = \frac{1000}{A_p} \sum_{d \in D} \eta_d\, \kappa_{dq}\, X^{\text{year}}_{ydp} \quad \forall\, y, q, p. \tag{6}$$

Modelling the heavy-metal contribution as uniformly distributed across the top 25 cm of soil (a standard estimate for organic amendment studies) and adding the digestate-driven conductivity change to the soil baseline give, respectively,

$$H^{\text{fin}}_{ph} = H^{\text{INI}}_{ph} + \frac{C_{hp}}{\Sigma_{\text{HM}}} \quad \forall\, p, h, \tag{7}$$

$$\gamma^{\text{fin}}_p = \gamma^{\text{INI}}_p + \frac{1}{\Sigma_{\text{EC}} A_p} \sum_{d \in D} \sum_{t \in T} \gamma_d\, x_{dpt} \quad \forall\, p. \tag{8}$$

Plan stabilisation uses non-negative slacks δ^+_{dpt} and δ^-_{dpt} (ton). Where the previous run committed $\hat{x}_{dpt} > 0$, the new allocation is written as that value plus a positive deviation minus a negative deviation; otherwise both slacks are zero:

$$\begin{aligned} x_{dpt} &= \hat{x}_{dpt} + \delta^+_{dpt} - \delta^-_{dpt} && \text{if } \hat{x}_{dpt} > 0, \\ \delta^+_{dpt} &= \delta^-_{dpt} = 0 && \text{otherwise.} \end{aligned} \tag{9}$$

The objective (19) minimises $\delta^+_{dpt} + \delta^-_{dpt}$, so at the optimum at most one is non-zero and their sum equals $|x_{dpt} - \hat{x}_{dpt}|$, the standard linearisation of an absolute value. Where nothing was committed the slacks vanish and x_{dpt} stays free, penalising only changes to committed allocations.

4.5. Physical and agronomic constraints

Application is prohibited during the harvest month of the parcel's crop and during the months between sowing and harvest, both collected in the set T^C_p:

$$x_{dpt} = 0 \quad \forall\, d,\ p,\ t \in T^C_p. \tag{10}$$

4.6. Regulatory constraints

The organic plus ammoniacal nitrogen applied per hectare must respect $\alpha\, N_p^{\mathrm{MAX}}$ both over the rolling horizon and within each calendar year intersected by the horizon. Inside nitrate-vulnerable zones (RD 47/2022) $N_p^{\mathrm{MAX}} = 170$ kg N/ha; outside such zones, N_p^{MAX} equals the crop demand set by the parcel's fertilization plan under RD 1051/2022. The two caps read

$$C_{\mathrm{N_{org}},p} + C_{\mathrm{N_{am}},p} \le \alpha\, N_p^{\mathrm{MAX}} \quad \forall\, p, \tag{11}$$

$$C^{\mathrm{year}}_{y,\mathrm{N_{org}},p} + C^{\mathrm{year}}_{y,\mathrm{N_{am}},p} \le \alpha\, N_p^{\mathrm{MAX}} \quad \forall\, y, p. \tag{12}$$

End-of-horizon soil salinity must not exceed the parcel-specific cap,

$$\gamma_p^{\mathrm{fin}} \le \gamma_p^{\mathrm{MAX}} \quad \forall\, p. \tag{13}$$

Final soil heavy-metal concentrations must respect the limit set for the parcel's pH stratum, both nationally (Annex IV of RD 1051/2022) and, where they apply, regionally:

$$H_{ph}^{\mathrm{fin}} \le \begin{cases} \min\{M_h^-, \theta_h^-\}, & p \in P^-, \\ \min\{M_h^+, \theta_h^+\}, & p \in P^+, \end{cases} \quad \forall\, p, h. \tag{14}$$

The mass of heavy metal added per hectare and year respects the national cap B_h (g/ha) and the tighter regional cap β_h where it applies; expressing C_{hp} in mg/ha,

$$\frac{C_{hp}}{1000} \le \min\{B_h, \beta_h\} \quad \forall\, h, p. \tag{15}$$

A country-wide ban suppresses any application during the months in T^F (typically the summer months), and additional crop-specific bans suppress application on the parcels declared with each affected crop:

$$X_{dt}^{\mathrm{tot}} = 0 \qquad \forall\, d,\ t \in T^F, \tag{16}$$

$$x_{dpt} = 0 \qquad \forall\, d,\ c,\ p \in P_c,\ t \in T_c^F. \tag{17}$$

4.7. Objective function

The base objective J_0 minimises residual inventory and the storage-overflow slack while rewarding nearby and priority application, with weights $w^I = 10$ and $w^S = 100$:

$$\min\ J_0 = w^I \sum_{s,t} I_{st} + w^S \sum_s \sigma_s - \sum_{d,p,t} (\ell_p + \pi_p)\, x_{dpt}. \tag{18}$$

These weights encode a priority ordering rather than monetary costs: the large ratio w^S/w^I ensures external disposal is the last resort before letting a tank overflow, while w^I keeps tanks as empty as possible to buffer the summer ban. Calibrating against explicit transport and waste-handling costs is left for future work.

5. Rolling-horizon approach

Operational conditions change every month in ways a single annual plan cannot anticipate: adverse weather, saturated soils, or the decision not to apply on a given day regularly prevent scheduled allocations from being executed. Re-solving the LP each month on a fresh snapshot accounts for this. This receding-horizon re-optimisation follows the principle of model predictive control: a full 12-month plan is computed each month, the imminent allocations are executed, and the horizon advances one step before re-solving. The committed plan from the previous run is fed back as the parameter $\hat{x}_{dpt}$; without continuity across runs churn arises, so deviations from that commitment are penalised in the objective.

5.1. Parameters and objective

- $\hat{x}_{dpt}$: allocation committed for (d, p, t) by the previous run, fed back as a fixed parameter (ton).
- δ^+_{dpt}, $\delta^-_{dpt} \ge 0$: positive and negative deviation slacks from the committed plan (ton).
- $w^\Delta = 20$: weight on the deviation penalty.

The complete objective used in all computations is:

$$\min\ J = w^I \sum_{s,t} I_{st} + w^S \sum_s \sigma_s - \sum_{d,p,t} (\ell_p + \pi_p)\, x_{dpt} + w^\Delta \sum_{d,p,t} (\delta^+_{dpt} + \delta^-_{dpt}), \tag{19}$$

where w^Δ is tuned so that deviation costs dominate proximity gains only when churn would compromise the following month's logistics.

6. Case study and results

The model is implemented in Pyomo 6 under Python 3.13 and solved by HiGHS 1.12.0 (Huangfu and Hall, 2018), an open-source solver. Each monthly instance contains about 166,000 variables and 149,600 constraints and is solved to optimality in roughly 8 s on a standard laptop, including model construction and data handling.

The model is evaluated on a synthetic dataset of 2,000 agricultural parcels covering a combined area of approximately 15,500 ha. Of these, 972 parcels (7,747 ha) lie within a nitrate-vulnerable zone and are therefore subject to the 170 kg N/ha annual cap of RD 47/2022; the remaining 1,028 parcels (7,760 ha) are governed by crop-demand limits under RD 1051/2022. Parcel areas range from 0.5 to 15 ha and road distances from the plant from 0.1 to 20 km. These attributes, with slope and the vulnerable-zone and priority flags, are independent random draws over realistic ranges under a fixed seed for reproducibility, whereas the digestate composition and soil baselines are set to representative laboratory measurements. Each parcel is assigned one of five crops representative of the Castilla y León cereal system (winter wheat, winter barley, maize, sunflower and sugar beet), drawn in proportion to their regional area shares so that autumn-sown winter cereals occupy about 80 % of the land. Their sowing–harvest calendars set, for each parcel, the months in which application is forbidden. The plant operates two storage tanks, 50,000 m^3 for the liquid fraction and 4,000 m^3 for the solid fraction, both close to full at the start of the horizon after the preceding summer ban. Weekly generation rates are 3,000 m^3 (liquid) and 250 m^3 (solid), or about 13,000 and 1,083 m^3 per month.

The blue bars in Figure 2 report the monthly plan for the September 2026 start (run 1, objective value 892,313). The liquid fraction accounts for 96 % of the 156,296 m^3 applied over the horizon, consistent with its larger generation rate. Application peaks in September (about 64,000 m^3), when the near-full tanks are emptied onto winter-cereal parcels in their pre-sowing window, the only month in which that 80 % of the land is open. From October to April the plant applies close to

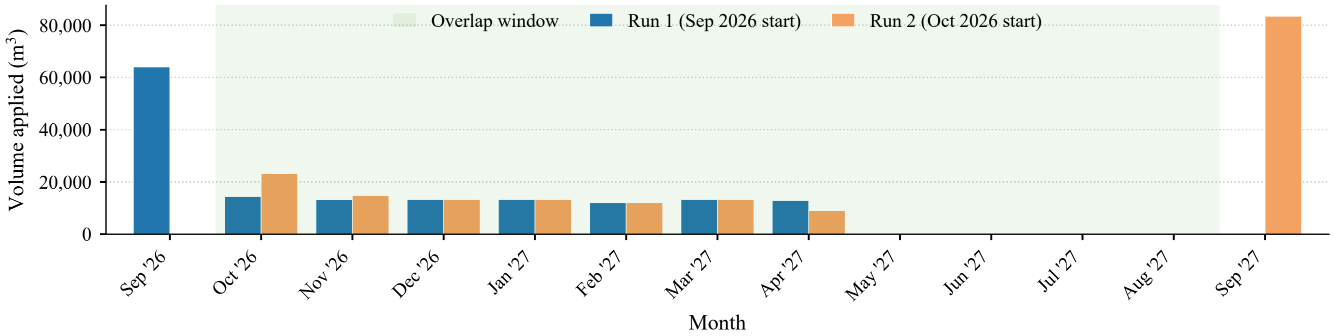

Figure 2: Monthly applied volume. Blue: run 1 (September 2026 start); orange: run 2, re-optimised from October after only 80 % of the September plan is executed. The plans nearly coincide over the shaded overlap window, differing mainly in October.

its monthly production (12,000–14,400 m^3) on the row-crop parcels that are free over winter, holding tank inventories near zero. The closed season then blocks application for four consecutive months: May because all five crops are simultaneously in the ground, and June to August under the national ban (RD 1051/2022). Production accumulates and the liquid tank fills and then exceeds its 50,000 m^3 capacity in August, where the storage slack of Eq. (2) activates: 2,192 m^3 of liquid and 6,514 m^3 of solid digestate must be removed through external channels at a penalty cost. The larger solid share reflects its small tank together with the fact that the liquid fraction consumes most of the available nitrogen budget on the limited winter land. No nitrogen, heavy-metal, or salinity limit is violated in any parcel or month.

The orange bars in Figure 2 show the rolling-horizon update. Once the September plan is computed, we assume that only 80 % of the planned September application is carried out, for instance because of adverse field conditions, and advance the horizon by one month. Run 2 re-optimises from October over its own 12-month window. The unapplied September volume remains in the tanks, raising the October starting inventory of the liquid fraction to 11,746 m^3, and the run 1 plan for the overlapping months is fed back as the committed reference $\hat{x}_{dpt}$ through the deviation term of Eq. (19). The updated plan stays close to the original over the overlap (October 2026–August 2027): the total L_1 deviation is 18.6 %, almost entirely concentrated in October, which rises from 14,393 to 23,152 m^3 to absorb the September shortfall. The remaining months reproduce the run 1 profile, and the next pre-sowing window (September 2027) again receives the bulk of the accumulated production. The deviation penalty thus keeps the operational plan stable under disturbances while respecting every storage and regulatory limit.

7. Conclusions

This work presents an LP model for digestate allocation in biogas plants, embedded in a rolling-horizon scheme that re-optimises a 12-month plan each month as field conditions change. The formulation handles whole, liquid and solid fractions in a unified model, enforces the three-tier Spanish regulatory stack at individual parcel resolution, and rewards nearby application while penalising inventory accumulation and schedule churn through a weighted objective.

On a case study of 2,000 parcels and two storage tanks, each monthly plan is found in roughly 8 s, confirming that the approach is computationally efficient for monthly replanning at plant scale. All regulatory thresholds (nitrogen caps, heavy-metal limits and salinity bounds) are satisfied in every parcel and every month; when the closed season leaves no eligible parcel and storage fills, the model quantifies the surplus that must be sent to external disposal through the capacity slack rather than returning an infeasible plan. By construction, the proximity term in the objective favours the parcels closest to the plant, so transport effort stays low without a separate distance-minimisation objective.

Two directions are identified for future work:

- Precipitation uncertainty will be incorporated into the planning model so that months with high expected rainfall are assigned reduced application volumes.
- The model will be extended to support multiple crops per parcel within the planning horizon.

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