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Statistical Analysis Based on Monte Carlo Method of the Technical and Economic Feasibility of Biomass Flame Weeding: Case Study of an Organic Farm

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Abstract: This work aims to evaluate the introduction of biomass flame weeding (FW) as a carbon-neutral technology for weed management in agricultural enterprises. The case study focuses on a biodynamic farm in the Molise region (Italy) introducing FW as a complementary technology alongside the traditional mechanical methods. In the project layout FW is applied exclusively around the trunks of olive and vine crops. The case study foresees the generation of thermal energy required for FW using a gasifier powered directly by the woody biomass waste produced by the farm. The production of biochar as a solid by-product of the gasification process was also examined. The economic analysis was conducted by structuring a simulation based on the Monte Carlo method, applied to the Net Present Value (NPV). Three output parameters were taken into consideration: NPV at the final year of investment, Internal Rate of Return and the payback period. For each parameter, a corresponding probability distribution was established. The results indicate that the average NPV can range from €6,342.27 to €9,796.06. Furthermore, the probability that the payback period is between zero and fifteen years can vary between 78.2% and 83.9%, suggesting a strong capacity for the project to be self-sustaining.

Keywords: Flame weeding; Weed management; Biochar; Monte Carlo; Statistical analysis

1. Introduction

In 2022, the total wasted generated within the European Union from all human activities amounted to 2,233 Mt, equivalent to 4.991 t per capita, which drops to 794.9 Mt if inert waste from extraction and demolition activities is excluded. In particular, waste originating from the agro-forestry sector amounted to 22.3 million tonnes (European Union, 2024).

The global population is expected to reach 9.7 billion by 2050 and 10.4 billion by 2100 (United Nations, 2019). Inevitably, the global demand for food and resources will increase, making it necessary to boost agricultural and food production. It is therefore crucial for the agricultural sector to adapt to these new external pressures in order to remain competitive while minimizing its environmental impact (Toop et al., 2017). Modern agriculture thus faces a major challenge that could lead to a radical transformation of the sector: the integration of circular economy principles as a resource management model, allowing farms to become self-sufficient ecosystems.

The current literature emphasizes that the circular economy model has not yet been comprehensively adapted to agriculture (Velasco-Muñoz et al., 2022).

Effective weed control is essential in agricultural practice to ensure optimal crop development. The presence of weeds is indeed directly associated with yield losses, competition for nutrients, and a heightened risk of fungal infections and pest infestations (Gagliardi et al., 2023).

The most widespread weed control techniques in agriculture can be categorized into four main groups (Gagliardi et al., 2023; Morselli et al., 2023):

❖ **Mechanical weeding**—such as shredding, ploughing, or hoeing, based on physical principles of weed and root system removal through mechanical action;

❖ **Chemical weeding**—using herbicidal substances, typically divided into contact herbicides, systemic herbicides, or residual herbicides;

❖ **Thermal weeding**—based on breaking cell membranes through thermal shock;

❖ **Physical barriers**—such as mulching, involving the application of various materials to physically prevent weed growth.

An Italian study conducted in 2022 in the provinces of Modena and Reggio Emilia shows that chemical and mechanical weeding are the most commonly used methods in vineyard cultivation, with chemical weeding being more prevalent when considering the treated surface area (Morselli et al., 2023). Chemical weeding techniques are generally preferred for their cost-effectiveness, operational simplicity, and rapid application. However, these methods can cause significant negative environmental impacts (Kudsk & Streibig, 2003).

Flame weeding (FW) is among the thermal weed control techniques used in agriculture. It was widely adopted from the 1930s until the mid-20th century, but declined with the rise of mass-produced and commercially available herbicides. Since the 1980s, FW has experienced a resurgence (particularly in organic farming) as a viable alternative to chemical methods. Its renewed adoption is driven by the ban on most commercial agrochemicals in organic systems, along with the technique's rapid application and environmentally sustainable potential (Bolat et al., 2017).

FW is technically based on the destruction of the cellular membranes of weeds. By applying a strong thermal shock, plant wilting is induced within a few days. The energy required for the process can be supplied in various ways, typically through an open flame (Bolat et al., 2017). Heat exchange occurs in fractions of a second at temperatures equal to or exceeding 100°C, triggering processes such as cellular membrane degradation and protein coagulation, which inhibit vital photosynthetic and respiratory functions (Hewitt et al., 1998).

Recent research on FW has increasingly focused on its potential for environmental sustainability. Several field trials have investigated FW systems powered by open flame generated through the combustion or gasification of woody biomass, often sourced from the farm's own organic waste. This approach substantially reduces CO_2 emissions per application compared to conventional weeding techniques, with the goal of achieving carbon neutrality. Emission reductions of up to 75% have been reported when compared to chemical weeding using glyphosate. Moreover, when biomass-based FW is compared to conventional LPG-powered FW, reductions can reach up to 118% if biochar is co-produced during the treatment process (Morselli et al., 2022; Pergher et al., 2019).

Gasification is defined as a thermal degradation process that occurs under oxygen-limited conditions, producing primarily synthesis gas (or 'syngas'), a mixture of reduced and oxidized gaseous compounds with variable calorific value. Industrial gasification typically operates at high temperatures (> 700°C), resulting in lower quantities of solid residues and greater syngas output compared to conventional methods such as pyrolysis. As a result, the biochar produced during gasification is generally considered a secondary by-product.

Biochar is defined as a carbon-rich solid material produced by heating biomass in an oxygen-limited environment (Joseph et al., 2010). Although predominantly composed of carbon, it also contains minor fractions of ash, hydrogen, nitrogen, and sulfur. Biochar can be derived from a wide range of organic feedstocks through thermal degradation processes such as pyrolysis or gasification (Hussain et al., 2017). Its physicochemical properties, particularly its macro and microporous structure, confer a high absorbent capacity, making it especially effective for rehabilitating degraded agricultural soils by enhancing water retention and nutrient holding capacity. These characteristics contribute to improved crop yields, reduced input requirements, and lower irrigation demand (International Biochar Initiative, 2024). As a result, biochar has generated significant interest for its agronomic potential and environmental benefits, and is increasingly recognized as a promising tool for climate change mitigation (Hussain et al., 2017).

Among long-term solutions for global warming one promising strategy involves producing biochar from biomass waste and storing it in the soil, where it can remain stable for hundreds or even thousands of years (Amonette et al., 2016). Implementing a circular economy model in agriculture presents considerable social and technological challenges. Advancing toward this objective requires innovation across multiple domains. This study aims to assess the potential of biomass-powered FW to capitalize on the current 'window of opportunity.' The analysis evaluates the feasibility and long-term economic sustainability of the technology over a fifteen-year horizon, taking into account recent technical advancements and the socio-economic context of a biodynamic farm in Italy. The results are analyzed to estimate the probability of the proposed scenario materializing.

2. Material and Methods

The subject of this case study is a farm located in the Molise region, in the municipality of Petacciato (CB). It is the largest agricultural enterprise in Molise by land area, covering approximately 530 hectares.

2.1 Residual Biomass Screening

In pursuit of optimal and circular resource management, an analysis was carried out on the material flows entering and leaving the farm system, the on-site agricultural activities, and the resulting biomass waste. The farm currently hosts approximately 300 dairy cattle, along with a smaller number of sheep and pigs. Most of the land is dedicated to the cultivation of diverse crops, including vineyards, olive groves, vegetables, cereals, and fodder.

The primary source of agricultural waste is animal manure, amounting to approximately 2,800 t y^{-1} predominantly from cattle. The second most significant biomass residue is derived from tomato processing, contributing around 360 t y^{-1}.

Additional notable sources include woody prunings from olive trees and vineyards (approximately 60 t y^{-1}), residues from both winter and summer vegetable cultivation (about 70 t y^{-1}), and olive pomace generated during oil extraction.

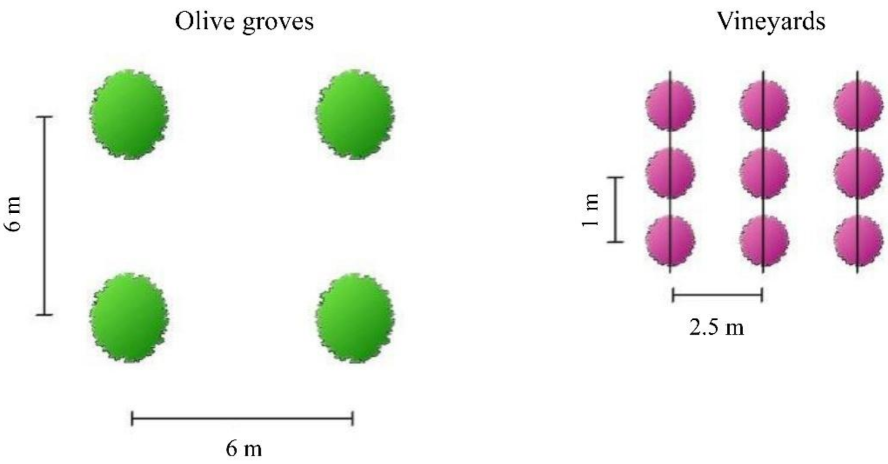


Figure 1. Standard layout of the farm's olive groves and vineyards

With regard to residual woody biomass, it is primarily composed of prunings generated during the winter maintenance of olive groves and vineyards, along with trimmings from minor or spring crops. Pruning in both crop types (olive and vine) is carried out manually, and the resulting woody materials differ significantly in terms of physical characteristics and size. The olive groves on the farm are mostly arranged in a 6 m × 6 m grid (Figure 1), allowing for semi-mechanized, low-intensity harvesting. Typically, between 10 kg and 40 kg of biomass is removed per olive tree during pruning, with branch diameters varying according to the technique used and the plant's developmental stage. In general, only branches with a diameter greater than 15–20 mm are collected and currently sold as firewood. The smaller-diameter material is left near the pruning site and subsequently shredded mechanically in the field.

The company vineyards are typically arranged in rows, most commonly following a 1 m × 2.5 m layout (Figure 1). Biomass yield per vine generally ranges from 0.8 kg to 1.5 kg of wet material, depending on the pruning technique employed and the plant's condition. The pruning residue from vines has markedly different physical characteristics compared to that of olive trees. Vine prunings, or 'sarments,' are generally slender, elongated branches with diameters ranging from 1 cm to 5 cm. Unlike olive prunings, they retain no foliage during winter pruning.

2.2 Project Description

Drawing on the input data gathered during the initial screening phase—and taking into account the operational needs of the farm—a project was developed to valorise a portion of the residual biomass. Specifically, the lignocellulosic fraction resulting from pruning activities was identified as having considerable potential to improve farm operations from both a technical and environmental perspective. The calorific value of these residues, estimated at approximately 18.84 MJ kg^{-1}, led to the development of a scenario focused on energy recovery through biomass-powered FW—a practice that has not yet been adopted in the farm's agricultural operations. This technique offers a dual benefit: the disposal of woody pruning waste and the management of weeds. The proposed project involves the use of a gasifier, with the simultaneous production of biochar as a solid by-product of the thermal process. The analysis was structured around two distinct management scenarios, followed by a detailed cost evaluation of each approach.

❖ **Scenario 1—Current practice.** Use of shredding alone as the method for both pruning waste disposal and weed control.

❖ **Scenario 2—Proposed solution.** Introduction of gasification-based FW as a means of valorizing woody pruning residues and controlling weeds. Shredding is retained as a complementary technology to support integrated weed management.

In order to assess the differences between the two biomass management approaches, average paths typically followed during the various operations on both olive groves and vineyards were estimated. For operational simplicity, the distances travelled were standardized per hectare, with each plot represented schematically as a square measuring 100 m by 100 m.

2.2.1 Current practice—Use of shredding only

Weed management on the farm is currently based on principles of operational simplicity, influenced in part by the prevailing agricultural traditions in the study area. Among the organic and biodynamic farms in the surrounding region, mechanical treatment represents the primary weed control technique in use.

Hammer or blade agricultural shredders powered by the tractor's power take-off (PTO) are the most commonly used machines, often complemented (particularly in vineyard) by mechanical inter-row cultivation tools.

Regarding the annual pruning activities, in both olive and vineyard plots, the woody residues produced are left directly on the ground, deposited in the central strip between rows. At a later stage, these residues are simply shredded, thereby optimizing both waste disposal and weed management operations. In the case of olive groves, larger-sized prunings are typically separated during pruning and sold as firewood. However, this portion represents only a small fraction of the total volume of prunings generated. The shredder used has an operational width of approximately 2.2 m. This means that, in olive groves laid out in a 6 m × 6 m configuration, three passes are required between each row. Based on this agricultural practice, the specific distance covered for shredding in olive groves under Scenario 1 is estimated at 5.41 km per hectare.

In vineyards, where the average spacing between rows is approximately 2.5 m, a single pass is typically carried out between each pair of rows using a hoeing blade, sucker remover, or similar inter-row implement, as a complementary technique to shredding.

2.2.2 Proposed solution—Introduction of flame weeding

The developed process layout involves allowing the woody biomass deposited between the rows to remain on the ground for a sufficient period, in order to reduce its moisture content and thereby optimize subsequent processing steps. When using a chipper towed by a suitable tractor and connected directly to the vehicle's PTO, the prunings are processed into wood chips of appropriate size. Commercially available chippers may be either trailer-mounted or configured with a three-point hitch. During chipping operations, the biomass is discharged via the machine's directional outlet into a trailer for subsequent transport and storage.

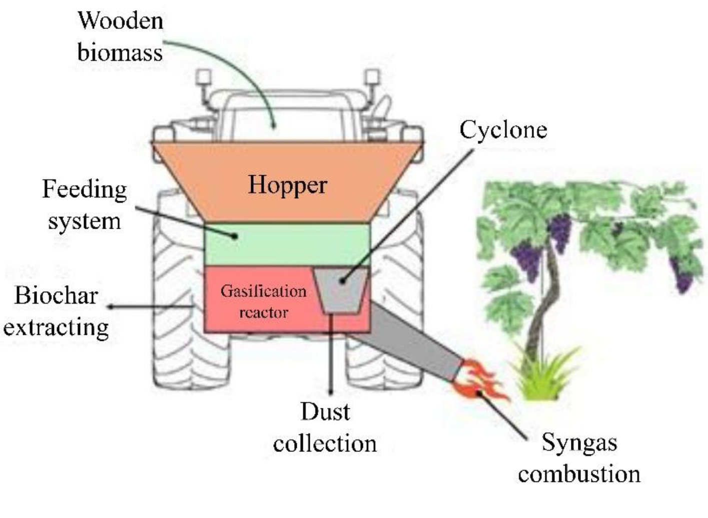


Figure 2. Biomass flame weeding layout

The wood chips produced through this process can be used to power a gasifier, which is likewise towed by an agricultural tractor (Figure 2). The aim of the gasification phase is the simultaneous production of biochar and weed control through FW. The outputs of the gasification process—distributed across solid, liquid, and gaseous phases—are managed as follows:

- ❖ Syngas, tars, and fine particular matter are combusted in a subsequent combustion chamber;
- ❖ The solid phase (biochar) is separated and recovered for use as an organic soil amendment.

The open flame generated by the combustion of syngas and its associated residues is captured by a ventilation system and directed onto unwanted vegetation through a dedicated distribution hood. As previously described, the thermal shock induced by FW causes the weeds to wilt without compromising the integrity of the cultivated woody plants.

The FW strip was considered to be 40 cm wide and applied along the entire length of each row. In both crop types, this results in a total treated width of 80 cm per row, accounting for application on both sides.

2.3 Economic Analysis

For the economic evaluation of the investment, the Net Present Value (NPV) method was selected, as it is considered one of the fundamental tools in financial analysis (Shou, 2022). The term NPV refers to the sum of all projected cash flows over the analysis period, discounted at a given rate. From a mathematical standpoint, the value of the invested capital at any point during the investment horizon is defined as shown in Eq. (1), where the year-zero cash flow corresponds to the initial investment cost:

$$NPV = \sum_{i=0}^{n} \frac{CF_i}{(1+r)^i} \tag{1}$$

where, CF_i is sum of the cash flows in the i^{th} year [€]; r is discount rate [%] and n is the investment time horizon [years].

By applying the Monte Carlo method, the computational model developed for this case study was structured to calculate a different NPV profile at each iteration, repeating the simulation for each selected discount rate. Through an optimisation cycle, a sufficient number of iterations was identified to ensure acceptable solution stability. Specifically, it was found that with 20,000 iterations, the mean NPV at the final investment year varied by approximately 0.55% between two independent Monte Carlo simulations. In the model presented, a 0.55% variation in the mean NPV corresponds to a deviation of €10^1, which is sufficiently small compared to the average NPV obtained, equal to €10^4.

The investment was modelled over a time horizon of 15 years, with cash flows discretised on an annual basis.

2.3.1 Input data—Definition of stochastic variables

Each variable selected for stochastic sampling via the Monte Carlo method was assigned an operational range along with a corresponding probability distribution function. With the exception of the market price of agricultural diesel, these distributions were chosen to be uniform, triangular, or Program Evaluation and Review Technique (PERT). In total, 24 variables were selected for stochastic sampling during each simulation cycle.

Table A1 lists all the model variables subjected to stochastic sampling at each iteration. For each variable, the corresponding probability distribution type and the operational range implemented are also provided.

The factors considered in the economic analysis were as follows:

1) Woody biomass production
2) Purchase price of the chipper
3) R&M (Repair & Maintenance) costs of the chipper
4) Price of agricultural diesel
5) Wood chip production costs
6) Purchase price of the gasifier
7) Costs differences in weed management
8) Avoided shredding of olive prunings
9) Biochar production
10) Biochar sale price
11) Wood chip sale price
12) Financing

Woody biomass production. With reference to the biomass screening previously conducted, the model incorporated benchmark values of 28.0 t y^{-1} for vineyard prunings and 32.6 t y^{-1} for olive prunings. In each iteration, these values were sampled uniformly within a ± 30% range, assuming equal probability of occurrence across the interval.

Purchase price of the chipper. Once the technical specifications suitable for the present project were defined, a market screening was conducted to assess the purchase prices of chippers that met the defined specifications. Fifteen models were selected along with their corresponding purchase costs. A basic statistical analysis was performed to eliminate potential outliers from the sample set. A PERT distribution was then constructed for the chipper purchase price, based on the minimum, maximum, and mean values of the validated sample.

R&M costs of the chipper. Based on a statistical study from the literature (Spinelli et al., 2019), these costs were estimated according to the number of operating hours and the initial purchase price of the chipper. Operating hours were calculated using a benchmark productivity rate of 1.27 t h^{-1}. This variable was sampled within a ± 20% uniform distribution, with an additional 1% annual reduction in productivity applied over the investment period.

Price of agricultural diesel. A sub-simulation was embedded within the main model to simulate variation in agricultural diesel prices over the investment time horizon during each iteration.

To implement this sub-model, a detailed statistical analysis was conducted on the historical dataset of agricultural diesel prices from January 2003 to December 2023. Subsequently, a review of the main statistical models commonly used for time series forecasting was carried out, ultimately selecting the GJR-GARCH model as the most appropriate.

Figure 3 illustrates, by way of example, a simulated trajectory of agricultural diesel prices from one of the 20,000 iterations of the overall simulation.

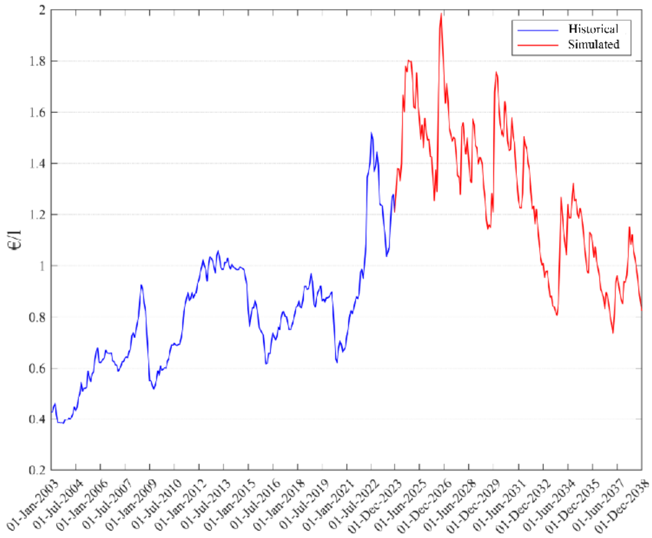


Figure 3. Agricultural diesel price—2003–2023 historical data and sample simulation of a model iteration

Wood chip production costs. The estimation of wood chip production costs from residual woody biomass was based on the following variables:

- ❖ Labour costs;
- ❖ Diesel consumption by the agricultural vehicle;
- ❖ Increase in the tractor's repair and maintenance (R&M) costs.

For labour costs in the first year of investment, reference was made to the 2024 regional wage tables. Starting from a base rate of €12.04 h^{-1}, the model implemented an annual wage increase of 1% over the investment period. Diesel consumption by the agricultural vehicle was modelled using a PERT distribution, ranging from 2 l h^{-1} to 8 l h^{-1}, with a mean value of 4 l h^{-1}. The increase in the tractor's repair and maintenance (R&M) costs was estimated using an empirical formulation found in the literature (Calcante et al., 2013), assuming that the tractor's operating hours matched those of the chipper and that the initial purchase price was €40,000.

Purchase price of the gasifier. In the model, this variable was implemented with a benchmark value of €10,000 and subjected to stochastic variation at each sampling step, using a uniform probability distribution within a ± 30% range (Morselli et al., 2023).

Costs differences in weed management. This assessment was carried out by estimating the current cost incurred by the farm under the baseline scenario, in which shredding alone is used, and comparing it with the projected expenditure required if FW were introduced. The following factors were considered in estimating this variable:

- ❖ Labour costs;
- ❖ Diesel consumption by the agricultural vehicle;
- ❖ R&M costs for the tractor;
- ❖ R&M costs for the shredder;
- ❖ R&M costs for the gasifier (applicable only in Scenario 2).

Labour costs, tractor R&M costs, and diesel consumption were estimated using the same approach adopted for chip production. In contrast, the annual number of hours required for shredding or FW operations across the farm plots was estimated as a function of the average distance to be covered for mechanical or thermal treatment, the operating speed of the agricultural vehicle, and the number of treatments carried out annually. The average treatment path was estimated based on the methodology outlined in Section 2.2 and was further subjected to stochastic sampling using a triangular probability distribution within a ± 10% range of the benchmark value. Similarly, the average application speed per treatment was modelled using random sampling with a uniform probability distribution, defined within an operational range informed by literature data and direct consultation with farm operators.

Eq. (2) provides an example of how the annual operating hours of the agricultural vehicle for shredding activities in the olive groves are calculated under Scenario 1.

$$h_{tu1} = \frac{L_{tu1}}{V_t} \cdot ha_u \cdot N_{t1} \quad (2)$$

where, L_{tu1} represents the average treatment path in km ha^{-1}, V_t is the treatment speed in km h^{-1}, ha_u is the total area of olive groves in hectares and N_{t1} denotes the number of annual treatments performed in Scenario 1.

The maintenance costs for the shredder were estimated using the same method applied to the chipper, while for the gasifier, a fixed cost of €5.84 h^{-1} was adopted, based on values reported in the literature (Morselli et al., 2023).

Avoided shredding of olive prunings. In current farm practice, woody biomass from olive pruning is placed in the central space between each pair of rows, allowing it to be shredded with a single pass per row. In Scenario 2, however, this biomass is instead used for chip production, resulting in cost savings due to the elimination of shredding operations. This effect was not considered for vineyard plots, as the shredding of vine prunings also serves the complementary function of weed control, due to the average row spacing in those systems.

This variable was defined using the same approach applied to the "Cost Differences in Weed Management" parameter.

Biochar production. Biochar production was determined based on the annual biomass consumption estimated for each year of the investment period. This value was multiplied by the percentage of biomass converted into biochar during FW operations, which was sampled using a uniform probability distribution between 2% and 7% (Morselli et al., 2022). Eqs (3) and (4) define this relationship, where B is the annual biochar production in t y^{-1}, p is the proportion of biomass converted to biochar $t_{biochar}$ $t_{biomass}^{-1}$, C_{ba} is the annual biomass consumption in t y^{-1}, $\dot{m}_{bio}$ is the hourly chip consumption of the gasifier in kg h^{-1}, h_{pu} and h_{pv} are the annual operating hours for FW in olive and vineyard plots respectively (h y^{-1}). The annual agricultural biomass consumption of the gasifier was estimated based on its hourly consumption rate and the treatment hours previously defined.

$$B = p \cdot C_{ba} \quad (3)$$

$$C_{ba} = \dot{m}_{bio} \frac{(h_{pu} + h_{pv})}{1000} \quad (4)$$

The required mass flow rate of wood chips was determined using the definition of gasification efficiency provided in FAO Forestry Department (1986), as shown in Eq. (5). By setting the technical parameters of the thermal treatment (listed below) the necessary mass flow rate of syngas can be estimated.

❖ *"Effective Dose of Energy"* (*ED*): the specific energy dose, relative to the ground footprint of the flame, required during treatment to induce weed wilting. This variable was implemented in the simulation with a value of 390 kJ m^{-2}, based on literature sources;

❖ Application speed of FW: equivalent to the travel speed of the agricultural vehicle. This was sampled using a uniform probability distribution within a range of 3–5 km h^{-1};

❖ Treatment width (*d*): set at 0.4 m.

$$\eta_G = \frac{LHV_{gas} \cdot \dot{m}_{gas}}{LHV_{bio} \cdot \dot{m}_{bio}} \cdot 100 \quad (5)$$

$$\dot{m}_{gas} = \frac{ED \cdot V_p \cdot d}{LHV_{gas}} \quad (6)$$

$$\dot{m}_{bio} = \frac{ED \cdot V_p \cdot d}{LHV_{bio} \cdot \eta_G} \quad (7)$$

where, η_G represents the gasification efficiency, LHV_{gas} and LHV_{bio} are the lower heating values of syngas and biomass respectively (expressed in MJ kg^{-1}), $\dot{m}_{gas}$ and $\dot{m}_{bio}$ denote the mass flow rates of syngas and biomass kg h^{-1}.

The lower heating value of the biomass was set at 18.84 MJ kg^{-1}, based on available literature (Morselli et al., 2023; Pedišius et al., 2021), and sampled using a uniform probability distribution within a ± 10% range. Given that the gasifier operates using wood chips rather than pellets, its efficiency was set at 60%. For each investment year, the theoretical biomass consumption of the gasifier was compared against the actual biomass produced, in order to verify availability.

Biochar sale price. A review of the current literature indicates that the biochar market is still undergoing significant development (Shabangu et al., 2014). In this simulation, the sale price of biochar was modelled using a PERT distribution, ranging from €100 to €2,500 t^{-1}, with a mean value set at €1,000 t^{-1}.

Wood chip sale price. The sale price of wood chips was modelled using a PERT distribution, with stochastic sampling in the range of €40 to €100 $t^{-1}$and a mean value of €60 t^{-1} (Bianchini & Simioni, 2021).

Financing. Based on an analysis of the main characteristics of financing options currently offered by funding institutions, it was assumed that 70% of the capital required for the investment (corresponding to the purchase costs of the gasifier and the chipper) would be provided by a third-party financial institution. The purchase cost of the agricultural tractor was excluded from the initial investment, as the machine was already owned by the farm. The financing period was set at five years and the Nominal Interest Rate at 10%. Regarding the cost of equity, three scenarios were evaluated for each simulation cycle, with values set at 3%, 10%, and 15%, respectively. The corresponding Weighted Average Cost of Capital (WACC) values used in the simulation are reported in Table 1.

Table 1. Applied discount rate values

Scenario 1	Scenario 2	Scenario 3
7.9%	10.0%	11.5%

2.3.2 Output data

The NPV at the final year of investment is, of course, a function of the cash flows and the discount rate applied. Therefore, NPV alone does not constitute a sufficient indicator for fully comparing different investment options. As a result, the following three parameters were defined as output variables of the model:

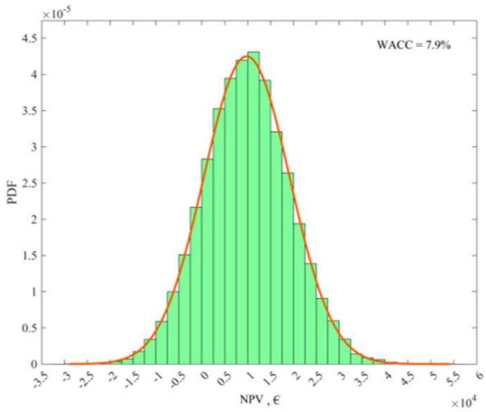
- NPV at the final year of investment;
- Internal Rate of Return (IRR);
- Payback period.

For each of the three indicators, a probability density distribution was generated, followed by a statistical analysis based on the resulting data sample, as illustrated in Section 3. This analysis allows for an understanding of the statistical probability associated with the distribution of possible outcomes produced by the structured model.

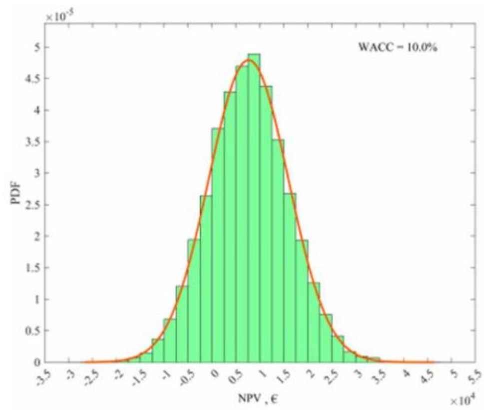
3. Results

At each iteration of the simulation, cash flows were computed as described in Section 2.3.1, based on the values of the set of stochastic variables sampled for that cycle. The sum of these cash flows was then discounted annually using each of the fixed WACC values (7.9%, 10.0%, and 11.5%) corresponding to equity capital costs of 3%, 10%, and 15%, respectively. This analysis made it possible to statistically describe and interpret the resulting data distributions through the following steps: construction of frequency histograms; selection of the most appropriate continuous Probability Density Function (PDF) to represent each sample; fitting of the continuous PDF to the population data; and extraction of key descriptive statistical parameters.

Figure 4 shows the probability density histogram and the corresponding continuous PDF for the sample of NPV at the final year of investment, obtained for the three WACC values considered. The PDF used for the statistical characterization of the sample is a normal distribution, which provides an almost perfect approximation of the sampled population.



(a)



(b)

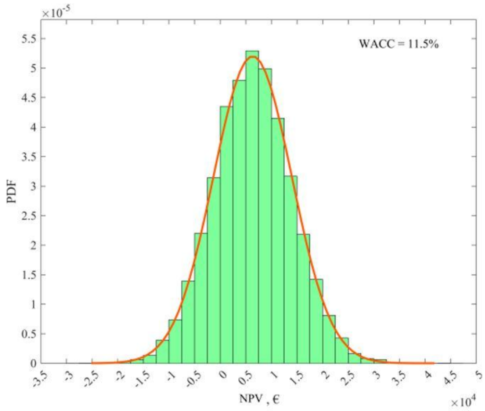


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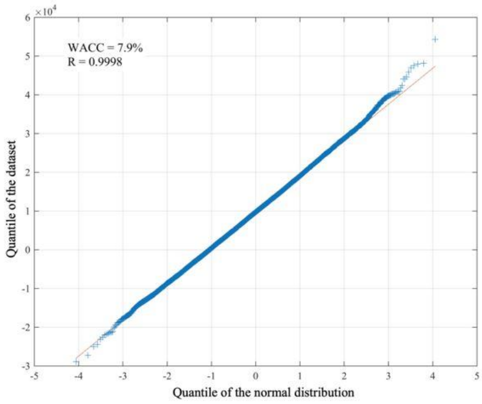
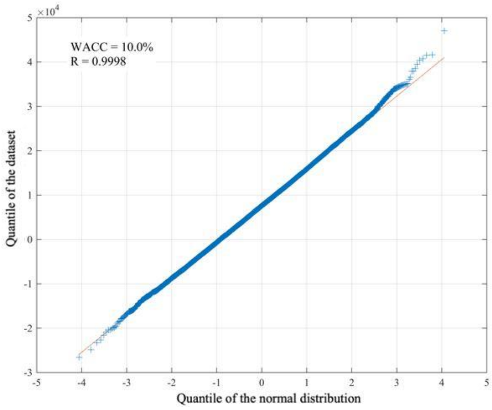
Figure 4. NPV–Probability density histograms and corresponding estimated continuous functions for WACC values: (a) 7.9%; (b) 10.0%; (c) 11.5%



(a)



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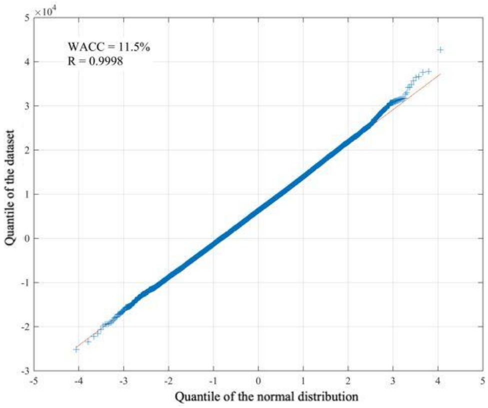

(c)

Figure 5. NPV–Q–Q plot comparison between sample population and normal distribution for WACC values: (a) 7.9%; (b) 10.0%; (c) 11.5%

Table 2. NPV–Descriptive statistics

WACC	PDF	Min; Max	μ	σ	CIμ, α = 0.1	CIσ, α = 0.1
7.9%	Normal	-28,870.77; 54,351.68	9,796.06	9,378.54	9,686.97 ÷ 9,905.14	9,302.09 ÷ 9,456.37
10.0%	Normal	-26,571.76; 47,068.17	7,628.00	8,314.37	7,531.29 ÷ 7,724.70	8,246.59 ÷ 8,383.37
11.5%	Normal	-25,150.04; 42,681.16	6,342.27	7,670.30	6,253.05 ÷ 6,431.48	7,607.77 ÷ 7,733.95

Note: Values in euros (€); WACC: Weighted Average Cost of Capital; PDF: Probability Density Function; μ: Location parameter; σ: Scale parameter; CI: Confidence interval

To assess the quality of the fit, Figure 5 presents the Q–Q plots comparing the sample quantiles with those of a standard normal distribution, along with the corresponding Pearson correlation coefficients for each WACC value. Referring to Table 2, under the Best Case scenario (i.e. assuming a WACC of 7.9%) the mean NPV is estimated at €9,796.06, falling within a 90% confidence interval of €9,686.97 to €9,905.14.

The minimum and maximum values observed were −€28,870.77 and €54,351.68, respectively. When applying a more conservative capital cost (11.5%), the mean NPV drops to €6,342.27, and varies, with a significance level of α = 10%, between €6,253.05 and €6,431.48. The standard deviation of the sample is calculated at €9,378.54 in the 7.9% WACC scenario and €7,670.30 in the 11.5% WACC scenario.

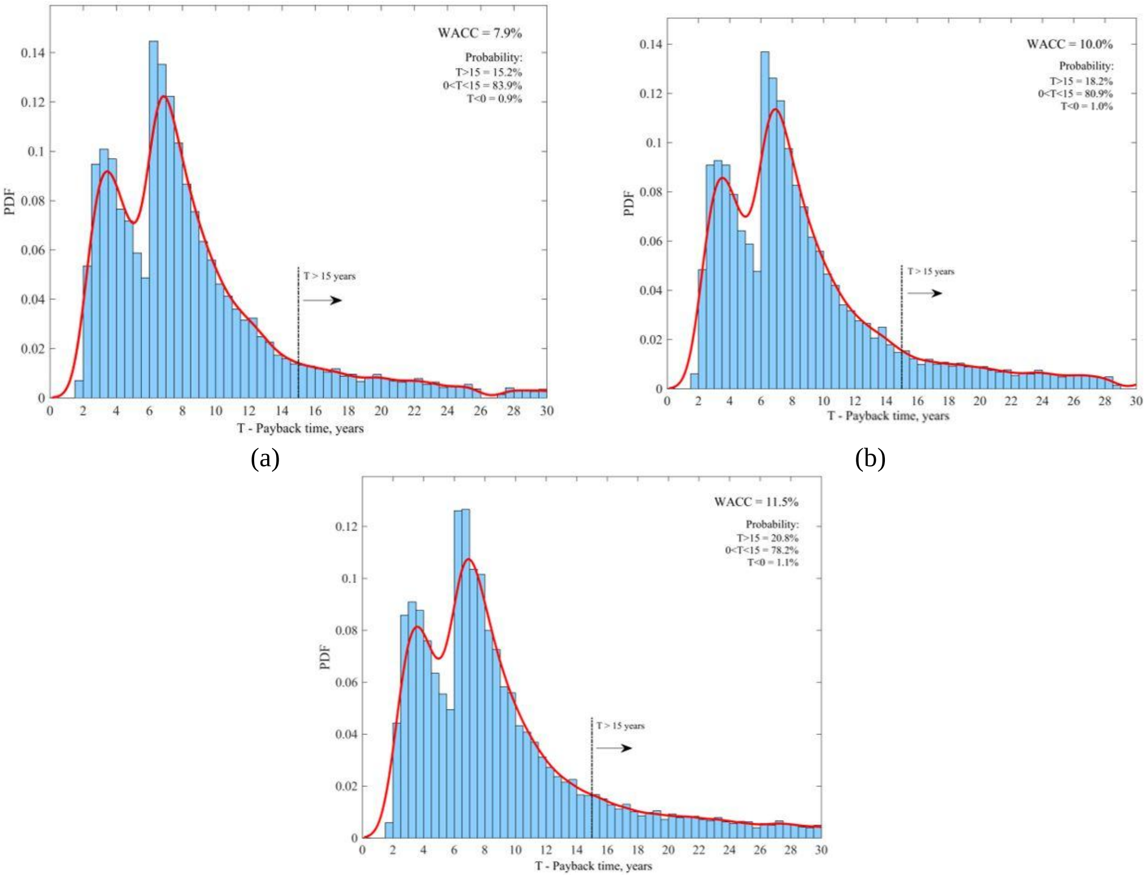

Figure 6. Payback period–Probability density histograms and corresponding estimated continuous functions for WACC values: (a) 7.9%; (b) 10.0%; (c) 11.5%

Regarding the payback period, Figure 6 presents the statistical samples obtained from the simulation based on the selected WACC values. The resulting frequency density histogram exhibits a bimodal distribution, which was described using a non-parametric probability distribution of the Kernel type. For this application, the estimator K was defined using a Gaussian Kernel function, with the interval width set at 0.1 years.

The probabilities that the payback period falls within each of the three previously defined intervals are also reported. For ease of visualization, each graph in Figure 6 displays only the values within the 0–30 year range, which are considered to be the most representative. However, it should be noted that the reported probabilities refer to the entire dataset.

Table 3. Payback period–Descriptive statistics

WACC	PDF	Mode 1 [years]	Mode 2 [years]	Probability		
				T > 0	0 < T < 15	T > 15
7.9%	Kernel	3.4	6.8	0.9%	83.9%	15.2%
10.0%	Kernel	3.5	6.9	1.0%	80.9%	18.2%
11.5%	Kernel	3.6	6.9	1.1%	78.2%	20.8%

Table 3 presents the statistical data describing the sample population for the payback period. In the Best Case scenario, the two modes were observed at 3.4 and 6.8 years. In 83.9% of cases, the investment proved to be profitable. Conversely, in 15.2% of the iterations, the payback period exceeded 15 years, and in 0.9% of cases, the investment never broke even.

Figure 7 displays the probability density histogram of the entire IRR sample, along with the estimated continuous PDF.

The IRR histogram reveals two distinct clusters within the sample population. The cluster composed of significantly lower values, with a lower probability of occurrence, corresponds to those scenarios previously identified as having a negative payback period.

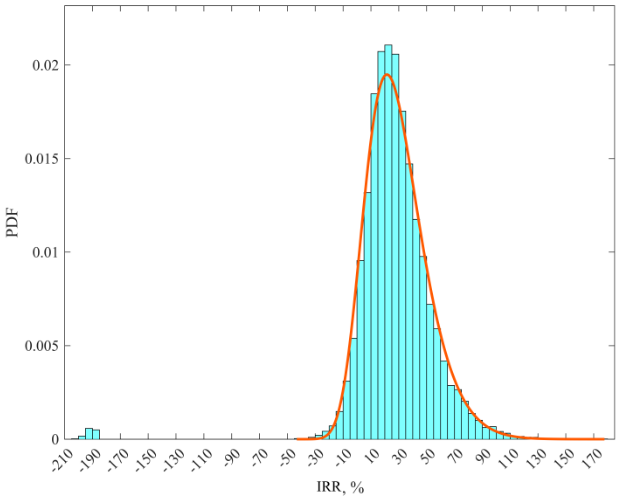

Figure 7. IRR–Probability density histogram and corresponding estimated continuous function

For the IRR data, a good fit was found between the sample and the Generalized Extreme Value (GEV) distribution, which, compared to other parametric models, provided a reliable approximation around the modal value. A *chi-squared* χ^2 test was conducted to evaluate the goodness of the fit of the GEV distribution to the observed data (Turhan, 2020). An appropriate binning interval was defined, and the test calculated the sum of the squared deviations between observed and expected frequencies across the identified bins (Eq. (8)). With a significance level of 5%, the test confirmed the null hypothesis H_0 indicating that the GEV function is a good fit for the sample, returning a *p*-value of 0.07.

$$\chi^2 = \sum_{i=1}^{m} \frac{(o_i - e_i)^2}{e_i} \tag{8}$$

where, m is the number of intervals; o_i are the observed frequencies and e_i are the theoretical frequencies.

Table 4 reports the main descriptive statistical parameters for the IRR sample. It is specified that these values refer exclusively to the cluster with the higher mean, which was considered the most significant. Additionally, the table presents the estimated parameters of the GEV distribution fitted to the sample, along with their respective 95% confidence intervals.

Table 4. IRR–Descriptive statistics

Min rel.; Max	Mean	Mode	Std. Dev.	PDF Parameters (GEV)			
					μ	**σ**	**k**
-43.24%; 178.67%	29.13%	21.76%	21.92	Value	19.74	18.95	-0.0893
				CI, α = 0.05	19.46 ÷ 20.03	18.75 ÷ 19.15	-0.0963 ÷ -0.0824

Note: CI: Confidence interval; μ: Location parameter; σ: Scale parameter; k: Shape parameter

4. Discussion and Conclusion

This research was conducted to explore and quantify the feasibility of integrating biomass-powered FW as a complementary practice alongside more common weed management techniques. The study was contextualised within the agricultural landscape of central-southern Italy, selecting a biodynamic farm as the case study. Once the investment evaluation model was structured through a system of equations, 20,000 simulations were carried out, varying the values of the defined stochastic variables using the Monte Carlo sampling method. A statistical analysis was then conducted on the resulting sample population to quantify the probability of occurrence of the proposed scenario.

The results obtained show that, for an average initial investment of €3,812.07, the mean value of discounted cash flows at 15 years from the start of the project ranges from €6,342.27 in the Worst Case scenario to €9,796.06 in the Best Case. With a WACC of 7.9%, 68% of NPV outcomes fell within the range of €417.52 to €19,175.60, while with a WACC of 11.5%, they ranged from −€1,328.03 to €14,012.57. The payback periods obtained suggest good economic sustainability of the project, considering that in 83.9% of the simulated cases under the Best Case scenario, and in 78.2% under the Worst Case, the investment payback time was below 15 years. The mean Internal Rate of Return, equal to 0.20, indicates that the cash flows generated by the proposed project provide a generally good rate of return, as the relatively modest investment enables meaningful valorization of the capital employed.

To facilitate operational simplicity in the analysis, minor factors were not taken into account, such as the movement of agricultural machinery from the shed to the production site, downtime during operations, and labour hours not directly associated with the use of productive equipment. Additionally, it is important to acknowledge the non-negligible environmental benefit associated with atmospheric carbon sequestration, achieved through the storage of carbon in soil in the form of biochar.

The proposed project was developed with the aim of integrating biomass-powered FW into agricultural practice by defining a simple operational layout that would not significantly alter the farm's current biomass management practices. Chipping systems for the production of wood chips from lignocellulosic pruning residues currently represent a viable option for the valorization of such waste, as they are relatively affordable, easy to operate, and widely available on the market. However, it must be noted that the gasifier proposed for the simultaneous production of biochar and execution of FW is not yet a fully established or commercially widespread technology.

Author Contributions

Conceptualization, N.M., S.P., G.A. and L.T.; methodology, L.T., N.M.; software, L.T., S.P..; validation, L.T.; formal analysis, L.T., S.P.; investigation, N.M., L.T., S.P. and G.A.; data curation, L.T.; writing—original draft preparation, L.T.; writing—review and editing, L.T., S.P., N.M. and G.A.; supervision, N.M. and S.P.; All authors have read and agreed to the published version of the manuscript.

Data Availability

The data used to support the research findings are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

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Appendix

Table A1. Stochastic variables implemented

Variables	Units	PDF	Min	Mean/Mode	Max
Woody biomass production (Vineyards)	t y^{-1}	Uniform	19.60	28.00	36.40
Woody biomass production (Olive groves)	t y^{-1}	Uniform	22.82	32.60	42.38
Chipper purchase price	€	PERT	1,237.0	2,591.8	4,633.0
Wood chip production by the chipper in the first year	t h^{-1} y^{-1}	Uniform	1.016	1.270	1.524
Annual mean price of the agricultural diesel	€ l^{-1}	Simulated (Gaussian)		See section 2.3.1	
Annual hourly mean consumption of the agricultural diesel by the tractor	l h^{-1}	PERT	2	4	8
Gasifier purchase price	€	Uniform	7,000	10,000	13,000
Number of annual FW treatments carried out*	y^{-1}	Uniform	3	-	4
Number of annual shredding treatments carried out (Scenario 1)*	y^{-1}	Uniform	4	-	6
Number of annual shredding treatments carried out (Scenario 2)*	y^{-1}	Uniform	1	-	2
FW application speed	km h^{-1}	Uniform	3	4	5
Shredding application speed	km h^{-1}	Uniform	2.5	3.0	3.5

Shredder working capacity in vineyards	ha h^{-1}	Uniform	0.4	0.7	1.0
Path required for the shredding of one olive grove hectare (Scenario 1)	km ha^{-1}	Triangular	4.87	5.41	5.95
Path required for the shredding of one olive grove hectare (Scenario 2)	km ha^{-1}	Triangular	3.29	3.66	4.02
Path required for the FW of one olive grove hectare	km ha^{-1}	Triangular	3.27	3.63	3.99
Path required for the FW of one vineyard hectare	km ha^{-1}	Triangular	7.01	7.79	8.56
Path required for the shredding of the olive groves pruning	km ha^{-1}	Triangular	1.54	1.71	1.88
Lower heating value of biomass	MJ kg^{-1}	Uniform	16.956	18.840	20.724
Annual mean produced biochar over consumed biomass ratio	t t^{-1}	Uniform	0.020	0.045	0.070
Biochar selling price	€ t^{-1}	PERT	100	1000	2500
Wood chip selling price	€ t^{-1}	PERT	30	50	90
Carbon presence in biochar (%)	t t^{-1}	Uniform	0.80	0.85	0.90