

Article

Integrated Life Cycle Assessment and Cost Analysis of Climate-Smart Agricultural Practices in Potato and Onion Cultivation

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Abstract

Although climate-smart agricultural practices are increasingly promoted, comparative environmental and economic assessments across multiple practices and crops remain limited. This study evaluates five climate-smart agricultural practices in Dutch potato and onion production, including soil management, biodiversity enhancement, sustainable irrigation systems, crop protection, and green energy use. It compares them with conventional production systems using integrated Life Cycle Assessment and Life Cycle Costing. Specifically, Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) methodologies were applied to assess the environmental and economic sustainability of the studied systems, respectively. Among the evaluated practices, soil management exhibited the best overall environmental performance for both crops, achieving reductions of up to 42% and 66% in greenhouse gas emissions for potatoes and onions, respectively, compared with the baseline under the modelled conditions. Biodiversity measures significantly reduced freshwater eutrophication and ecotoxicity-related impacts, particularly in potato cultivation, while crop protection practices mainly improved pesticide-related toxicity categories. Similarly, soil management and biodiversity demonstrated the best economic performance, with profits increasing to approximately €3318/ha and €3121/ha for potatoes and €3898/ha and €3694/ha for onions, respectively, compared with baseline profits of €2879/ha and €3526/ha. The results suggest that the implementation of CSA practices can improve both the environmental and economic sustainability of intensive vegetable production systems under the modelled Dutch conditions, although the effectiveness of each practice depends strongly on crop-specific environmental hotspots and management assumptions. The findings provide evidence to support farmers and policymakers in selecting cost-effective climate-smart practices while identifying priorities for future field validation and uncertainty assessment.

Keywords: sustainability; climate smart agriculture; environmental assessment; economic assessment; crops production



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1. Introduction

European arable farming is increasingly required to maintain high productivity while reducing environmental burdens related to greenhouse gas emissions, nutrient losses, pesticide use, fossil energy consumption, soil degradation and water demand. These pressures are particularly relevant in intensive open-field systems, where fertiliser production and

application, mechanised operations, irrigation, crop protection and post-harvest handling can represent major environmental hotspots. Climate-Smart Agriculture (CSA) offers a useful framework for addressing these challenges by integrating three interrelated objectives: increasing agricultural productivity, strengthening adaptation and resilience to climate change, and reducing or removing greenhouse gas emissions where possible [1].

Potato and onion production are economically important components of Dutch arable farming and are commonly associated with intensive input use. In Dutch ware potato systems, recent field-level evidence shows substantial farm-to-farm variability in fertiliser, water and crop-protection inputs, indicating that environmental impacts can be reduced without necessarily compromising yield [2]. Additional evidence suggests that current phosphorus and potassium fertiliser rates do not consistently limit potato yield or tuber quality, highlighting scope for improved nutrient management and reduced fertiliser-related burdens [3]. At the same time, climate variability is already affecting Dutch crop production. Recent weather extremes, including drought, excessive rainfall and waterlogging, have negatively influenced crop yields in the Netherlands [4], while extreme drought and high-intensity rainfall between 2015 and 2020 had a large impact on potato production [5]. Modelling studies further confirm that water-limited potato yields vary spatially across the Netherlands depending on soil, weather and water-management conditions [6].

Biotic stresses also influence the environmental and economic performance of potato and onion systems. In potato cultivation, late blight caused by *Phytophthora infestans* remains one of the most destructive diseases and is a major driver of fungicide use [7]. Integrated Pest Management (IPM), including resistant cultivars, disease monitoring, decision-support systems and targeted fungicide application, can reduce pesticide dependency while maintaining disease control [8]. In onion production, important sustainability challenges include onion thrips, bacterial bulb rot, weed pressure and storage-related quality losses [9]. However, onion-specific sustainability evidence under Dutch conditions remains more limited than for potato. Studies on onion irrigation and disease management indicate that management timing can affect bacterial disease incidence and storage quality, confirming the importance of crop-specific assumptions in sustainability assessment [10].

Several CSA practices may improve the sustainability of Dutch potato and onion farming. Biodiversity-enhancing measures, such as flower strips, field margins and unsprayed buffer zones, can support natural enemies, pollinators and wider agroecosystem functioning, although their effects on pest suppression and yield are context-dependent [11,12]. Sustainable irrigation strategies, including soil-moisture sensors, weather-based scheduling and decision-support tools, may improve water-use efficiency and yield stability, but their performance depends on local water availability, energy requirements, infrastructure and crop sensitivity to water stress [13–15]. Renewable energy technologies can reduce fossil energy dependency in irrigation, storage and other electricity-consuming operations, although they do not directly address nutrient losses, pesticide-related impacts or field emissions [16,17]. Soil-management practices, including cover crops, organic amendments, mulching, reduced tillage and improved rotations, can improve soil structure, microbial activity, water retention and long-term resilience, but may also involve short-term trade-offs related to labour, nutrient-release dynamics, weed pressure and yield variability [18–21].

Several studies have applied Life Cycle Assessment (LCA) to evaluate the environmental impacts of potato and onion production, identifying fertiliser use, pesticide application, and energy consumption as the main contributors to greenhouse gas emissions, eutrophication, and ecotoxicity [2,22]. Other studies have incorporated Life Cycle Costing (LCC) to assess the economic feasibility of alternative agricultural management practices [23]. However, these assessments have generally focused on individual crops or single management

interventions and have often evaluated environmental and economic performance separately [22]. Consequently, the trade-offs between multiple climate-smart agriculture (CSA) practices and their simultaneous environmental and economic effects remain insufficiently understood, particularly under Dutch production conditions. Furthermore, previous studies have typically relied on empirical comparisons of existing farming systems or have examined only one sustainability dimension. Few studies have employed an integrated LCA–LCC framework to compare several CSA practices using a consistent modelling approach across different vegetable crops. This methodological limitation restricts the ability to identify practices that simultaneously reduce environmental burdens while maintaining economic viability and limits the transferability of findings for decision-making and policy development.

Although CSA practices are widely promoted as sustainable alternatives, their actual performance depends on crop type, local pedoclimatic conditions, baseline input use, management intensity, and farm-level investment requirements. Therefore, sustainability assessment should consider both environmental impacts and economic feasibility. Life Cycle Assessment (LCA) provides a systematic framework for quantifying environmental burdens across agricultural production systems and identifying hotspots in agri-food value chains [22,24]. In accordance with ISO 14040 and ISO 14044, LCA includes goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation [25–27]. The ReCiPe2016 method is particularly suitable for multi-impact agricultural assessment because it translates life-cycle inventory flows into midpoint and endpoint indicators such as climate change, acidification, eutrophication, land use, water use and ecotoxicity [28].

However, LCA alone does not determine whether CSA practices are economically feasible for farmers. Life Cycle Costing (LCC) can complement LCA by accounting for investment costs, operational expenses, labour, fuel, electricity, fertilisers, pesticides, irrigation, machinery use, maintenance and potential savings from improved resource efficiency [23,29]. This is important because environmental improvements do not automatically generate economic benefits. Some practices may reduce emissions or resource use while increasing capital costs, labour requirements or production risk, whereas others may provide both environmental and economic benefits through input reduction, yield stability or lower energy demand. Recent reviews also show that LCC in agri-food systems remains less standardised than LCA, with cost categories, system boundaries and methodological assumptions strongly influencing comparability across studies [30].

Despite growing research on sustainable agriculture, CSA and agricultural LCA, important gaps remain. Existing studies often focus on individual practices, single crops or isolated sustainability dimensions, limiting comparison among alternative interventions. For Dutch potato systems, recent evidence supports the relevance of input-use efficiency, nutrient management and climate vulnerability [2–6]. In contrast, onion-specific environmental and economic evidence under Dutch production conditions remains comparatively limited, despite the crop's sensitivity to water availability, pest and disease pressure, weed control and storage-related losses [9,10]. Moreover, few studies have jointly evaluated the environmental and economic performance of multiple CSA practices in Dutch potato and onion farming using harmonised system boundaries, functional units, inventory assumptions and cost structures. As a result, trade-offs between environmental improvement, production risk and farm-level economic feasibility remain insufficiently quantified.

The present study addresses this gap by assessing selected CSA practices in Dutch potato and onion farming through an integrated LCA and LCC approach. The practices considered include biodiversity measures, sustainable irrigation, integrated pest management, renewable energy use and improved soil management. These scenarios are compared

with conventional baseline production to identify environmental hotspots, cost drivers, trade-offs and synergies. Specifically, the objectives of this study are to: (i) quantify the environmental impacts of selected CSA practices using LCA; (ii) assess the economic implications of each practice through LCC; and (iii) identify trade-offs and synergies between environmental and economic performance across the assessed CSA scenarios. Unlike previous studies that primarily evaluate individual CSA practices or single crops, this study provides a harmonised comparison of five climate-smart agricultural practices across two major Dutch vegetable production systems using a consistent LCA-LCC framework. This enables the identification of environmental-economic trade-offs between practices and crops under identical modelling assumptions.

2. Materials and Methods

Life Cycle Assessment (LCA) was conducted in accordance with the ISO 14040 series guidelines (ISO 14040:2006 and ISO 14044:2006) [25,26]. The ReCiPe 2016 (Hierarchist) method was used as the impact assessment framework to convert life cycle inventory data into environmental impact indicators through characterisation factors. The LCA was performed using SimaPro Craft software (version 10.3), developed by PRé Sustainability in Amersfoort, The Netherlands.

Life Cycle Costing (LCC) was carried out in Microsoft Excel (v15.0), considering all relevant economic flows and including all operating expenditures (OPEX). Capital expenditures (CAPEX) were estimated for the sustainable irrigation system, as the implementation of this practice involved the purchase of equipment including soil moisture sensors, automated controllers, data logging, and IoT platforms.

2.1. Goal & Scope

The main objective of this study is to evaluate the environmental and economic performance of different CSA practices in the cultivation of onions and potatoes and to compare them with conventional production systems. Accordingly, the environmental impacts of standard onion and potato cultivation systems were first assessed, followed by the evaluation of the five alternative scenarios, each representing one of the selected CSA practices.

2.2. Functional Unit

The selected functional unit for the LCA analysis is 1 kg of harvested onions and 1 kg of harvested potatoes. In addition, for the LCA results, impacts are also reported per ha of cultivated land to enable a more comprehensive comparison of the evaluated CSA practices.

The selected functional unit for the LCC analysis is 1 ha of cultivated area for both product systems.

2.3. System Boundaries

The objective of this study is to compare the implementation of CSA practices with conventional onion and potato cultivation over a single harvest cycle. To this end, a cradle-to-gate approach was applied, considering only on-farm processes. The system boundaries include all stages from soil preparation of the farm through to potato and onion harvesting. Specifically, the system boundaries include land preparation, seed production, fertiliser manufacture, pesticide production, irrigation, fuel and electricity consumption, field operations, fertiliser and pesticide emissions, and harvesting. Post-harvest storage, packaging, transport to wholesalers or retailers, processing, consumer use, and end-of-life stages were excluded because the objective was to compare farm-level management practices. Upstream production of agricultural inputs was included through the Ecoinvent

and Agri-footprint databases, whereas downstream processes after harvest were excluded consistently across all scenarios.

2.4. Data Requirements

This research was conducted within the framework of the BEATLES project (Horizon Europe—Grant ID: 101060645). The study focused on one use case in the Netherlands, where different CSA practices in onion and potato production were evaluated. Primary data were gathered through structured questionnaires administered by project partners in the Netherlands, who communicated directly with farmers implementing the studied CSA practices.

The questionnaire was designed to collect detailed information on input use (e.g., fertilisers, pesticides, diesel, and water), onion and potato cultivation practices, the implementation of CSA measures, as well as yield and production outcomes.

The collected information was used to develop the Life Cycle Inventory (LCI) and to support assumptions related to input reductions and management modifications. Data quality was ensured through cross-validation with project partners and comparison with literature sources and database values from Ecoinvent, Agri-footprint, and Agribalyse. Consequently, the dataset represents a hybrid approach in which primary data are supplemented with modelled and aggregated information. Therefore, the results should be interpreted as scenario-based rather than purely empirical outcomes.

The selected CSA practices were chosen because they represent interventions currently promoted within the BEATLES project and Dutch agricultural policy, addressing the dominant environmental hotspots identified for potato and onion production, namely fertiliser use, pesticide use, irrigation, energy consumption, and biodiversity conservation. The study was based on primary data collected from six representative potato and onion farms participating in the Dutch use case of the BEATLES project during the 2023–2024 growing seasons. Although the sample is not statistically representative of all Dutch farms, it was selected to reflect representative production practices and management conditions relevant to the evaluated climate-smart agriculture (CSA) scenarios.

All procedures complied with GDPR requirements, while data quality assurance followed the guidelines of the project's Management Handbook and the relevant European Union directives.

2.5. Assumptions and Limitations

In all scenarios, the data were collected from farms located in the Netherlands, cultivating onions and potatoes. For all systems, the dataset refers to 1 hectare of cultivated land. The selected CSA practices were chosen based on their potential to reduce emissions and input use, improve soil quality and system resilience, and enhance economic performance. However, their classification as CSA practices should be understood within this context-specific framework.

2.5.1. Baseline

The collected data correspond to a farm located in the Netherlands that is representative of conventional onion and potato cultivation.

2.5.2. Biodiversity

The system represented a typical arable potato and onion farm implementing biodiversity-enhancing measures without significantly changing crop type or overall production. Improvements in biodiversity were inferred from reductions in pesticide use and increases in soil organic matter. A 20% decrease in pesticide application was assumed, reflecting more effective pest management strategies. As no direct measurements of species

richness or ecological indicators were available, results were interpreted using input reductions and values reported in the literature. Additionally, the implementation of vegetative buffer strips along field margins for biodiversity enhancement was assumed to reduce nutrient runoff by approximately 53% for nitrogen and 62% for phosphorus. However, to account for potential variability in reductions of pesticide use, two additional scenarios were considered, assuming decreases of 10% and 30% in pesticide applications [31]. Although the reduction coefficients were derived from published studies, they were selected because they represent buffer-strip and integrated biodiversity measures commonly promoted under Dutch agri-environmental schemes. The values therefore represent plausible scenario assumptions rather than measured reductions for individual farms.

2.5.3. Sustainable Irrigation System

The collected data correspond to a Dutch potato and onion farm operating under average irrigation conditions, using sensor-based automated management that resulted in a 38% reduction in both water and energy consumption [32]. Additionally, photovoltaic electricity replaced the conventional electricity mix [33]. The system's energy efficiency was kept constant in order to isolate the effects of the renewable energy contribution. The purchase cost of the smart irrigation system was estimated at approximately €220 per hectare, and using a straight-line depreciation over an assumed lifespan of 10 years, the annual capital expenditure (CapEx) was calculated at €22/ha.

2.5.4. Crop Protection

The collected data correspond to a Dutch potato and onion production farm that implements integrated pest management (IPM) with an emphasis on reducing insecticide use through monitoring and the conservation of natural enemies, resulting in a 95% reduction in insecticide application [34].

2.5.5. Green Energy

The collected data correspond to a Dutch potato and onion production farm, in which a portion of conventional grid electricity is replaced with wind-generated renewable energy, while all other farming practices remained unchanged. No additional infrastructure requirements or economic costs were considered.

2.5.6. Soil Management

The collected data correspond to a Dutch potato and onion production farm that encompasses the complete substitution of synthetic nitrogen, phosphorus, and potassium fertilisers with compost-based organic inputs. In addition, the implementation of vegetative buffer strips along field margins was performed to reduce nutrient runoff by approximately 53% for nitrogen and 62% for phosphorus [31]. Crop yield was assumed constant across scenarios to isolate the influence of management changes on environmental and economic performance. Although complete substitution of mineral fertilisers with compost may influence yields depending on nutrient availability and management practices, published studies report that comparable yields can be maintained when nutrient supply is properly balanced. Nevertheless, this assumption represents an important source of uncertainty and should be validated under long-term field conditions.

2.6. Life Cycle Inventory (LCI)

The Life Cycle Inventory (LCI), created using data collected via interviews with involved stakeholders and supplemented with related literature sources, is presented in Tables 1 and 2 for potato and onion cultivation, respectively. The estimation of the initial emission distribution fractions of the applied chemical agents (fungicides, herbicides,

insecticides and phyto regulators) was based on emission modelling for pesticides provided in the literature [35]. Fertiliser emissions in air, soil and water were estimated using the IPCC guidelines [36].

Table 1. Life Cycle Inventory (LCI) of studied CSA practices in potato cultivation.

Parameter	Baseline (BL)	Biodiversity (BIO)	Sustainable Irrigation System (SIS)	Green Energy (GE)	Soil Management (SM)	Crop Protection (CP)
Inputs						
Land use (ha)	1	1	1	1	1	1
Potato seed (kg)	2700	2700	2700	2700	2700	2700
Inorganic nitrogen fertiliser (kg)	250	250	250	250	-	250
Inorganic phosphorus fertiliser (kg)	83.3	83.3	83.3	83.3	-	83.3
Inorganic potassium fertiliser (kg)	300	300	300	300	-	300
Organic nitrogen fertiliser (kg)	-	-	-	-	250	-
Organic phosphorus fertiliser (kg)	-	-	-	-	83.3	-
Organic potassium fertiliser (kg)	-	-	-	-	300	-
Herbicides (kg)	7.4	5.92	7.4	7.4	7.4	7.4
Insecticides (kg)	0.263	210.4	0.263	0.263	0.263	0.132
Fungicides (kg)	13.7	10.95	13.7	13.7	13.7	13.7
Mineral oils (kg)	16.6	16.6	16.6	16.6	16.6	16.6
Water (m ³)	300	300	186	300	300	300
Diesel (MJ)	10,159	10,159	10,159	10,159	10,159	10,159
Electricity (kWh)	747	747	-	-	747	747
Renewable Electricity (kWh)	-	-	463	-	-	-
Electricity from wind power (kWh)	-	-	-	747	-	-
Outputs						
Potatoes (kg)	48,200	48,200	48,200	48,200	48,200	48,200
Emissions to Air						
Emissions from fungicides (kg)	1.4	1.1	1.4	1.4	1.4	1.4
Emissions from insecticides (g)	26	20.8	26	26	26	1.3
Emissions from herbicides (kg)	0.74	0.592	0.74	0.74	0.74	0.74
Nitrogen monoxide (kg)	3.93	1.84	3.93	3.93	1.84	3.93
Ammonia (kg)	30.36	14.27	30.36	30.36	14.27	30.36
Emissions from mineral oil (kg)	1.38	1.38	1.38	1.38	1.38	1.38
Emissions to Water						
Emissions from fungicides (g)	3	2.4	3	3	3	3
Emissions from herbicides (g)	2	1.6	2	2	2	2
Phosphate (kg)	110.71	42.07	110.71	110.71	42.07	110.71
Nitrate (kg)	0.63	0.30	0.63	0.63	0.63	0.63
Emissions from mineral oil (g)	0.17	0.17	0.17	0.17	0.17	0.17
Emissions to Soil						
Emissions from fungicides (kg)	2.5	2	2.5	2.5	2.5	2.5
Emissions from insecticides (g)	48	38.4	48	48	48	2.4
Emissions from herbicides (kg)	5.6	4.48	5.6	5.6	5.6	5.6
Nitrate (kg)	75	35.3	75	75	75	75
Emissions from mineral oil (kg)	6.75	5.74	6.75	6.75	6.75	6.75

Table 2. Life Cycle Inventory (LCI) of studied CSA practices in onion cultivation.

Parameter	Baseline (BL)	Biodiversity (BIO)	Sustainable Irrigation System (SIS)	Green Energy (GE)	Soil Management (SM)	Crop Protection (CP)
Inputs						
Land use (ha)	1	1	1	1	1	1
Onion seed (kg)	3.8	3.8	3.8	3.8	3.8	3.8
Inorganic nitrogen fertiliser (kg)	630	630	630	630	-	630
Inorganic phosphorus fertiliser (kg)	93	93	93	93	-	93
Inorganic potassium fertiliser (kg)	300	300	300	300	-	300
Organic nitrogen fertiliser (kg)	-	-	-	-	630	-
Organic phosphorus fertiliser (kg)	-	-	-	-	93	-
Organic potassium fertiliser (kg)	-	-	-	-	300	-
Herbicides (kg)	11	8.8	11	11	11	11
Insecticides (kg)	1.15	0.92	1.15	1.15	1.15	0.06
Fungicides (kg)	3.4	2.72	3.4	3.4	3.4	3.4
Mineral oils (kg)	3.8	3.8	3.8	3.8	3.8	3.8
Water (m ³)	288	288	179	288	288	288
Diesel (MJ)	8994	8994	8994	8994	8994	8994
Electricity (kWh)	1600	1600	-	-	1600	1600
Renewable Electricity (kWh)	-	-	992	-	-	-
Electricity from wind power (kWh)	-	-	-	1600	-	-
Outputs						
Onions (kg)	50,000	50,000	50,000	50,000	50,000	50,000
Emissions to Air						
Emissions from fungicides (kg)	0.34	0.272	0.34	0.34	0.34	0.34
Emissions from insecticides (g)	115	92	115	115	115	5.8
Emissions from herbicides (kg)	1.1	0.88	1.1	1.1	1.1	1.1
Nitrogen monoxide (kg)	9.89	4.65	9.89	9.89	4.65	4.65
Ammonia (kg)	76.46	35.94	76.46	76.46	35.94	35.94
Emissions to Water						
Emissions from fungicides (g)	3	2.4	3	3	3	3
Emissions from herbicides (g)	1	0.8	1	1	1	1
Phosphate (kg)	278.84	105.96	278.84	278.84	105.96	278.84
Nitrate (kg)	0.7	0.33	0.7	0.7	0.33	0.7
Emissions to Soil						
Emissions from fungicides (kg)	620	496	620	620	620	620
Emissions from insecticides (g)	210	168	210	210	210	2.4
Emissions from herbicides (kg)	8.4	6.72	8.4	8.4	8.4	8.4

2.7. Sensitivity Analysis

To evaluate the robustness of the modelling assumptions, a deterministic sensitivity analysis was performed for the biodiversity scenarios considering pesticide reductions of 10%, 20% and 30%. The analysis examined the influence of parameter variation on both LCA and LCC results. Broader probabilistic uncertainty analysis (e.g., Monte Carlo simulation) was beyond the scope of this study.

3. Results and Discussion

3.1. LCA Results—Potato Cultivation

Figure 1 presents the LCA results of the baseline scenario, along with the different studied CSA practices regarding the cultivation of potatoes in the selected midpoint impact categories. The results are discussed both per kilogram of harvested potatoes and per hectare of cultivated land, since the two perspectives provide complementary interpretations. The product-based results reflect the environmental efficiency of producing 1 kg of potatoes, while the hectare-based results describe the cumulative environmental pressure generated by one hectare of cultivation.

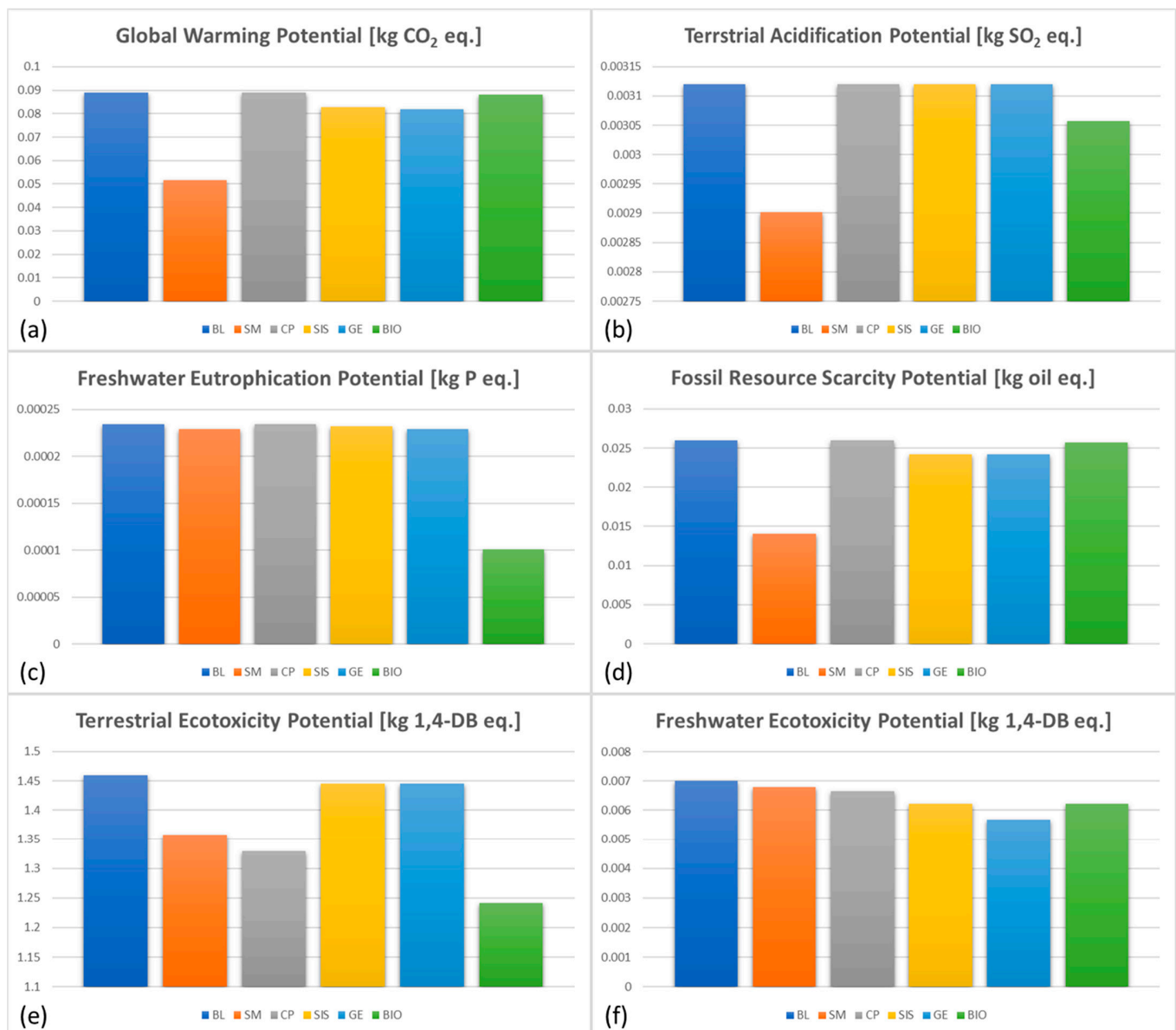


Figure 1. Environmental impact of the baseline (BL), soil management (SM), crop protection (CP), sustainable irrigation system (SIS), green energy (GE), and biodiversity (BIO) for potato cultivation on (a) global warming potential (kg CO₂ eq.), (b) terrestrial acidification potential (kg SO₂ eq.), (c) freshwater eutrophication potential (kg P eq.), (d) fossil resource scarcity potential (kg oil eq.), (e) terrestrial ecotoxicity potential (kg 1,4-DB eq.), and (f) freshwater ecotoxicity potential (kg 1,4-DB eq.).

The baseline scenario presented a global warming potential of 0.089 kg CO₂ eq. per kg of potatoes, corresponding to 4289.8 kg CO₂ eq. per hectare. Among the studied CSA practices, soil management achieved the largest reduction, decreasing GWP to 0.0516 kg CO₂ eq./kg and 2488.1 kg CO₂ eq./ha, equal to an approximate 42% decrease compared with the baseline. This reduction is mainly attributed to the substitution of synthetic fertilisers with organic inputs, which reduces the upstream impacts associated with synthetic fertiliser production and the related field emissions. Fertiliser production and nitrogen emissions are widely recognised as major contributors to agricultural climate impacts [35,36].

The sustainable irrigation system and green energy scenarios also reduced GWP, but to a smaller extent. SIS decreased GWP to 0.0828 kg CO₂ eq./kg and 3989.5 kg CO₂ eq./ha, while GE reached 0.0819 kg CO₂ eq./kg and 3946.6 kg CO₂ eq./ha. These reductions correspond to approximately 7% and 8%, respectively, and are mainly linked to lower electricity demand and the replacement of conventional electricity with renewable energy. Smart irrigation technologies can reduce water and energy requirements in agriculture, especially when combined with renewable energy systems [32]. The biodiversity scenario produced a smaller GWP reduction, reaching 0.0881 kg CO₂ eq./kg and 4246.9 kg CO₂ eq./ha, while crop protection did not alter GWP compared with the baseline because the modelled intervention mainly affected insecticide use rather than fuel, fertiliser, or electricity consumption.

Regarding terrestrial acidification potential, the baseline value was 0.00312 kg SO₂ eq./kg, corresponding to 150.38 kg SO₂ eq./ha. Soil management reduced this impact to 0.00290 kg SO₂ eq./kg and 139.86 kg SO₂ eq./ha, representing a 7% reduction. This improvement is linked to the lower dependence on synthetic nitrogen fertilisers and the associated reduction in acidifying emissions. Biodiversity produced a smaller reduction, reaching 0.00306 kg SO₂ eq./kg and 147.38 kg SO₂ eq./ha, while CP, SIS, and GE remained similar to the baseline. This indicates that acidification in the modelled potato system is mainly driven by nutrient management rather than pesticide or electricity substitution.

Freshwater eutrophication potential showed a different pattern. The baseline value was 0.000234 kg P eq./kg and 11.28 kg P eq./ha. The biodiversity scenario achieved the strongest reduction, decreasing FEP to 0.000101 kg P eq./kg and 4.85 kg P eq./ha, corresponding to a 57% decrease compared with the baseline. This result is primarily associated with the assumed reduction in nutrient runoff due to vegetative buffer strips and biodiversity-enhancing measures. Buffer strips have been shown to reduce nutrient transport from agricultural fields to water bodies, particularly phosphorus losses [31]. Soil management and green energy produced smaller reductions, both reaching 0.000229 kg P eq./kg and 11.05 kg P eq./ha, while SIS reached 0.000232 kg P eq./kg and 11.17 kg P eq./ha. Crop protection did not affect this category.

For fossil resource scarcity potential, the baseline value was 0.026 kg oil eq./kg and 1253.2 kg oil eq./ha. Soil management achieved the most substantial improvement, reducing this impact to 0.0140 kg oil eq./kg and 676.7 kg oil eq./ha, corresponding to a 46% reduction. This reduction is explained by the avoidance of the production and use of fossil-intensive synthetic fertilisers. SIS and GE both reduced fossil resource scarcity to 0.0242 kg oil eq./kg and 1165.5 kg oil eq./ha, representing a 7% decrease. Biodiversity showed only a minor reduction, while CP remained equal to the baseline.

The terrestrial ecotoxicity potential of the baseline scenario was 1.46 kg 1,4-DB eq./kg and 70,372 kg 1,4-DB eq./ha. The biodiversity scenario achieved the lowest value, decreasing the impact to 1.241 kg 1,4-DB eq./kg and 59,816.2 kg 1,4-DB eq./ha, corresponding to a 15% reduction. Crop protection also improved this category, reducing the value to 1.329 kg 1,4-DB eq./kg and 64,038.5 kg 1,4-DB eq./ha, equal to a 9% reduction. These reductions

are directly associated with lower pesticide and insecticide emissions. Pesticide emission modelling remains an important source of uncertainty in agricultural LCA, but pesticide use is consistently recognised as a major contributor to ecotoxicity impacts [37].

Freshwater ecotoxicity potential showed the greatest improvement in the green energy scenario, decreasing from 0.007 kg 1,4-DB eq./kg and 337.4 kg 1,4-DB eq./ha in the baseline to 0.00567 kg 1,4-DB eq./kg and 273.29 kg 1,4-DB eq./ha, corresponding to a 19% reduction. SIS and BIO both reached 0.00623 kg 1,4-DB eq./kg and 300.29 kg 1,4-DB eq./ha, while CP reached 0.00665 kg 1,4-DB eq./kg and 320.53 kg 1,4-DB eq./ha. These results indicate that freshwater ecotoxicity is affected not only by pesticide management but also by the modelled electricity mix and upstream processes.

The superior environmental performance of the soil management scenario in the global warming potential and fossil resource scarcity categories is primarily attributable to the replacement of synthetic mineral fertilisers with compost. The manufacture of nitrogen fertilisers is highly energy-intensive and represents one of the largest contributors to greenhouse gas emissions in crop production. Consequently, reducing the demand for synthetic fertilisers substantially decreases both fossil energy consumption and associated emissions. Similar findings have been reported for potato production systems, where fertiliser manufacture and application were identified as the dominant environmental hotspots [2,22].

The biodiversity scenario achieved the greatest reductions in freshwater eutrophication and terrestrial ecotoxicity because lower pesticide application and reduced nutrient losses directly decrease emissions affecting aquatic and terrestrial ecosystems. Likewise, crop protection practices mainly influenced toxicity-related categories, while their effect on climate-related indicators remained limited because pesticide manufacture contributes relatively little to total greenhouse gas emissions compared with fertiliser production. These findings demonstrate that different CSA practices target different environmental hotspots and therefore should be selected according to the dominant sustainability challenge within each production system.

Overall, the LCA results show that no single CSA practice performs best in all environmental categories. Soil management is the most effective option for reducing GWP and fossil resource scarcity, biodiversity is the most effective for reducing freshwater eutrophication and terrestrial ecotoxicity, and green energy provides the greatest improvement in freshwater ecotoxicity. The hectare-based results follow the same percentage trends as the product-based results, since yield was kept constant across scenarios. However, the per-hectare results are particularly useful for understanding the total environmental pressure associated with land management.

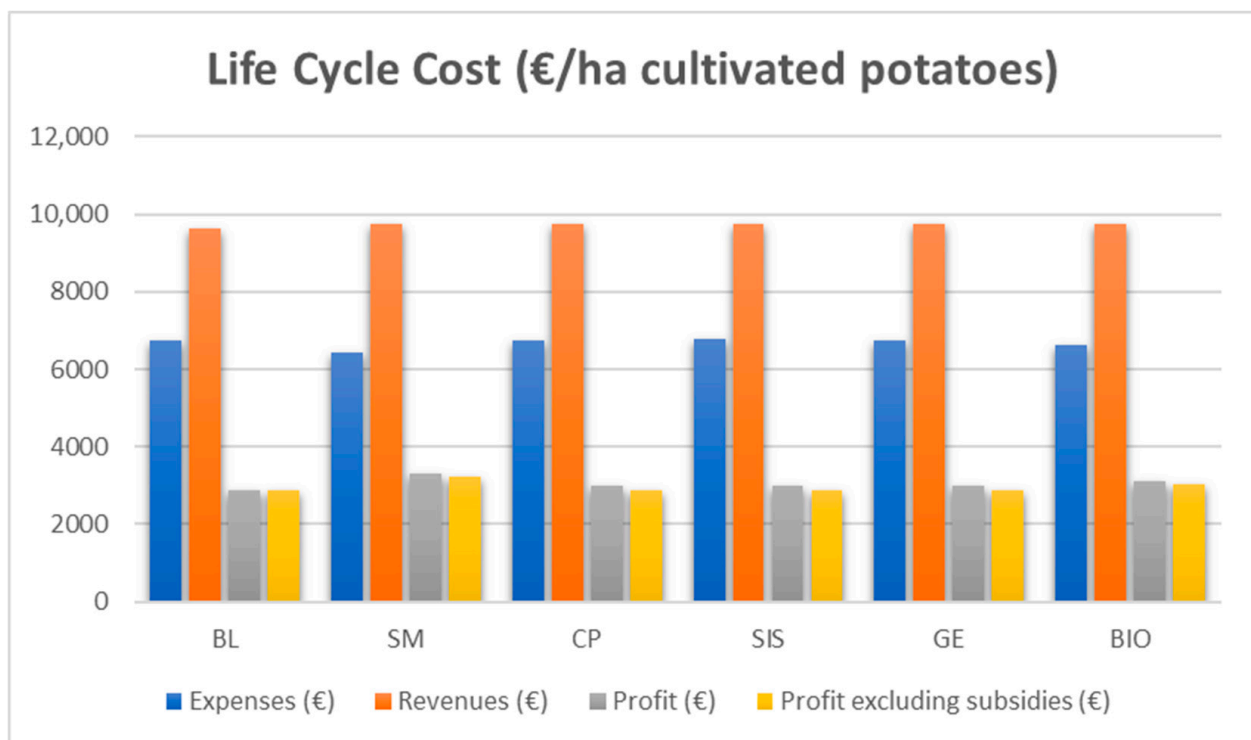
3.2. LCC Results—Potato Cultivation

The results of the LCC analysis for the potato cultivation of the baseline scenario and of the different studied CSA practices are presented in Table 3 and Figure 2.

The baseline potato system presented total expenses of €6761/ha and total revenues of €9640/ha, resulting in a profit of €2879/ha. Soil management achieved the highest profitability, with expenses decreasing to €6428/ha and revenues increasing to €9746/ha due to the included subsidy. This resulted in a profit of €3318/ha, corresponding to an increase of approximately 15.3% compared with the baseline. Even without subsidies, the profit of the SM scenario remained higher than the baseline, reaching €3212/ha. This indicates that the reduction in fertiliser-related expenses was the main driver of the improved economic performance.

Table 3. LCC results of the baseline and the different CSA practices for the cultivation of potatoes.

Cost Category (€/ha)		Baseline (BL)	Soil Management (SM)	Crop Protection (CP)	Sustainable Irrigation System (SIS)	Green Energy (GE)	Biodiversity (BIO)
Expenses	CAPEX	-	-	-	22	-	-
	Seeds	1296	1296	1296	1296	1296	1296
	Energy	447	447	447	447	447	447
	Fertilisers	332	-	332	332	332	332
	Plant protection products	1036	1036	1036	1036	1036	900
	Water	30	30	30	19	30	30
	Maintenance	33	33	33	33	33	33
	Labor	2838	2838	2838	2838	2838	2838
	Rent	600	600	600	600	600	600
	Other (taxes, admin, etc.)	148	148	148	148	148	148
	Total	6761	6428	6761	6771	6761	6625
	Change over BL (%)		−4.9%	-	0.2%	-	−2%
	Potatoes	9640	9640	9640	9640	9640	9640
Revenues	Subsidies	-	106	106	106	106	106
	Total	9640	9746	9746	9746	9746	9746
	Change over BL		1.1%	1.1%	1.1%	1.1%	1.1%
	Profit	2879	3318	2985	2975	2985	3121

**Figure 2.** Economic performance of the baseline and the different CSA practices for the cultivation of potatoes.

The biodiversity scenario also improved profitability. Total expenses decreased to €6625/ha due to the reduced use of plant-protection products, while revenues increased to €9746/ha. The final profit reached €3121/ha, corresponding to an increase of approximately 8.4% compared with the baseline. Excluding subsidies, the profit remained €3015/ha, still higher than the baseline. Therefore, biodiversity-oriented measures appear economically

favourable under the assumptions of this study, mainly because they reduce input costs without affecting yield.

Crop protection and green energy both generated a profit of €2985/ha. Their expenses remained equal to the baseline at €6761/ha, while revenues increased to €9746/ha due to the subsidy. However, when subsidies were excluded, their profit returned to €2879/ha, equal to the baseline. This shows that, under the modelled assumptions, these practices provide environmental benefits but limited direct economic improvement unless supported by policy incentives.

The sustainable irrigation system presented the highest expenses among the studied potato scenarios, reaching €6771/ha. This is mainly due to the annualised capital expenditure of €22/ha associated with the smart irrigation system. Nevertheless, total revenues reached €9746/ha, resulting in a profit of €2975/ha. Excluding subsidies, profit decreased to €2869/ha, slightly below the baseline. Therefore, the economic attractiveness of SIS depends strongly on subsidy support, equipment lifespan, water cost, and the degree of water and energy savings achieved in practice.

Overall, the LCC results indicate that soil management and biodiversity are the most economically favourable CSA options for potato cultivation. Soil management provides the highest profit because of reduced fertiliser costs, while biodiversity improves profitability by reducing pesticide-related expenses. SIS, CP, and GE provide more modest economic benefits, mainly through subsidies rather than direct cost savings. Therefore, although all CSA scenarios remain profitable, their financial attractiveness varies depending on the type of intervention and the cost category affected.

The economic results are consistent with previous studies reporting that fertiliser optimisation and reductions in agrochemical inputs can improve farm profitability while simultaneously reducing environmental impacts. However, investments in irrigation technologies and renewable energy systems generally require financial incentives or long-term cost recovery to become economically attractive [38,39].

3.3. Biodiversity Sensitivity Analysis—Potato Cultivation

The results of the biodiversity CSA practice sensitivity analysis in the environmental and economic performance regarding the cultivation of potatoes are presented in Figures 3 and 4, respectively.

The biodiversity CSA practice sensitivity analysis evaluated pesticide reduction levels of 10%, 20%, and 30% under fixed assumptions regarding nutrient-runoff mitigation and constant crop yields. Increasing pesticide reduction levels progressively improved the environmental performance of potato cultivation across all evaluated impact categories. Global warming potential decreased from 4268.4 kg CO₂ eq./ha under BIO 10% to 4225.5 kg CO₂ eq./ha under BIO 30%, while freshwater eutrophication showed the greatest improvement, decreasing from 8.06 kg P eq./ha to 1.64 kg P eq./ha. Similar declining trends were observed for terrestrial ecotoxicity and freshwater ecotoxicity, confirming the strong influence of pesticide and nutrient-runoff reductions on toxicity-related impact categories.

Economically, higher pesticide reductions resulted in moderate but consistent reductions in production costs due to lower expenditures on plant-protection products. Consequently, profitability improved slightly across the biodiversity scenarios while maintaining stable revenues under the assumption of constant yields. Overall, the biodiversity scenario demonstrated environmentally favourable performance, particularly for eutrophication and ecotoxicity categories, while maintaining positive economic performance across all sensitivity levels.

Although sensitivity analyses were performed for selected parameters related to pesticide reduction efficiency, additional analysis could further assess the influence of variables such as yield variability, fertiliser efficiency, diesel consumption, and market price fluctuations. Expanding the sensitivity analysis would improve the robustness of the conclusions and better represent uncertainties associated with real agricultural systems.

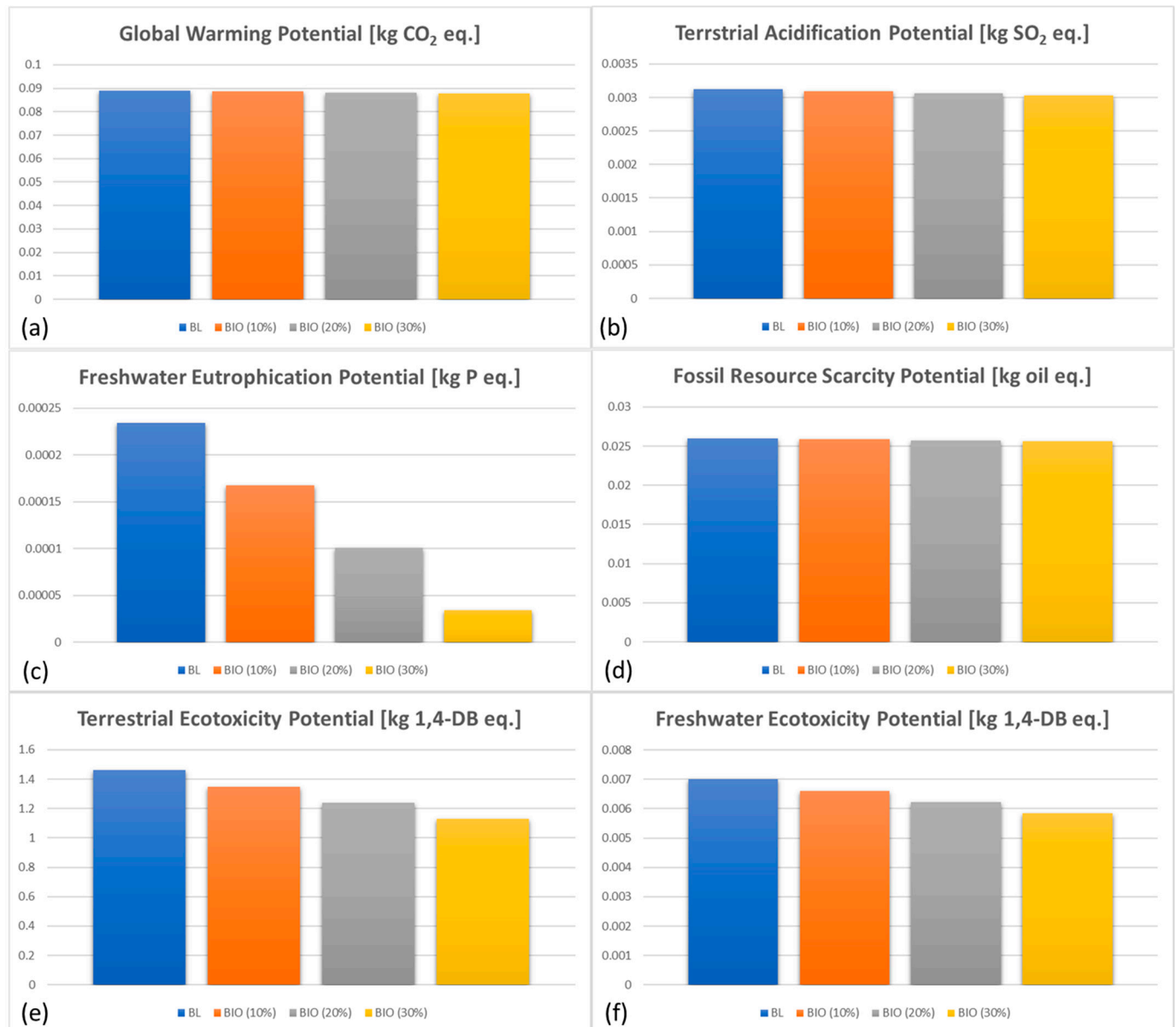


Figure 3. Environmental impact of the baseline (BL) and the different studied biodiversity scenarios for the cultivation of potatoes on (a) global warming potential (kg CO₂ eq.), (b) terrestrial acidification potential (kg SO₂ eq.), (c) freshwater eutrophication potential (kg P eq.), (d) fossil resource scarcity potential (kg oil eq.), (e) terrestrial ecotoxicity potential (kg 1,4-DB eq.), and (f) freshwater ecotoxicity potential (kg 1,4-DB eq.).

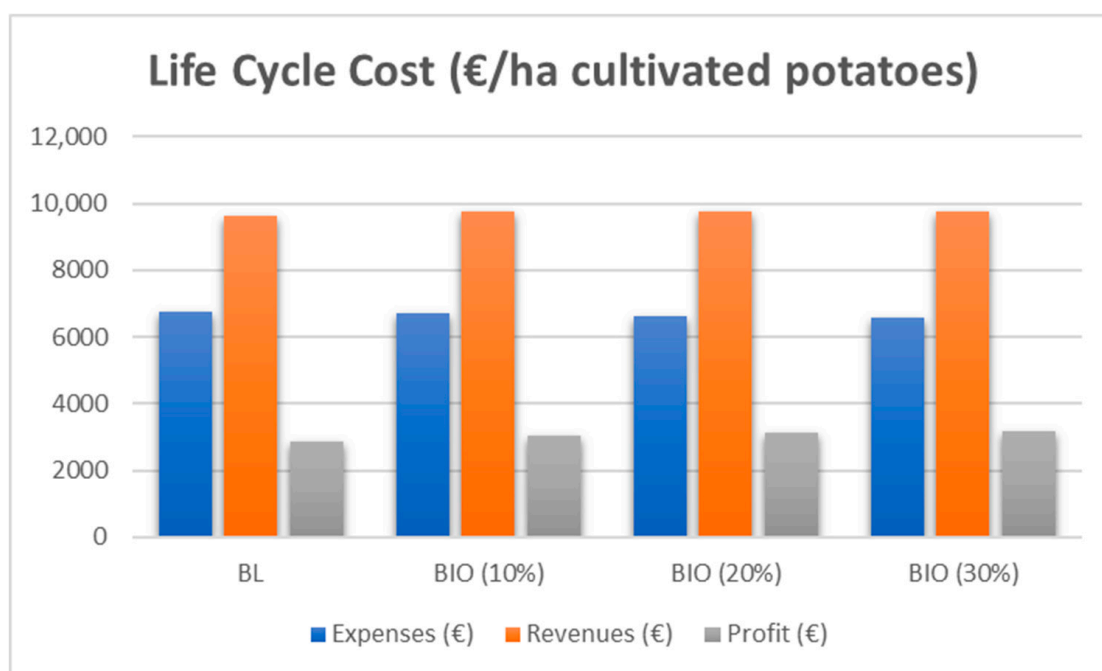


Figure 4. Economic performance of the baseline (BL) and the different studied biodiversity scenarios for the cultivation of potatoes.

3.4. LCA Results—Onion Cultivation

Figure 5 presents the LCA results of the baseline scenario, along with the different studied CSA practices regarding the cultivation of onions in the selected midpoint impact categories. As in the case of potatoes, the results were assessed both per kilogram of harvested onions and per hectare of cultivated land. This dual interpretation is particularly important for onions because the crop presents different input requirements and environmental profiles compared with potatoes.

The baseline onion system presented a global warming potential of 0.107 kg CO₂ eq./kg and 5350 kg CO₂ eq./ha. Soil management achieved the largest reduction, decreasing GWP to 0.0364 kg CO₂ eq./kg and 1819 kg CO₂ eq./ha, corresponding to a 66% reduction. This strong reduction is associated with the replacement of synthetic fertilisers with organic alternatives [40]. The high fertiliser requirements of onions make the crop particularly sensitive to changes in nutrient management. SIS, GE, and BIO all reduced GWP to 0.0952 kg CO₂ eq./kg and 4761.5 kg CO₂ eq./ha, equal to an 11% reduction compared with the baseline. Crop protection remained equal to the baseline because insecticide reduction does not significantly affect the modelled climate-related flows.

The terrestrial acidification potential of the baseline was 0.00688 kg SO₂ eq./kg and 344 kg SO₂ eq./ha. Soil management reduced this value to 0.00310 kg SO₂ eq./kg and 154.8 kg SO₂ eq./ha, corresponding to a 55% decrease. Biodiversity produced a smaller reduction, reaching 0.00674 kg SO₂ eq./kg and 337.12 kg SO₂ eq./ha. CP, SIS, and GE remained unchanged. This confirms that acidification in onion cultivation is mainly associated with nitrogen fertiliser use and related ammonia emissions [41].

Freshwater eutrophication potential was 0.000016 kg P eq./kg and 0.80 kg P eq./ha in the baseline scenario. Soil management achieved the lowest value, decreasing the impact to 0.00000864 kg P eq./kg and 0.432 kg P eq./ha, corresponding to a 46% reduction. Biodiversity reached 0.00000992 kg P eq./kg and 0.496 kg P eq./ha, equal to a 38% reduction. SIS and GE also improved this category, with hectare-based values of 0.544 and 0.560 kg P eq./ha, respectively. CP achieved only a small reduction, reaching 0.792 kg P eq./ha.

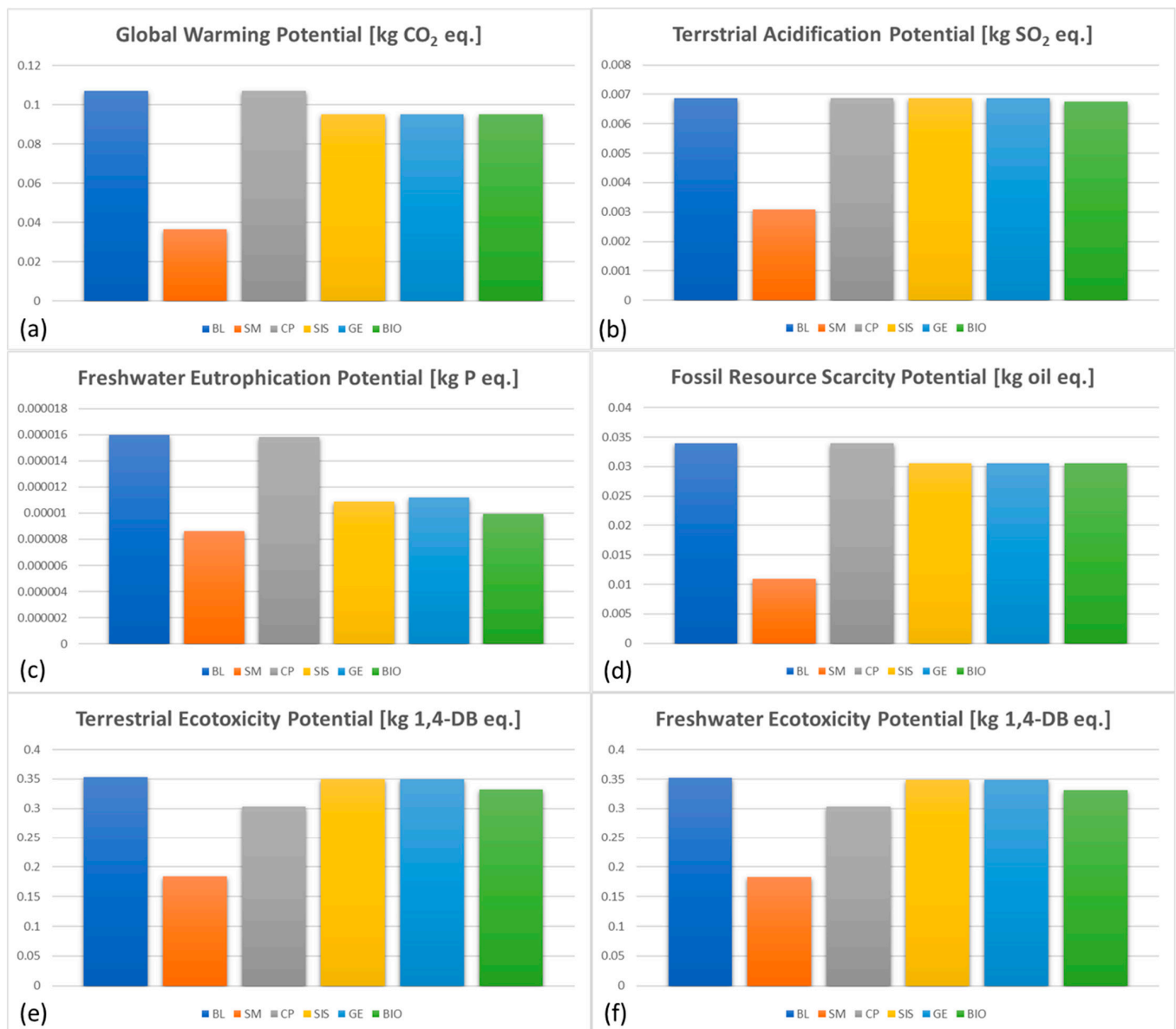


Figure 5. Environmental impact of the baseline (BL), soil management (SM), crop protection (CP), sustainable irrigation system (SIS), green energy (GE), and biodiversity (BIO) for onion cultivation on (a) global warming potential (kg CO₂ eq.), (b) terrestrial acidification potential (kg SO₂ eq.), (c) freshwater eutrophication potential (kg P eq.), (d) fossil resource scarcity potential (kg oil eq.), (e) terrestrial ecotoxicity potential (kg 1,4-DB eq.), and (f) freshwater ecotoxicity potential (kg 1,4-DB eq.).

Fossil resource scarcity potential was 0.034 kg oil eq./kg and 1700 kg oil eq./ha in the baseline. Soil management reduced this impact to 0.0109 kg oil eq./kg and 544 kg oil eq./ha, equal to a 68% decrease. SIS, GE, and BIO reduced the impact to 0.0306 kg oil eq./kg and 1530 kg oil eq./ha, corresponding to a 10% reduction. CP remained unchanged compared with the baseline.

Terrestrial ecotoxicity potential was 0.353 kg 1,4-DB eq./kg and 17,650 kg 1,4-DB eq./ha in the baseline. Soil management achieved the largest reduction, reaching 0.1836 kg 1,4-DB eq./kg and 9178 kg 1,4-DB eq./ha, corresponding to a 48% reduction. Crop protection also improved this category, decreasing the impact to 0.3036 kg 1,4-DB eq./kg and 15,179 kg 1,4-DB eq./ha. Biodiversity reached 0.3318 kg 1,4-DB eq./kg and 16,591 kg 1,4-DB eq./ha, while SIS and GE produced only minor reductions.

Freshwater ecotoxicity potential decreased from 0.001 kg 1,4-DB eq./kg and 50 kg 1,4-DB eq./ha in the baseline to 0.00073 kg 1,4-DB eq./kg and 36.5 kg 1,4-DB eq./ha in the SM scenario. Biodiversity also performed well, reaching 0.00078 kg 1,4-DB eq./kg and 39 kg 1,4-DB eq./ha. CP reached 43 kg 1,4-DB eq./ha, SIS reached 44.5 kg 1,4-DB eq./ha, and GE reached 45 kg 1,4-DB eq./ha.

Overall, the onion LCA results demonstrate that soil management is the most effective CSA strategy across most impact categories. This is mainly because onion cultivation has high fertiliser requirements, making nutrient substitution highly influential. Biodiversity and crop protection mainly improve toxicity-related categories, while SIS and GE mostly affect energy- and resource-related indicators.

The larger environmental improvements observed for onions compared with potatoes under the soil management scenario reflect the greater dependence of onion production on nitrogen fertilisation. Because onions require relatively high nutrient inputs, fertiliser substitution produces proportionally larger reductions in greenhouse gas emissions, acidification, and fossil resource use. Similar conclusions have been reported in previous LCA studies of vegetable production, which identify fertiliser management as one of the principal determinants of environmental performance [22,42].

The comparatively smaller improvements associated with green energy and sustainable irrigation indicate that these practices mainly reduce indirect energy-related burdens while leaving fertiliser-derived emissions largely unaffected. Consequently, integrated implementation of several CSA practices may provide greater environmental benefits than adopting individual measures in isolation.

3.5. LCC Results—Onion Cultivation

The results of the LCC analysis for the onion cultivation of the baseline scenario and of the different studied CSA practices are presented in Table 4 and Figure 6.

Table 4. LCC results of the baseline and the different CSA practices for the cultivation of onions.

Cost Category (€/ha)		Baseline (BL)	Soil Management (SM)	Crop Protection (CP)	Sustainable Irrigation System (SIS)	Green Energy (GE)	Biodiversity (BIO)
Expenses	CAPEX	-	-	-	22	-	-
	Seeds	1824	1824	1824	1824	1824	1824
	Energy	535	535	535	535	535	535
	Fertilisers	267	267	267	267	267	267
	Plant protection products	200	200	200	200	200	138
	Water	29	29	29	18	29	29
	Maintenance	34	34	34	34	34	34
	Labor	2838	2838	2838	2838	2838	2838
	Rent	600	600	600	600	600	600
	Other (taxes, admin, etc.)	148	148	148	148	148	148
	Total	6474	6208	6474	6485	6474	6412
	Change over BL (%)		−4.12%	-	0.17%	-	−0.95%
	Potatoes	10,000	10,000	10,000	10,000	10,000	10,000
Revenues	Subsidies	-	106	106	106	106	106
	Total	10,000	10,106	10,106	10,106	10,106	10,106
	Change over BL		1.1%	1.1%	1.1%	1.1%	1.1%
	Profit	3526	3898	3632	3621	3632	3694

The baseline onion system presented total expenses of €6474/ha and revenues of €10,000/ha, resulting in a profit of €3526/ha. Soil management produced the highest profit, reaching €3898/ha. This was due to reduced expenses, which decreased to €6208/ha, and

increased revenues of €10,106/ha due to subsidy inclusion. Without subsidies, the profit of SM remained high at €3792/ha, confirming that cost reduction rather than subsidy alone was the main economic driver.

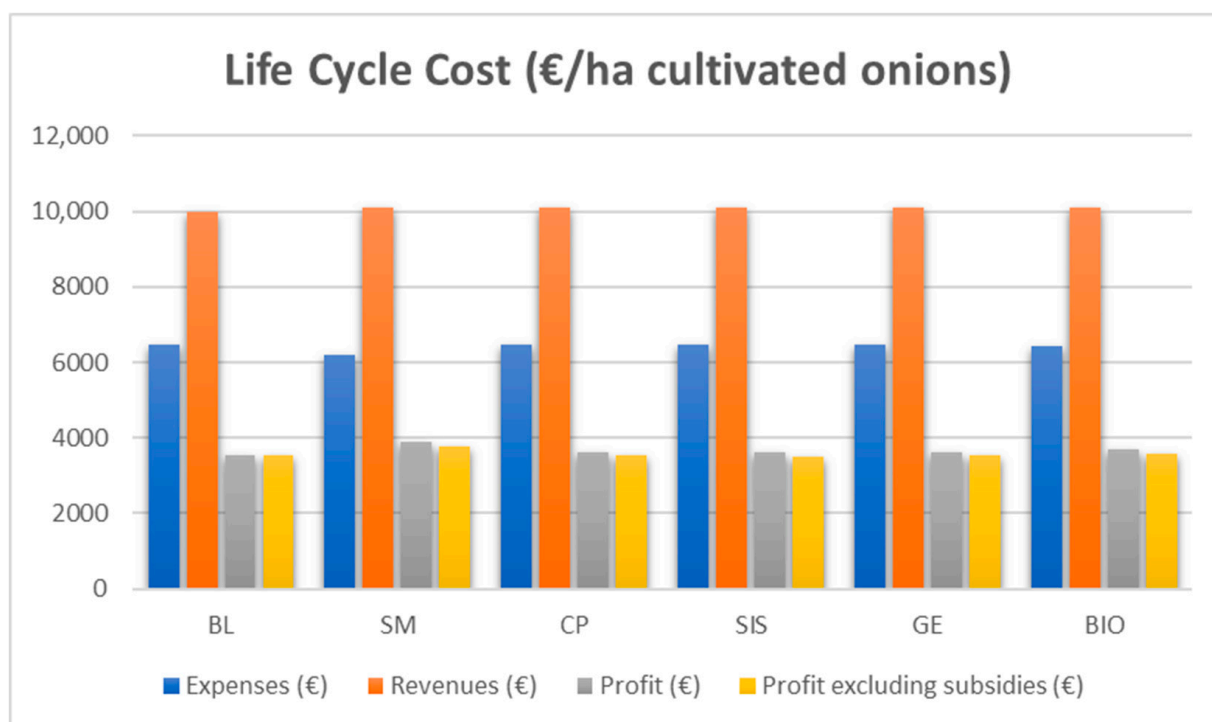


Figure 6. Economic performance of the baseline and the different CSA practices for the cultivation of onions.

The biodiversity scenario generated the second-highest profit, reaching €3694/ha. Total expenses decreased to €6412/ha due to lower plant-protection costs, while revenues increased to €10,106/ha. Excluding subsidies, the profit was €3588/ha, still higher than the baseline. This indicates that biodiversity measures can improve economic performance even when policy support is not considered.

Crop protection and green energy both generated profits of €3632/ha. Their total expenses remained equal to the baseline at €6474/ha, while revenues increased to €10,106/ha. However, when subsidies were excluded, their profit was €3526/ha, equal to the baseline. This indicates that these measures provide limited direct cost savings in the current modelling framework.

The sustainable irrigation system generated a profit of €3621/ha. Expenses increased slightly to €6485/ha because of the annualised capital cost of the irrigation system. Although reduced water consumption partly compensated for this additional cost, the profit without subsidies was €3515/ha, slightly below the baseline. Therefore, the economic viability of SIS for onions depends on the cost of technology, subsidy availability, and the value of water and energy savings.

Overall, the LCC results show that all CSA practices remain economically viable for onion cultivation. Soil management provides the strongest economic performance, followed by biodiversity. CP, GE, and SIS provide smaller financial improvements and depend more strongly on subsidy support.

The economic results are consistent with previous studies reporting that fertiliser optimisation and reductions in agrochemical inputs can improve farm profitability while simultaneously reducing environmental impacts. However, investments in irrigation

technologies and renewable energy systems generally require financial incentives or long-term cost recovery to become economically attractive [38,39].

3.6. Biodiversity Sensitivity Analysis—Onion Cultivation

The results of the biodiversity CSA practice sensitivity analysis in the environmental and economic performance regarding the cultivation of onions are presented in Figures 7 and 8, respectively.

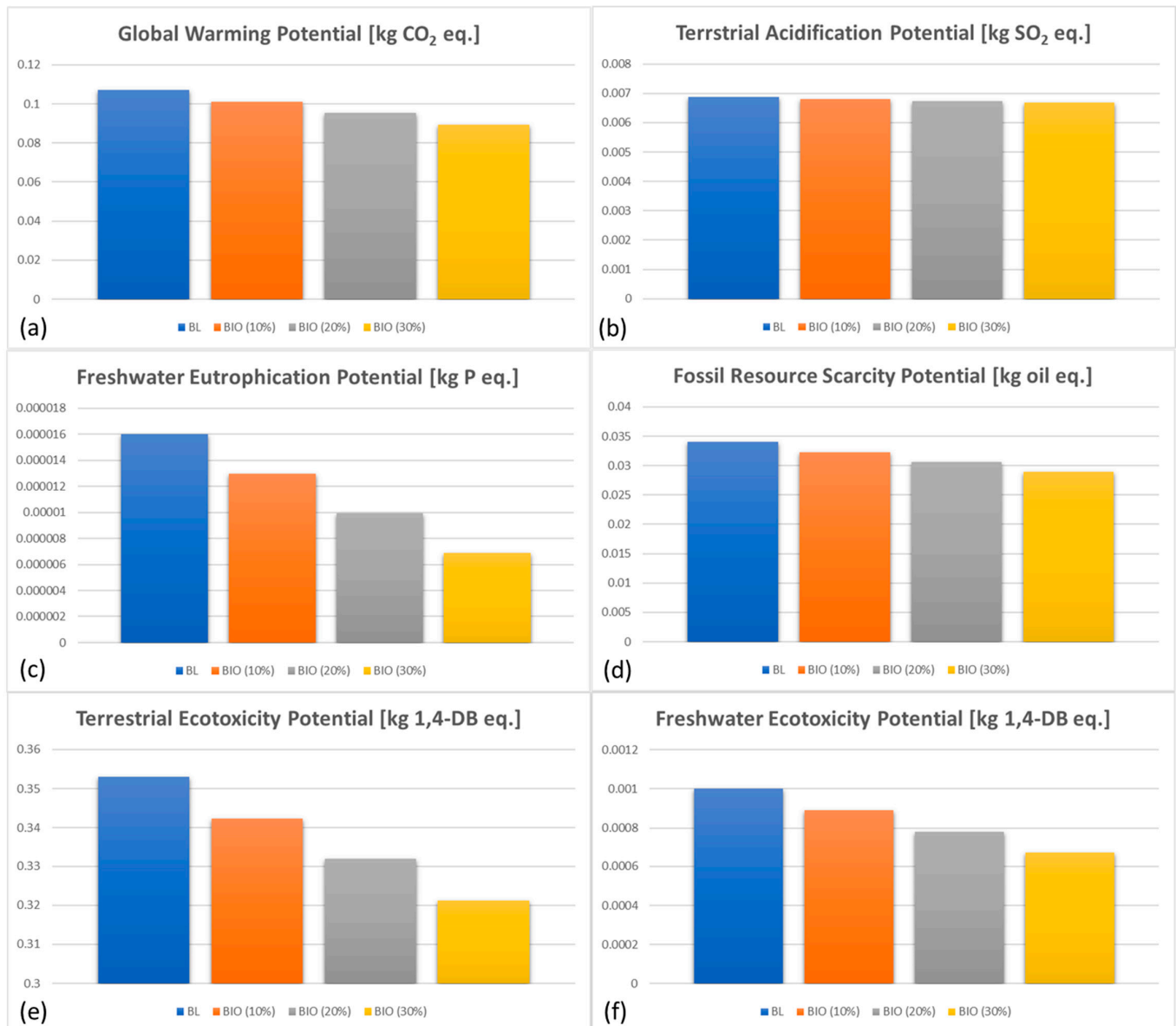


Figure 7. Environmental impact of the baseline (BL) and the different studied biodiversity scenarios for the cultivation of onions on (a) global warming potential (kg CO₂ eq.), (b) terrestrial acidification potential (kg SO₂ eq.), (c) freshwater eutrophication potential (kg P eq.), (d) fossil resource scarcity potential (kg oil eq.), (e) terrestrial ecotoxicity potential (kg 1,4-DB eq.), and (f) freshwater ecotoxicity potential (kg 1,4-DB eq.).

The biodiversity CSA practice sensitivity analysis evaluated pesticide reduction levels of 10%, 20%, and 30% under fixed assumptions regarding nutrient-runoff reduction and stable crop productivity. Increasing pesticide reductions progressively improved the environmental performance of onion cultivation in all evaluated categories. Global warming

potential decreased from 5055.8 kg CO₂ eq./ha under BIO 10% to 4467.3 kg CO₂ eq./ha under BIO 30%, corresponding to a reduction of approximately 16.5% compared with the baseline scenario. Freshwater eutrophication and freshwater ecotoxicity exhibited the greatest sensitivity to the modelled reductions, decreasing to 0.344 kg P eq./ha and 33.5 kg 1,4-DB eq./ha, respectively, under the highest biodiversity scenario.

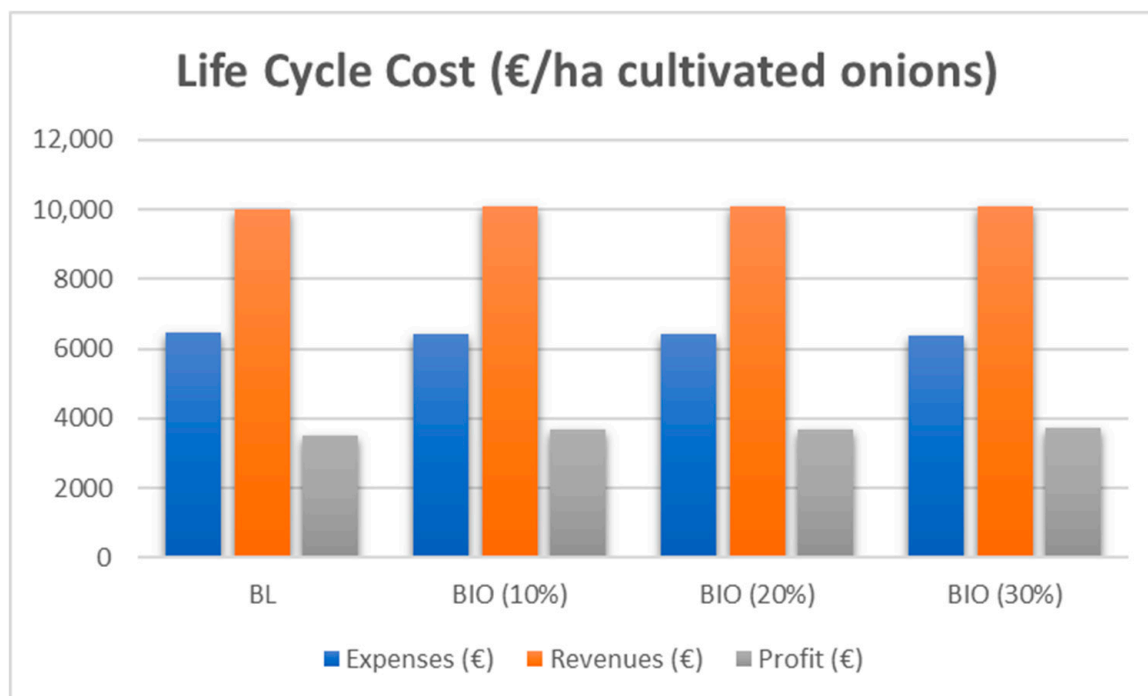


Figure 8. Economic performance of the baseline (BL) and the different studied biodiversity scenarios for the cultivation of onions.

From an economic perspective, increased pesticide reductions generated small but consistent decreases in operating expenses due to reduced plant-protection requirements, while revenues remained stable because yields were assumed constant. Therefore, profitability improved slightly across the biodiversity scenarios without introducing major additional costs. Overall, the biodiversity CSA practice demonstrated environmentally beneficial performance while maintaining economic viability across all evaluated sensitivity levels.

Although sensitivity analyses were conducted for selected pesticide-reduction assumptions, further analysis could evaluate the influence of additional variables such as fertiliser substitution efficiency, irrigation performance, yield variability, energy prices, and market fluctuations. Incorporating broader sensitivity and uncertainty analyses would improve the robustness and applicability of the reported results under real farming conditions.

3.7. Comparison of Potato and Onion Cultivation

A comparative assessment between potato and onion cultivation shows clear differences in environmental and economic performance. Although both crops benefit from the implementation of CSA practices, the magnitude of improvement varies depending on crop-specific input requirements, yield, and the environmental category considered.

For the baseline scenario, onions presented a higher global warming potential than potatoes. The baseline GWP was 0.107 kg CO₂ eq./kg for onions compared with 0.089 kg CO₂ eq./kg for potatoes. On a hectare basis, onions also had a higher GWP, reaching 5350 kg CO₂ eq./ha compared with 4289.8 kg CO₂ eq./ha for potatoes. This indicates that

onion cultivation creates higher climate-related pressure in the modelled system, mainly because of higher input requirements.

The same trend was observed for terrestrial acidification. Baseline onions reached 0.00688 kg SO₂ eq./kg and 344 kg SO₂ eq./ha, while potatoes reached 0.00312 kg SO₂ eq./kg and 150.38 kg SO₂ eq./ha. This difference indicates that onion cultivation is more sensitive to nitrogen-related emissions. Soil management reduced acidification by 55% in onions, compared with only 7% in potatoes, showing that fertiliser substitution has a much stronger relative effect in the onion system.

Freshwater eutrophication showed a different pattern. Potatoes had a higher baseline value per hectare, reaching 11.28 kg P eq./ha, compared with only 0.80 kg P eq./ha for onions. Therefore, although onions presented higher climate and acidification impacts, potatoes generated greater eutrophication pressure in the modelled baseline. The biodiversity scenario was particularly effective in potatoes, reducing FEP by 57%, while soil management was the strongest option for onions, reducing FEP by 46%.

For fossil resource scarcity, onions again presented a higher baseline impact, with 0.034 kg oil eq./kg and 1700 kg oil eq./ha, compared with 0.026 kg oil eq./kg and 1253.2 kg oil eq./ha for potatoes. Soil management produced the largest reduction in both crops, decreasing fossil resource scarcity by 46% in potatoes and 68% in onions.

The ecotoxicity categories showed crop-specific behaviour. Potatoes had much higher terrestrial ecotoxicity per hectare, reaching 70,372 kg 1,4-DB eq./ha in the baseline, compared with 17,650 kg 1,4-DB eq./ha for onions. This suggests that pesticide-related burdens are considerably higher in the modelled potato system. Biodiversity achieved the strongest reduction in potatoes, while soil management showed the strongest reduction in onions. Freshwater ecotoxicity was also higher in potatoes, with 337.4 kg 1,4-DB eq./ha compared with 50 kg 1,4-DB eq./ha for onions.

From an economic perspective, onions generated higher baseline profitability than potatoes. The baseline profit was €3526/ha for onions and €2879/ha for potatoes. Under CSA implementation, soil management provided the highest profit for both crops: €3318/ha for potatoes and €3898/ha for onions. Biodiversity was the second most profitable option in both systems, reaching €3121/ha for potatoes and €3694/ha for onions.

Overall, the comparison demonstrates that onion cultivation presents higher climate, acidification, and fossil resource impacts, while potatoes present higher eutrophication and ecotoxicity burdens in the modelled system. Soil management is the most effective cross-cutting strategy for reducing fertiliser- and energy-related impacts, while biodiversity and crop protection are more relevant for reducing pesticide-related burdens. Therefore, the selection of CSA practices should be crop-specific and should consider the dominant environmental hotspots of each production system.

The comparative assessment also has important implications for Dutch and European agriculture. The results indicate that no single CSA practice is universally optimal across all crops and environmental impact categories. Instead, management strategies should be tailored to crop-specific environmental hotspots. Within the Netherlands, where nutrient management and pesticide reduction remain central objectives of agricultural policy, soil management and biodiversity enhancement appear particularly promising. More broadly, the methodology presented in this study can support the evaluation of climate-smart agriculture strategies in other European vegetable production systems facing similar challenges related to greenhouse gas mitigation, nutrient management, and resource efficiency.

3.8. Limitations and Uncertainty

The present study incorporates sensitivity analyses for selected parameters, primarily focusing on variations in pesticide reduction levels within the biodiversity scenarios for

potato and onion cultivation. However, additional sources of uncertainty remain that may influence the robustness of the environmental and economic results. Key parameters such as diesel consumption, fertiliser substitution efficiency, pesticide emission factors, irrigation performance, yield variability, and market prices can significantly affect both LCA and LCC outcomes.

Furthermore, several assumptions adopted in the modelling framework—particularly those related to pesticide-reduction efficiency, nutrient-runoff mitigation, renewable energy substitution, and the maintenance of constant crop yields across all scenarios—introduce additional uncertainty. These assumptions represent plausible but not universally applicable conditions and may vary depending on regional climatic conditions, soil characteristics, farm management practices, and technology performance.

Although deterministic sensitivity analyses were performed for the biodiversity scenarios, a comprehensive quantitative uncertainty analysis, such as Monte Carlo simulation or probabilistic uncertainty propagation, was not conducted because several scenario parameters were based on literature-derived assumptions rather than probability distributions. Consequently, the reported results should be interpreted as indicative of the relative performance of the evaluated CSA practices rather than as precise predictions of environmental and economic outcomes. Future studies should incorporate probabilistic uncertainty analysis as additional empirical data become available.

Uncertainty is particularly important in the ecotoxicity-related impact categories, where pesticide emission modelling and characterisation factors remain associated with relatively high variability. In addition, the environmental benefits attributed to soil management practices may differ substantially under field conditions because long-term effects such as soil carbon sequestration, soil fertility improvement, and changes in nutrient cycling were not explicitly quantified in the present analysis.

A comprehensive uncertainty analysis, such as Monte Carlo simulation or probabilistic modelling, was beyond the scope of the present study. Therefore, the results should be interpreted with caution, especially for scenarios that rely heavily on modelled assumptions, including biodiversity enhancement and soil management practices. Furthermore, the practical implementation of the evaluated CSA practices may produce different outcomes under varying climatic conditions, soil characteristics, farm sizes, management intensity, and policy environments. For example, the environmental benefits associated with fertiliser substitution, biodiversity enhancement, or precision irrigation may vary depending on nutrient availability, local weather conditions, and farmer management practices. Therefore, while the findings provide useful guidance for Dutch potato and onion production systems, caution should be exercised when extrapolating the results to other regions or agricultural contexts without appropriate local adaptation and validation. Future research should incorporate broader uncertainty propagation approaches, field-scale validation, and multi-year datasets in order to better assess the variability and reliability of the reported environmental and economic outcomes.

4. Conclusions

This study addressed the lack of integrated environmental and economic assessments of multiple climate-smart agriculture (CSA) practices by applying a combined Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) framework to potato and onion production systems in the Netherlands. By evaluating five representative CSA practices using a consistent methodological approach, the study demonstrated that the environmental and economic performance of these practices depends on both the crop and the dominant environmental hotspot, highlighting the importance of crop-specific management strategies.

The findings indicate that soil management offers the greatest potential for improving overall sustainability through reductions in fertiliser-related environmental impacts while maintaining economic viability. Biodiversity-oriented practices were particularly effective in reducing eutrophication and ecotoxicity, whereas sustainable irrigation systems and green energy primarily contributed to resource efficiency. These results demonstrate that no single CSA practice is universally optimal, reinforcing the need for integrated decision-making that considers both environmental and economic objectives.

From a practical perspective, the findings support farmers in selecting management practices that improve resource efficiency while maintaining farm profitability. They also provide evidence for policymakers to design targeted incentive schemes that encourage the adoption of crop-specific climate-smart practices, particularly those related to nutrient management, biodiversity enhancement, and efficient resource use within Dutch and European vegetable production systems.

Future research should validate the scenario-based assumptions under commercial farming conditions using multi-year field experiments, incorporate probabilistic uncertainty analysis, and evaluate additional sustainability indicators such as soil carbon sequestration, biodiversity outcomes, and social impacts. Such work would further strengthen the evidence base for implementing climate-smart agriculture in European cropping systems.

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Informed Consent Statement: Informed consent was obtained from all people that participated in data collection for the scope of this study.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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