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Microbial applications and agricultural sustainability: A simulation analysis of Dutch potato farms

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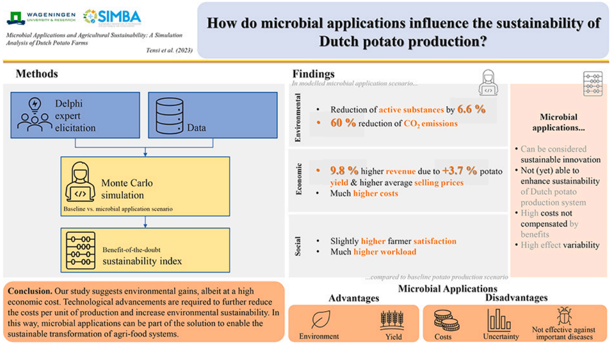
HIGHLIGHTS

- Food production impacts the environment, but the footprint can be reduced through sustainable innovations.
- We assess the sustainability of microbial applications in Dutch potato production.
- With microbial applications the environmental footprint is reduced, but the costs outweigh the benefits.
- Microbial applications do not enhance the sustainability of the Dutch potato production system yet.
- We quantify the effect and uncertainty of microbial applications in a primary food production system with novel data.

GRAPHICAL ABSTRACT



Microbial Applications and Agricultural Sustainability: A Simulation Analysis of Dutch Potato Farms

Tensi et al. (2023)

How do microbial applications influence the sustainability of Dutch potato production?

Methods

Delphi expert elicitation

Data

Monte Carlo simulation

Baseline vs. microbial application scenario

Benefit-of-the-doubt sustainability index

Findings

In modelled microbial application scenario...

Environmental
- Reduction of active substances by 6.6 %
- 60 % reduction of CO_2 emissions

Economic
- 9.8 % higher revenue due to +3.7 % potato yield & higher average selling prices
- Much higher costs

Social
- Slightly higher farmer satisfaction
- Much higher workload

...compared to baseline potato production scenario

Microbial applications...
- Can be considered sustainable innovation
- Not (yet) able to enhance sustainability of Dutch potato production system
- High costs not compensated by benefits
- High effect variability

Conclusion. Our study suggests environmental gains, albeit at a high economic cost. Technological advancements are required to further reduce the costs per unit of production and increase environmental sustainability. In this way, microbial applications can be part of the solution to enable the sustainable transformation of agri-food systems.

ARTICLE INFO

Keywords:
Microbial applications
Simulation modelling
Delphi
Expert elicitation
Dutch potato production

ABSTRACT

CONTEXT: Fertilisers and plant protection products are essential for the economic viability of arable agriculture, but their overuse leads to environmental problems. Microbial applications have been proposed as a solution to reduce these environmental problems in arable farming. Experimental results suggest that microbial applications can increase yields and reduce abiotic stresses with fewer fertilisers and plant protection products. However, the overall effects of microbial applications on farm economics, the environment and social dimensions have not been quantified yet.

OBJECTIVE: In this study, we assess the capacity of microbial applications to enhance the sustainability, including environmental, economic and social dimensions, of Dutch potato production.

METHODS: We model a baseline scenario and a microbial application scenario with Monte Carlo simulation, and compare the scenarios using a composite sustainability index. The microbial application scenario is based on data from a Delphi expert elicitation.

RESULTS AND CONCLUSIONS: The model indicates that, at present, microbial interventions do not contribute to the sustainability of Dutch potato production. In fact, the conventional baseline approach is more sustainable compared to the scenario involving microbial applications. In the microbial application scenario, cost per hectare of potato production is almost three times higher than in the baseline scenario, which are not covered by the 3.7% yield and 9.8% revenue increase. However, microbial applications can reduce CO_2 emissions by 60% and active substances by 6.6%. Technological advancements are necessary to reduce costs per unit of production and increase environmental sustainability.

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SIGNIFICANCE: This study explores the impact of microbial applications on agricultural sustainability amid uncertainty, emphasising the need to quantify their effects. This study highlights the importance of economically viable sustainable practices to incentivise farmers' adoption. While efficient microbial applications can reduce reliance on conventional pesticides and fertilisers, they currently cannot contribute to the Farm-to-Fork reduction goals. Future research should focus on cost-effective microbial applications for disease prevention. We provide four routes for further research on microbial applications.

1. Introduction

Fertilisers and plant protection products (PPP) are essential for the economic viability of arable agriculture, but their overuse leads to environmental problems (Sud, 2020; Sidhoum et al., 2020; Skevas et al., 2014). In light of this, the European Commission has introduced the 'Farm-to-Fork' strategy: Farmers need to use 50% fewer PPP and 20% fewer fertilisers by 2030 compared to the baseline average of 2015–2017. In Dutch arable agriculture, the Farm-to-Fork reduction goals for fertilisers have almost been met in 2020, but continued reduction efforts are needed to reduce PPP. The use of active substances in 2020 has been twice as high as the 2030 reduction goal.[1] This paper addresses the problem of how to simultaneously reduce use of fertilisers and PPP and ensure economic viability by assessing the potential impact of microbial innovations.

Microbial applications have recently been proposed as an innovative solution to substitute or complement PPP and fertilisers, while increasing yields and alleviating drought and other abiotic stresses (Belimov et al., 2015; de Souza et al., 2015; Gong et al., 2020; Grossi et al., 2020; Lutfullin et al., 2022). Reducing PPP and fertiliser use has a positive effect on environmental sustainability by lowering active substances and CO_2 emissions. A microbial application is a consortium of various microorganisms (Tshikantwa et al., 2018). Beneficial rhizobacteria, microorganisms living in the root-soil interface, can improve the productivity and quality of crops, suppress plant diseases and control pathogens (Gouda et al., 2018).

Data on the performance of microbial applications are scarce and preliminary (Kołodziejczyk, 2014). Experimental results suggest the potential of microbial applications (Elnahal et al., 2022), but on the farm their costs, effectiveness in reducing PPP and fertiliser use, and in increasing crop yield have not been reliably quantified (Mitter et al., 2019; Shameer and Prasad, 2018). First calculations show that production costs of microbial applications are not yet competitive with available chemicals (Lobo et al., 2019). Microbial applications are not widely available on the market (Russo et al., 2012), and also the number of farmers using microbial applications is limited. Due to the absence of on-farm data, the actual environmental and economic effects of microbial application use are unknown and social aspects of microbial applications have not been investigated yet. Therefore, the overall impact of microbial applications on the sustainability of agricultural production is unclear. To address this information and data gap, we have elicited experts in form of a Delphi study.

In this study, we aim to assess the capacity of microbial applications to enhance the sustainability, including environmental, economic and social dimensions of primary food production systems. We focus on the Dutch potato production system. Potatoes are important for world-wide food security, but their input-intensive production has a considerable environmental footprint (Koch et al., 2020). Also in the Netherlands, potato production has a considerable impact on the environment while being economically relevant: Potatoes are produced on 31% of Dutch arable farm land and 1.3 million tonnes of consumption potatoes have been exported in 2020 (Berkhout et al., 2022). In Dutch seed potato production, 37.9 kg ha^{-1} active substances are used. In comparison, this is seven times more than what is used in the input intensive Dutch sugar beet production (5 kg ha^{-1}) (Smit, 2022). Farmers apply active substances in PPP to mitigate production risks, such as yield and quality reducing nematodes (Herrera et al., 2022; Orlando et al., 2020), and *Phytophthora infestans*. *Phytophthora* causes potato late blight, the most important disease in potatoes (Schepers et al., 2018). To reduce the use of active substances, farmers need reliable alternatives. Switching to alternative products will be less of a choice than a necessity, as some harmful active substances are already or will be banned in the near future (Goffart et al., 2022). To date, possible alternatives such as microbial applications are understudied (Aloo et al., 2020).

This study contributes to fill this knowledge gap by demonstrating to what extent microbial applications can serve as sustainable alternative and achieving Farm-to-Fork reduction goals. We answer the research question 'How do microbial applications influence the sustainability of Dutch potato production?' We model a baseline potato production system (hereafter called baseline scenario) and a potato production system that incorporates microbial applications (hereafter called microbial application scenario) with Monte Carlo (MC) simulation, and compare the scenarios with a composite sustainability index. The microbial application scenario is based on data from a Delphi expert elicitation. We provide insights into advantages and disadvantages of using microbial applications.

2. Materials and methods

2.1. Model structure, boundaries and assumptions

We employ a MC simulation model to simulate the environmental, economic and social outcomes of a Dutch potato production system with and without microbial applications. The overall model is a static stochastic partial budget model. MC simulations are a common tool to assess *ex ante* environmental and economic impacts of novel technologies. For example, Tillie et al. (2014) simulate the impacts of adopting genetically modified herbicide tolerant maize on farmers' gross margin with a stochastic partial budget model. Mavrotas and Makryvelios (2021) combine a multi-criteria analysis, mathematical programming and MC simulation to assess the uncertainty in research and development projects.

In the *baseline scenario*, the parameters and distributions are based on historic production data and literature. The *microbial application scenario* is the baseline scenario multiplied by the *microbial change model*. In the microbial change model the effects of microbial applications on the amount of production inputs and outputs is quantified. Parameters of the microbial change model are drawn from a Delphi expert elicitation study. The model outputs are aggregated in a composite sustainability index. See Fig. 1 for a visual summary of the model structure.

The system boundary of the model is the farm gate. The unit of analysis is one hectare of conventional potato production in the Netherlands in the time frame of one growing season. In the simulation, we distinguish between seed, starch and consumption potato production, but results are aggregated per production scenario.

The baseline scenario reflects the average potato production system in the Netherlands in 2010 to 2018. To reflect the true shares of utilised agricultural area of each potato crop, we simulate $N = 500$ ha of consumption potatoes and $N = 250$ ha each of seed and starch potatoes. We assume average Dutch growing conditions in terms of weather, soil and location and average management in terms of production inputs and

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[1] own calculations (see Appendix A), based on Agrimatie data

outputs applied at ideal dosage. We assume all other inputs, such as seedlings, energy, and working hours for the harvest, to be fixed, and that microbial applications are allowed by legislation.

2.2. *Input data*

2.2.1. *Baseline data*

The baseline model input parameters and their distributions are summarised in Table 1 below. The model variables are grouped into economic and environmental in and output factors and social factors. We impose stochasticity on all variables, except for production input prices to introduce variability in production because there are large differences in yield between fields and farms (Den et al., 2022). Prices for fertilisers and PPP are fixed because of low price variability in the considered time frame.

2.2.2. *Expert elicitation*

The goal of the Delphi expert elicitation is to gain parameters to quantify the microbial change model. We selected experts with heterogeneous backgrounds. Their expertise spans diverse disciplines, from agronomy to microbiology. The majority of experts in our panel are researchers in academia and institutes, in addition to a few participants from industry. Several studies suggest that experts with commercial interests should not partake (Ehlers et al., 2021). However, we deliberately chose to include industry representatives for their knowledge on marketed microbial products. By including industry experts, we alleviate scientists' "T-focused" bias. The T-focused bias makes scientists prone to be too optimistic in the short-term. They feel that an innovation is feasible and therefore will be implemented, but underestimate the organisational or other non-technical difficulties that may impede implementation and market uptake (Linstone and Turoff, 2011). All experts are directly involved in the European Horizon 2020 SIMBA project. Their identity is known to the authors, and their answers are anonymous or with an identifier. The entire panel consists of sixteen experts, who have all been invited to partake in the workshop to pretest the survey and to the two-iteration Delphi study.

The expert elicitation consists of three rounds, namely a two-hour workshop with a pre-test of the survey in June 2022 and two Delphi iterations. An overview of the expert elicitation procedure is provided in Fig. 1 in the box on the left. During the in-person workshop, we present the research questions and background of our study, why we involve experts, and how we use the experts' estimates. We introduce the baseline and microbial application scenarios and our assumptions. After this introductory presentation, the experts have filled in the pre-test survey online which we discussed afterwards. Twelve of the sixteen experts have pretested the questionnaire. The survey questions are based on Foolen-Torgerson (2022, Chapter 3). The pre-test allows to clarify questions on the spot and to simplify the survey later.

In the second round, the first Delphi iteration, we use the simplified survey and ask the experts to provide their estimates. The online survey is sent via e-mail on 27 June 2022 and a reminder is sent on 6 July 2022. Participation takes circa 30 min. Five experts provide estimates on the minimum, maximum and most likely effect of microbial applications. Effects are expressed in percentage change of yield, fertiliser and PPP use and prevalence of diseases. Baseline satisfaction, a score of five points on a scale from one (dissatisfied) to ten (very satisfied), is given and experts estimate the score for adopters. Further, the experts provide absolute three point estimates on the current and future prices and dosage of microbial applications. We also ask the experts how they would weigh each of the three sustainability dimensions. We ask the experts 'Which weight would you give to each sustainability pillar, adding to 100% and considering the Dutch arable farming sector?'

In the last round, the second Delphi iteration, the responses of round two are summarised and returned to the panel for further reflection in form of another online survey. The link is sent out via e-mail on 9 August 2022 and two reminders are sent two and three weeks later. In the last round, participation time is reduced to 20 min and ten answers have been recorded. We show summary statistics (mean, standard deviation, minimum and maximum) of each lower and upper bound and most likely estimate from the previous round. We ask the experts to take a look at the means, evaluate whether they seem reasonable and whether they want to confirm the provided means.

The goal of the Delphi elicitation is not to reach consensus, but the experts are encouraged to rethink and review the estimate. If they cannot agree, they are asked to provide new estimates. The simulated effect of microbial applications is based on the confirmation rate, the

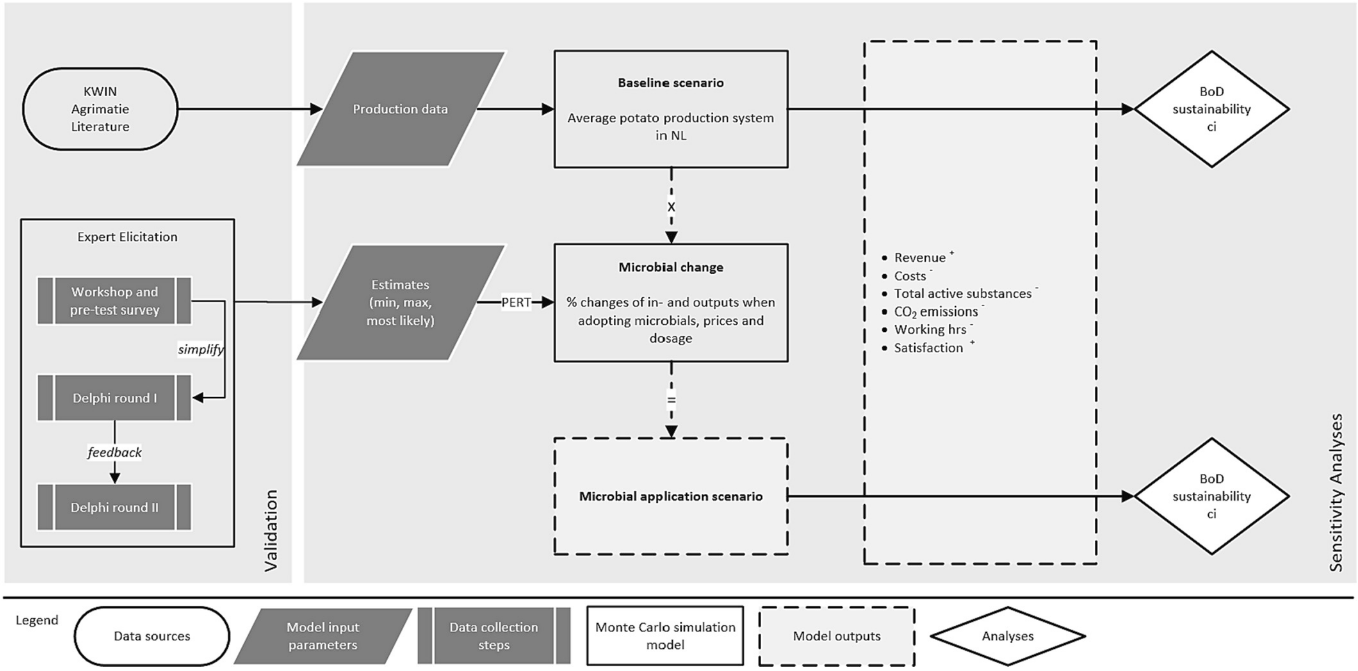

Fig. 1. Visualisation of the structure of the model, its input data, outputs and analyses.

Table 1

Baseline model parameter, distributions and paramter sources for each potato crop.

Variable	Default			Description *Distribution*	Source
	Starch	Seed	Cons		
A. Farm Inputs, amounts and prices					
PPP, amount in kg ha^{-1}					
Insecticides	$\mu = 10.0$	$\mu = 0.00$	$\mu = 2.50$	With a minimum threshold of 3 kg ha^{-1}, most important PPP are selected per crop. We compute average for different production regions and soil types. PPP use simulated with truncated normal distribution. Lower bound is = 0. $\xi(\mu, o = 2, a = 0, b = \infty)$	KWIN-AGV (2018)
Fungicides	$\mu = 4.04$	$\mu = 3.31$	$\mu = 4.33$		
Herbicides	$\mu = 4.50$	$\mu = 3.80$	$\mu = 3.06$		
PPP, costs in € kg^{-1}					
Insecticides	14	–	3.5	With a minimum threshold of 3 kg ha^{-1}, we selected the most important PPP for each potato crop. We use the average price of these inputs in the simulation model. *Fixed*	KWIN-AGV (2018)
Fungicides	32.33	36.5	34.1		
Herbicides	16.25	13.0	24.91		
Fertilisers, amount in kg ha^{-1}					
N	$\mu = 230$	$a = 0, b = 140$	$a = 188, b = 250$	For starch, there is only one production area provided in KWIN. Therefore, we use normal distribution N with standard deviation = 1. For the other potato products, we use the minimum and maximum values from KWIN as the bounds in a continuous uniform distribution U. $N(\mu, \sigma = 1)$ or $U_{[a,b]}$	KWIN-AGV (2018)
P	$\mu = 60$	$a = 20, b = 185$	$a = 50, b = 60$		
K	$\mu = 110$	$a = 0, b = 320$	$a = 140, b = 210$		
Fertilisers, amount in € 100 kg^{-1}					
N		114		These are the average prices for the different fertiliser products. The prices are identical for the different potato crops. *Fixed*	KWIN-AGV (2018)
P		78			
K		50			
B. Farm Outputs, amounts and prices					
Yield, to ha^{-1}	$\alpha = 64.79, \beta = 1.62$	$\alpha = 352.75, \beta = 9.89$	$\alpha = 186.17, \beta = 3.83$	We analysed the yield data from 2010 to 2020 and fitted a gamma distribution by maximum likelihood estimation. The resulting distribution parameters (shape α, rate β) have been used to simulate yield. $Gamma(\alpha, \beta)$	CBS (2022)
Price, € 100 kg^{-1}	$\mu = 7.71, \sigma = 1.3, \alpha = 5.18$	$\mu = 28.89, \sigma = 3.37, \alpha = 24.68$	$\mu = 14.36, \sigma = 4.63, \alpha = 7.55$	Average prices for potato products between 2010 and 2021. We computed the average and standard deviation of the price data. These are used together with the min bound α. $\xi(\mu, \sigma, \alpha, b = \infty)$	Agrimatie (2022)
C. Environmental Inputs					
Active substances in kg ha^{-1}				Average active substances used from 2010 to 2020 $Triangular(a, b, c) : a \le c \le b$	Agrimatie (2022)
Insecticides	$a = 0.02, c = 0.04, b = 0.06$	$a = 0.21, c = 0.25, b = 0.34$	$a = 0.05, c = 0.22, b = 1.78$		
Fungicides	$a = 9.27, c = 13.2, b = 16.11$	$a = 5.64, c = 7.33, b = 8.93$	$a = 5.43, c = 8.37, b = 9.93$		
Herbicides	$a = 1.13, c = 2.01, b = 3.44$	$a = 1.78, c = 2.49, b = 3.24$	$a = 2.64, c = 3.33, b = 3.85$		
D. Environmental Outputs					
CO_2 footprint inputs in kg CO_2 per tonnes of potato yield					

(*continued on next page*)

Table 1 (*continued*)

Variable	Default			Description *Distribution*	Source
	Starch	Seed	Cons		
Fertiliser production	μ = 12	μ = 40	μ = 25	Environmental 'costs' of potato production. Provided in Table 13 of the cited source. Normally distributed with σ = 2. $N(\mu, \sigma = 2)$	Goffart et al. (2022)
Fertiliser emission	μ = 32	μ = 18	μ = 25		
Biocides	μ = 10	μ = 16	μ = 5		
Total environmental points per ha of potato crop					
Soil	a = 250, c = 714.5, b = 1120	a = 310, c = 529.09, b = 930	a = 240, c = 466.36, b = 690	Total environmental impact of PPP, expressed in points as calculated by WEcR, for soil, ground and surface water per hectare of potato production. Not all PPP have the same environmental impact. This has been taken into account when calculating environmental burden. $\mathit{Triangular}(a, b, c) : a \leq c \leq b$	Agrimatie (2022)
Groundwater	a = 570, c = 650.9, b = 730	a = 100, c = 167.27, b = 280	a = 250, c = 383.6, b = 790		
Surfacewater	a = 980, c = 1763, b = 3590	a = 1430, c = 1830, b = 3210	a = 1170, c = 1884, b = 2950		
E. Social					
Working hours per ha potato crop for each activity					
Tillage		μ = 6.1		Identical for all potato crops. Provided in KWIN. $N(\mu, \sigma = 1)$	KWIN-AGV (2018)
Fertilising		μ = 1.2			
PPP		μ = 6.5			
Satisfaction		μ = 5		$N(\mu, \sigma = 1)$	*This study*

degree to which experts agree on the estimates of an effect. Thereby, we preserve the prevailing uncertainty among experts in the final estimates. We define the confirmation rate as the percentage of experts agreeing on the mean estimate from the previous round.[2] In the last round, we also ask the experts to justify the satisfaction estimates they have provided. We ask 'what does farmer satisfaction entail and how can it change through microbial application use?'

2.2.3. Validation data

We discuss validation data together with our findings in the Results and Discussion Section. We comment on similarities and differences, and discuss sources for the latter. We use three sources of data and information to validate our baseline and expert input data and results. First, the summary statistics (see Table 2) from the SIMBA farmer survey (Slijper et al., 2022) of fifty-two non-adopters and thirty-three adopters on their potato production in the Netherlands are discussed together with the microbial application scenario. Second, pricing and dosage information from one of the few providers of microbial applications in the Netherlands are discussed in conjunction with the microbial application model results and used as input for a sensitivity analysis.

Third, we explore the literature on *Web of Science* and *GoogleScholar*. We specifically search for greenhouse and/or field experiments conducted in Europe on potatoes with plant growth promoting rhizobacteria and microbial applications. We exclude reviews and studies conducted in Asian countries as they are not informative for the European context because climate and soils are not comparable. We limit our search to the time frame of beginning of 2010 to the beginning of 2022. Further details on the literature search, including the search term, are provided in Appendix B.

2.3. Composite sustainability index

We aggregate a sustainability index for each of the two scenarios. An aggregated index provides a more concise overview when looking at multiple variables (Luzzati and Gucciardi, 2015), allows direct comparison of multiple scenarios (Munda, 2005) and quantifies trade-offs between sustainability pillars. Each of the three sustainability dimensions is represented by two single indicators, which are aggregated in the composite sustainability index. We select relevant indicators from Van Asselt et al. (2014) based on whether we expect the single indicators to change due to microbial applications, and based on data availability (Niemeijer, 2002). Details on the single indicators are provided in Appendix C. We normalise the single indicators with the min-max method ($Y = \frac{x - x_{min}}{x_{range}}$). An overview of the single indicators and their normalisation sign is provided in Fig. 1 (see the dashed box on the righthand side of the figure).

Each normalised single indicator is first multiplied with an indicator specific weight w_p and then aggregated into a composite index c_i. We use two different weighting methods, which are explained in further detail in Appendix C. First, we use the weights provided by the experts in the survey. Second, we use the Benefit-of-the-Doubt (BoD) approach (Cherchye et al., 2007). With the BoD approach, observation-specific weights are endogenously assigned such that the composite index yields the highest possible score and the objective function of each observation is maximised. For each observation f, we solve the following optimisation problem:

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[2] If the confirmation rate is <75%, this indicates that some of the experts have a strong opinion about the variable and cannot agree with the estimates of their peers (Diamond et al., 2014). Then, the final change rate is computed 50% on the second round and 50% on the third round. When the confirmation rate is 80%, the change rate is based 80% on the third round and 20% on the second round. If the confirmation rate is larger or equal to 90%, we only use the final round results. Such corrections are customary in expert elicitation analyses (Dalkey and Helmer, 1963).

Table 2

Summary statistics of SIMBA farmer survey: Selected input and output data of non-adopters compared to adopters of microbial applications.

	Non-adopters ($N = 91$)			Adopters ($N = 42$)		
	N	Mean	St dev	N	Mean	St dev
Fertiliser use and costs						
N (kg ha^{-1})	65	150.72	173.74	35	151.51	187.88
P (kg ha^{-1})	62	12.88	23.31	35	15.61	20.06
K (kg ha^{-1})	62	52.01	53.84	33	67.62	66.02
Cost (€ ha^{-1})	63	84.96	111.86	35	88.17	98.14
PPP use and costs						
Use (kg ha^{-1})	38	8.77	11.12	27	6.34	6.14
Cost (€ ha^{-1})	38	408.27	518.11	27	295.22	285.92
Farm outputs (tonne ha^{-1})						
Seed potato yield	12	40.12	3.12	11	39.14	5.12
Ware potato yield	27	55.76	9.89	18	54.42	7.48

Notes. Data from Slijper et al. (2023).

$$max \sum_{f=1}^{S} \omega_{fi} I_{fi} \tag{1}$$

$$\text{s.t. } max \sum_{f=1}^{S} \omega_{fi} I_{fi} \leq 1 \ \forall f = 1, \ldots, N \tag{2}$$

We maximise each observation's composite sustainability index *ci*. The normalised score I_{fi} of the i^{th} single indicator of observation f is weighted with the endogenous weight w_{fi} (Gan et al., 2017; Van Puyenbroeck and Rogge, 2017). The resulting *ci* cannot exceed one.

2.4. Sensitivity analyses

With the sensitivity analyses, we investigate the consequences of a microbial application price and effectivity change. The sensitivity of prices for microbial applications is assessed by reducing the prices by 30% and by using estimated future prices. To assess the sensitivity of microbial application effectivity, we look at the effect of a 10%, 30% and 50% raise in yield increase, and fertiliser and PPP reduction potential. In a separate sensitivity analysis, we use the industry values for prices, dosage and effectivity. We also investigate the sensitivity of the baseline and microbial application scenarios to an increase in fertiliser and PPP prices. All sensitivity analyses are summarised in Table 3.

We assess the sensitivity of the production system to a change in these variables in two ways. First, we visually assess how the change affects the main output variable and the sustainability index. Second, we conduct two-sample *t*-tests on the sustainability indices from different scenarios to evaluate if a change in the models' parameters has an influence on the sustainability of the production system.

Table 3

Overview of sensitivity analyses: Variable change and scenario.

Sensitivity analysesVariable changes	Variable changes	Applied to scenario
Effectivity of microbial applications:		
Fertiliser reduction potential	−10%, −30%, −50%	Microbial change
PPP reduction potential	−10%, −30%, −50%	Microbial change
Yield increase	+10%, +30%, +50%	Microbial change
Price changes:		
Conventional fertiliser	double, triple	Baseline, microbial change
PPP	+10%	Baseline, microbial change
Microbial applications	potential future prices, −30%	Microbial change
Industry example	Dosage: N(μ = 35.8, σ = 1), price: U[8,10], yield: consumption pot. N (3.9,2), seed pot. N (7.5,2)	Microbial change

3. Results and discussion

3.1. Expert elicitation

The results of the expert elicitation are used in the simulation of the microbial change scenario. In Table 4 and in Figs. 2 and 3, summary statistics, probability densities and cumulative distribution functions (cdf) of the most important consolidated expert elicitation variables are provided. Results of the first Delphi round are provided in Appendix D. We discuss the confirmation rates and main findings in the following. The experts' estimates are compared to the validation data.

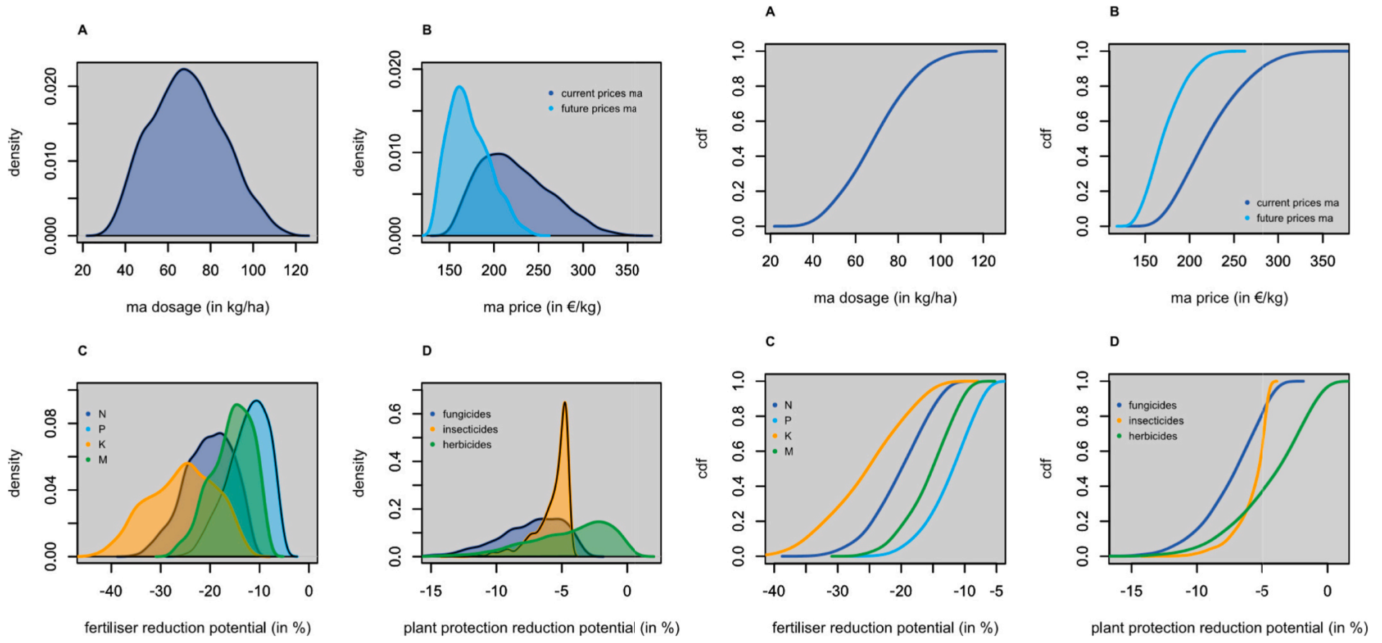
The simulation of the change scenario depends on the confirmation rates. In the final expert elicitation round, three variables have a confirmation rate of 80%: microbial application dosage, and the reduction potential of herbicides and insecticides. Two variables have a confirmation rate of <75%: the reduction potential of fungicides and microbial application prices. This signals uncertainty about the effects and general disunity. All other variables have a confirmation rate of at least 90%. The parameters for the change model are computed accordingly.

According to industry data, the current advised dosage of microbial applications is between 8 and 10 kg ha^{-1}, and prices are around e33.80 kg^{-1}. Compared to these industry figures, our experts' estimated dosage is twice the industry dosage, and estimated prices are ten times the industry prices. According to the experts, the probability that Nitrogen (N), Phosphorous (P) and Potassium (K) fertiliser inputs can be reduced by 10% to 20% through microbial applications is 50%, 62% and 23%, respectively. NPK reduction is one of the main intentions of microbial application usage. By contrast, a 0.5%, 21% and 30% NPK *increase* is reported in the SIMBA farmer survey. Thus, the experts' and the farmers' evaluation are contradictory. Notably however, both the farmer sample and the current expert sample are small. Further, we found no data in

Table 4

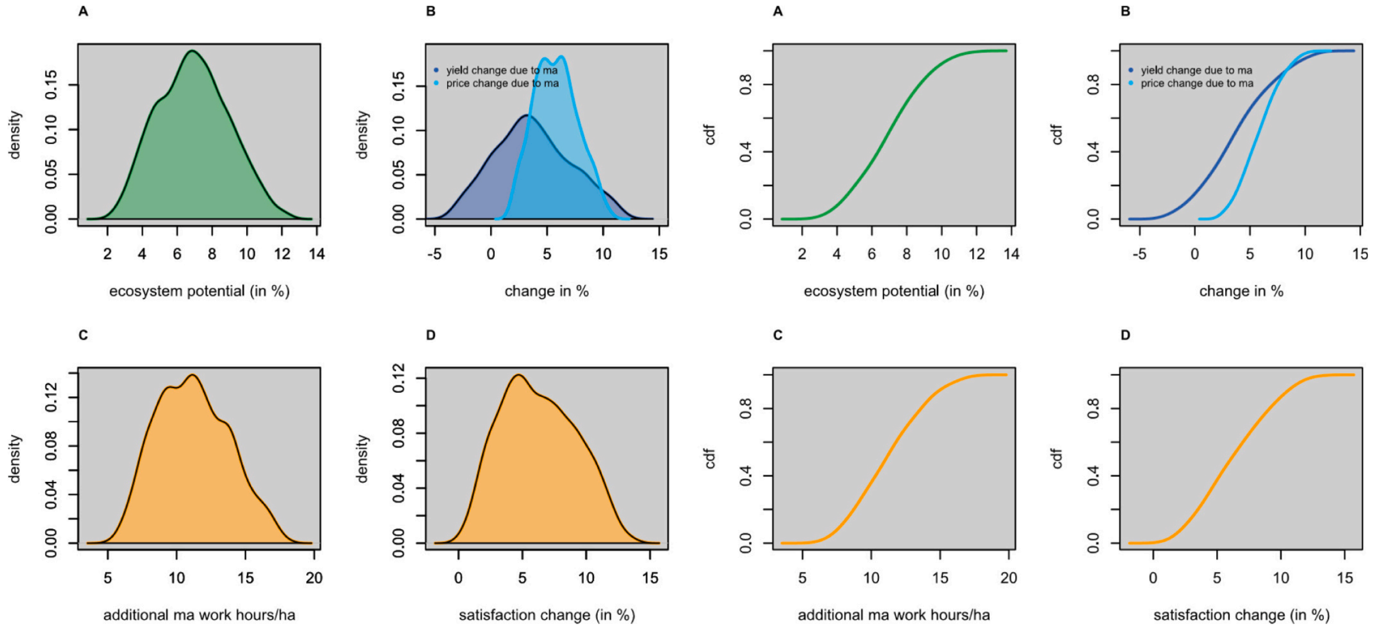
Summary statistics of consolidated expert estimates: dosage, current and future prices, effect of microbial applications on potato production in %, working hours, farmer satisfaction; mean sustainability dimension weights used in index construction.

Statistic	Mean	St. Dev.	Min	Max
Microbial application				
Dosage (in kg ha^{-1})	69.19	16.69	33.08	114.89
Price (in €/kg)	223.45	38.99	155.77	352.34
Future price (in €/kg)	172.26	22.67	133.42	246.86
Fertiliser usage (expected change in %)				
N	−20.30	4.80	−35.53	−11.17
P	−12.35	4.07	−26.08	−5.11
K	−25.73	6.64	−43.42	−12.52
PPP usage (expected change in %)				
Fungicides	−7.36	2.45	−17.58	−3.48
Insecticides	−5.74	1.35	13.50	−4.60
Herbicides	−4.34	3.03	−14.85	0.08
Irrigation (expected change in %)	0.77	0.88	−1.46	2.83
Effect on ecosystem health (in %)	6.92	2.02	2.21	12.34
Yield change (in %)	3.73	3.40	−3.62	12.12
Potato price change (in %)	5.78	1.93	1.72	11.01
Prevalence of diseases (in %)	−0.22	2.47	−6.94	5.72
Working hours (expected change in %)				
Application of PPP	−6.85	1.48	−10.45	−3.95
Fertilisation	−6.88	1.43	−11.16	−3.88
Tilling	−5.51	1.11	−8.43	−3.20
Application of microbes (in hrs)	11.18	2.60	5.28	18.05
Farmer Satisfaction (on a scale 1–10)	6.28	2.92	0.13	13.74
Sustainability dimension weights				
Economic	0.35			
Social	0.27			
Environmental	0.37			



(a) Densities (b) Cumulative distribution function (cdf)

Fig. 2. Densities and cumulative distribution function of expert estimated production inputs. Experts report a potential increase of ecosystem health by 6.92%. Potential ecosystem health effects include impacts on biodiversity and soil health, and have been mentioned during the expert elicitation workshop.



(a) Densities (b) Cumulative distribution function (cdf)

Fig. 3. Densities and cumulative distribution function of expert estimated production outputs.

literature that can reliably validate these findings in the context of Dutch potato farming. Some authors claim to have found a reduction, but do not quantify the reduction effect and/or the studies have been conducted in a different geographical context (e.g. Trabelsi et al. (2012)).

In addition to fertiliser reduction, one of the main objectives of using microbes is PPP reduction. Our experts expect a large PPP reduction potential with fungicides. Accordingly, there is a 15% probability of reducing fungicide use by 10% to 20%. These findings are in line with the validation data in Orlando et al. (2020). However, Orlando et al. (2020) also state that the biggest problem in potato cultivation are nematodes, which cannot be reduced with biocides. Compared with the SIMBA farmer survey in which adopters use 28% fewer PPP than non-adopters, experts underestimate the PPP reduction potential of microbial applications.

On average, yield is expected to be increased by nearly 4% with a rather narrow confidence interval ([3.52,3.94]). A 4% increase per hectare is a substantial increase! However, there is also a 15% probability that yields are decreasing according to our experts. The possibility

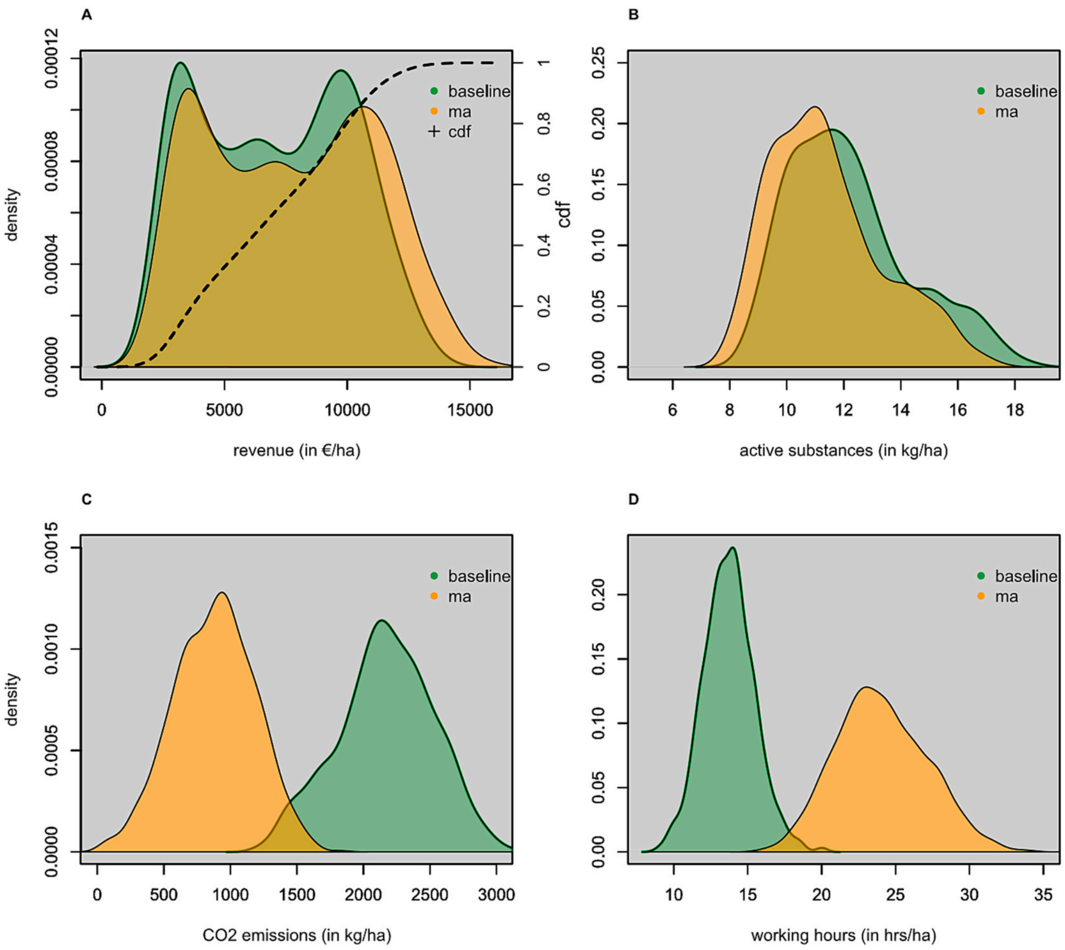


Fig. 4. Selected simulation outputs comparing baseline and microbial application scenario. In both models, costs consist of variable inputs only. Labour hours, which are considerably higher in the microbial application scenario (see panel D), are excluded.

of a yield decrease is confirmed by the SIMBA farmer survey data in which adopters have about 2.4% lower yield per hectare than non-adopters. Yet, according to the industry information, consumption and seed potato farmers who adopted microbial applications experience yield increases by 3.9% and 7.5% respectively. Our experts' estimates are close to these industry claims. In the validation literature, we find a wide range of yield increase claims, much larger than the experts' estimates. However, in most studies the control is not conventional crop production, but production without fertiliser and PPP use. Therefore, the yield gains in literature cannot be compared directly with our data.[3]

In literature, it is assumed that microbial applications suppress plant diseases and control pathogens (Gouda et al., 2018). According to our expert panel, on average, prevalence of diseases can be reduced by 0.22%. However, there is a 47% probability that the prevalence of diseases increases.

Our findings from the Delphi expert elicitation and the validation data are not always in line. The experts overestimate current dosage and market prices, which could be a consequence of the panel composition. As most experts are researchers, they may not have correct pricing information on the current market situation. However, as the effects reported in literature are not always reliable either (Kołodziejczyk, 2014), and considering the data scarcity on microbial applications, the expert elicitation provides valuable insights and novel data. The expert elicitation confirms that the effects of microbial applications are uncertain. This highlights the need for reliable, replicable research on the effects of microbial applications.

Further, there is a reasonable explanation for the large difference between expert estimates and current industry dosages: Researcher are aware that much larger amounts of microorganisms than recommended by manufacturers need to be applied to the soil, as they need to compete with a large mass of soil microorganisms (Kołodziejczyk, 2014). Furthermore, the use of expert judgements introduces uncertainties. However, there is only limited peer-reviewed evidence on the effectiveness of microbial applications in general and on environmental performance in particular.

3.2. Simulation

In this section, the most important simulation results are discussed. The results are visualised in Figs. 4 to 6. We provide insights into the advantages and disadvantages of using microbial applications in a primary crop production system. The major advantages of microbial applications are their yield increase potential and their positive effect on the environment by reducing CO_2 emissions and active substances.

Average yield is 44.08 t ha^{-1} in the baseline scenario and 45.63 t ha^{-1} in the microbial application scenario (+3.7%) across potato

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[3] We report the findings for completeness: The biggest potato yield increase has been found by Belimov et al. (2015) in field experiments with rhizobacteria. They have found a potato yield increase of up to 27%. Yield increase is caused by an increase in the number of tubers rather than by an increase of tuber weights. The authors conclude that the rhizobacteria accelerate vegetative development. Mülner et al. (2020) report a 24% yield increase and Larkin (2016) find an increase average between 11% and 15%. Buysens et al. (2016) have investigated the impact of a rhizobacteria application to a cover crop preceding potato planting and to potatoes directly and find a 6.9% yield increase.

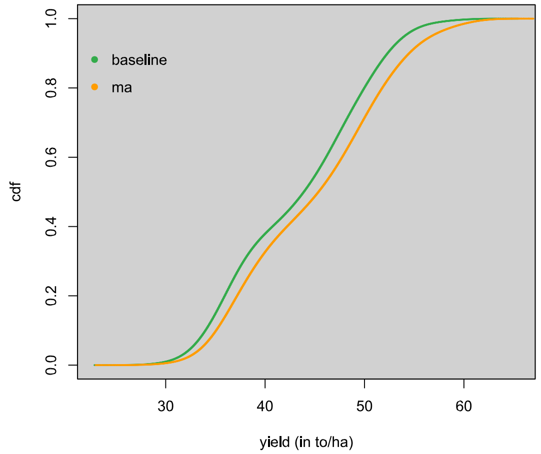

Fig. 5. Cumulative Density Function (CDF) of simulated baseline and microbial application potato yield.

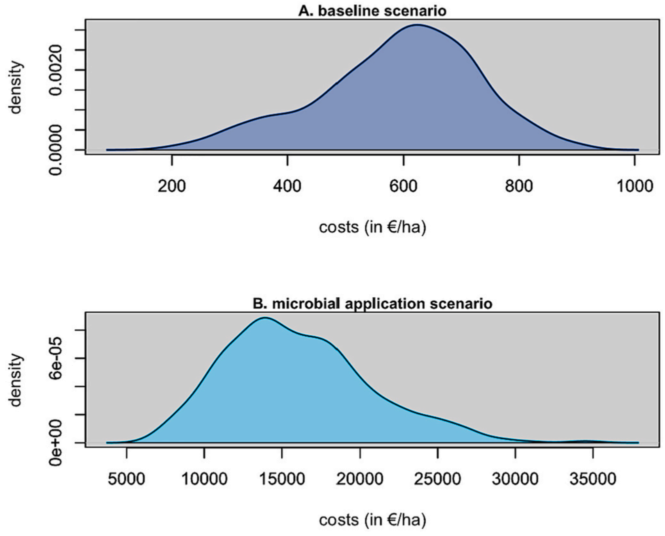

Fig. 6. Simulated costs of production in baseline and microbial application scenario.

products (see Fig. 5). As a result of the yield increase and an increase in selling prices (baseline: € 16.75; microbial application scenario: € 17.73, both per 100 kg of potatoes), we find a 9.8% higher revenue in the microbial application scenario with an average of € 7,714 ha^{-1} compared to € 7,027 ha^{-1} in the baseline scenario.

PPP use is slightly reduced when microbial applications are adopted, leading to a 6.6% reduction of active substances. Fertiliser reduction is substantial when microbial applications are adopted which leads to an almost 60% reduction of CO_2 emissions compared to the baseline scenario. The probability that the CO_2 emissions are the same in both scenarios is only 14%. Since this is the first study investigating environmental effects of microbial applications, there are no validation data available for these findings. However, there may be other beneficial environmental effects, such as ecosystem services and effects on biodiversity (Arif et al., 2020). These environmental effects are usually difficult to measure.

Another advantage is the additional satisfaction that a farmer receives when using microbial applications and fewer harmful substances. Farmers in the microbial application scenario have a slightly higher satisfaction index with an average of 6.28 and a large standard deviation of 2.92. The Welch two-sample *t*-test reveals that there is a statistically significant, but small difference between the satisfaction indices of the two production systems. Experts argue that farmers might be more satisfied because they believe that this farming practice is better for the environment, improves soil quality in the long-run as well as yield and quality. All qualitative expert answers are provided in Appendix E.

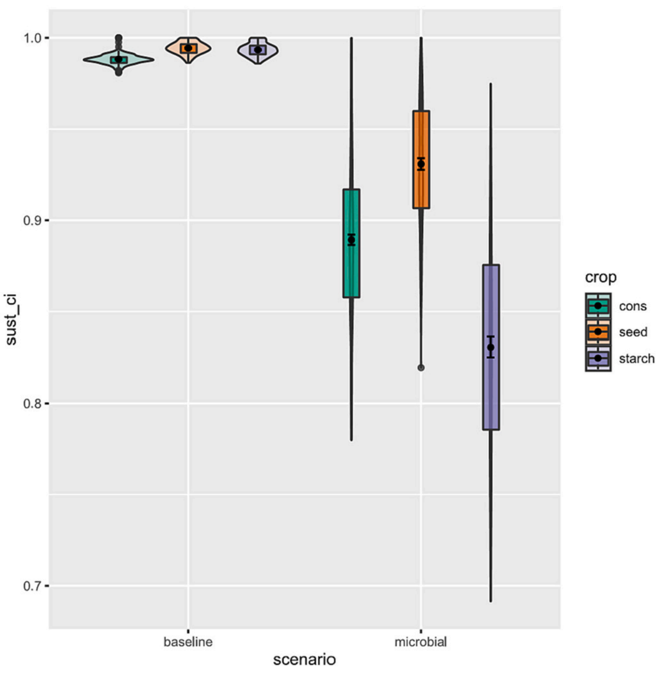

Fig. 7. Sustainability indicator in baseline vs. microbial application scenario.

In this study, we found two main disadvantages. First, the costs in the microbial application scenario are a multiple of the costs in the baseline scenario (see Fig. 6). The substantial differences are caused by estimated high costs for microbial applications and dosages which are not compensated for by reduced fertiliser inputs and even less by increased yields or reduced PPP. On average, the costs are € 591 ha^{-1} in the baseline scenario, and € 15,994 ha^{-1} in the microbial application scenario! Microbial applications are currently not cost-effective, even if we factor the costs for CO_2 emissions in. One ton of CO_2 is traded at around € 63 in 2022. Accordingly, the costs in the baseline scenario would be about € 130 higher but still far from the costs in the microbial application scenario. Considering that about 40% of the Dutch arable farmers are operating below minimum income levels (Berkhout et al., 2022), the cost increase simulated in the microbial application scenario is infeasible for the majority of farmers.

Second, the effects of microbial applications are highly uncertain. As the yield increasing effects are not stable, nor guaranteed, farmers will not take the risk of paying a high price for microbial applications nor of reducing their use of fertilisers and PPP. Currently, the main biotechnological challenge is to develop a low-cost, effective and stable microbial application (Romano et al., 2020). Further, we find that the prevalence of diseases is most likely not reduced by microbial applications. Therefore, also the risks posed by nematodes and *Phytophthora* are unlikely to be alleviated by microbial applications. According to a study, nematodes can reduce yield by 23% to 30% in the Netherlands (Orlando et al., 2020). If microbial applications were a reliable solution for prevalent pests and diseases, their uptake would be stimulated.

3.3. Sustainability analysis

The microbial application scenario has an average sustainability index of 0.81 and can thus be considered sustainable. Six out of thousand observations have a sustainability index larger than 0.99. The baseline scenario has an average sustainability index of 0.99 with 429 observations having an index larger than 0.99. When comparing the sustainability index of the baseline scenario and the microbial application scenario, we conclude that to date potato production without microbial

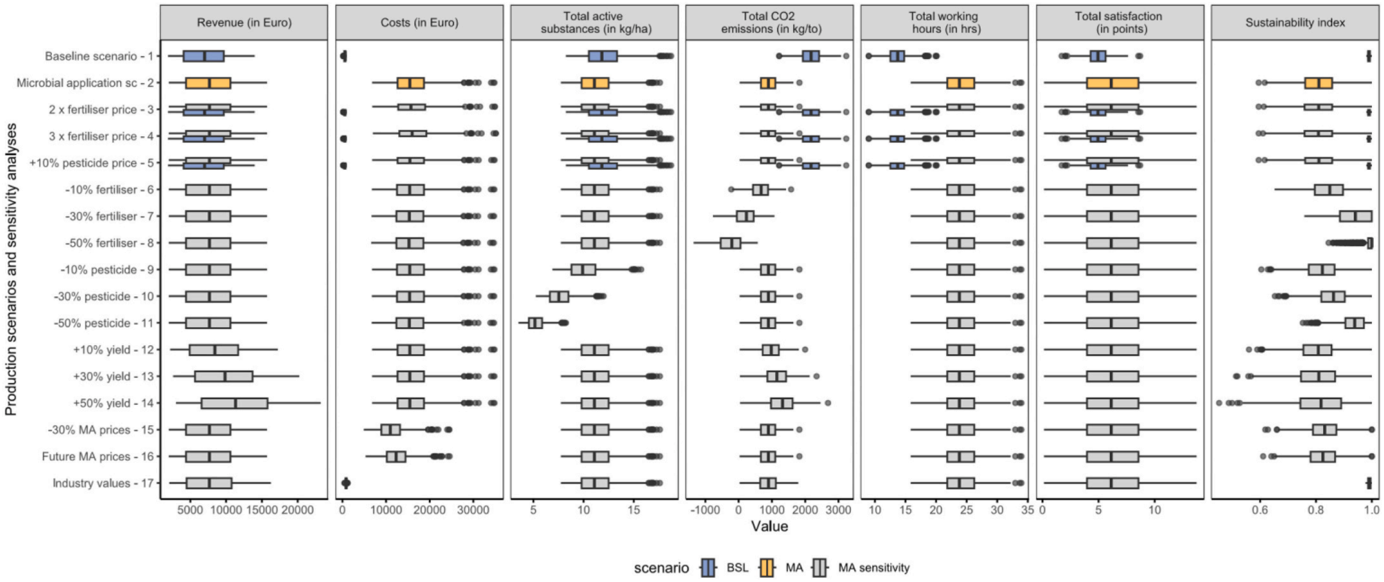

Fig. 8. Box plots comparing baseline and microbial application scenarios (row 1 and 2), and all sensitivity changes: Row 3–5 fertiliser and PPP price changes in both scenarios, Row 6–8 higher fertiliser reduction potential of microbial application, Row 9–11 higher PPP reduction potential, Row 12–14 higher yield increase potential, Row 15 and 16 different microbial application prices, Row 17 industry values. Note. 'Pesticides refers to all PPP, but for visual purposes the shorter term is used. The three potato crops are pooled.

applications is more sustainable than production with microbial applications. We want to stress that the sustainability indicator is not an absolute measure of sustainability, but a relative estimate of sustainability, comparing one system with the other. Two-sample *t*-tests reveal that the composite indices are significantly ($p < 0.001$) different. The adoption of microbial applications at their current state, as described by experts, could reduce the sustainability of Dutch potato production. The results hold under the different robustness checks.

There is almost no difference in BoD scores in the baseline scenario between the different potato crops but a large difference between the potato crops in the microbial application scenario (see Fig. 7). In the latter scenario, seed potatoes are more sustainable than both consumption and starch potatoes.

The most important sustainability dimension for all three potato products is the environmental one. CO_2 emissions are the most important single indicator, followed by income and costs, which are the two indicators from the economic dimension. Large costs decrease the sustainability performance of the microbial application scenario.

In this study, we compare the effectiveness of microbial applications in potato production with a baseline scenario, which represents the current production situation in the Netherlands. However, the choice of the baseline scenario could be questioned. On the one hand, if PPPs lose their license and farmers are required to reduce the use of fertilisers to mitigate nitrogen and phosphorus concentrations in surface waters, the appropriate baseline should be a clean control. In this case, we would compare the microbial application scenario with a control scenario that does not involve the use of PPPs or fertilisers. On the other hand, farmers are likely to be convinced to adopt microbial applications only if they are competitive in all sustainability dimensions. In this case, the baseline should reflect the current production situation, as we have done in this study.

The long-term effects of microbial applications are not investigated in this study due to a limited understanding of the long-term environmental benefits of using microbial applications. In future studies the long-term economic effects of reduced environmental damage need to be quantified.

3.4. Sensitivity analysis

Fig. 8 shows the effect of a change in the model inputs on the model outputs and the aggregated sustainability index. In the two top rows, the baseline and the microbial application scenario are depicted. All other boxplots visualise sensitivities. The social indicators (working hours and satisfaction) are not affected by the changes applied in the sensitivity analyses, but are included in the figure for completeness.

Generally, the effect on the model's outputs (revenue, costs, active substances, CO_2 emissions) highly depends on the extend of the changes in the model's inputs (effectivity in terms of yield increase, PPP and fertiliser decrease; price changes). For instance, when effectivity in terms of fertiliser and PPP reduction or yield increase potential is raised by 50%, there are visible impacts on the single indicators and also on the composite sustainability index. The microbial application scenario becomes almost as sustainable as the baseline scenario when the fertiliser reduction potential of microbial applications is increased by 50% (Row 8 in Fig. 8). The experts report a NPK reduction potential of 20%, 12% and 26% respectively, but the sensitivity analysis shows that an NPK reduction of 70%, 62% and 76% respectively is needed to enhance the sustainability of the baseline production system. Likewise, the microbial application scenario with industry data (Row 17 in Fig. 8) is as sustainable as the baseline scenario.

From the visual analysis, we conclude that microbial applications can have a considerable CO_2 reduction potential when fertiliser use can be further reduced. More effective microbial applications also have a potential to reduce active substances. Through lowering the environmental footprint, overall sustainability increases of the potato production system can be achieved. As much as effectivity improvements are a necessary condition for environmental sustainability, cost reduction is a necessary condition for economic sustainability. A combination of multiple improvements of microbial applications is the only way to increase the sustainability of potato production through microbial applications including lower costs and higher effectivity.

The two-sample *t*-test results confirm the findings from the visual analysis. The baseline scenario ($\mu = 0.99$) would still be significantly ($p < 0.001$) more sustainable than the microbial application scenario ($\mu = 0.81$), even if fertiliser prices tripled or PPP prices increased by 10%.

4. Conclusion

In this study, we assess the capacity of microbial applications to enhance the sustainability of primary food production systems. Our research question is targeted at the sustainability of Dutch potato production. Results show that microbial applications, as described by the experts, are not yet up for the task. To date, microbial applications are not effective enough in reducing the need for PPP and are not expected to bring adopting farmers closer to the 50% reduction goal of the Farm-to-Fork strategy. Since farmers need a product that helps them to reduce the amount of PPP and microbial applications fail to do so, we conclude that to date microbial applications cannot - as a single measure - improve the sustainability of Dutch potato production. However, the sensitivity analyses show that an increase of effectivity of microbial applications can improve the overall sustainability of potato production.

To answer the research question how microbial applications affect the sustainability of Dutch potato production, we have conducted a Delphi expert elicitation, modelled a Dutch potato production system with and without microbial applications with MC simulation, and computed a comparative composite sustainability index. Through the expert elicitation we have provided novel data on the effects of microbial applications. In the simulation model, we have quantified microbial application effect uncertainty. Employing the composite sustainability index, we have assessed the capacity of microbial applications to enhance the sustainability along environmental, economic and social dimensions, of the Dutch potato production system. We find three main disadvantages of the microbial application potato production system. First, due to their very high costs, microbial applications are to date not financially viable. Second, in line with previous studies, we find that the size effect of microbial applications is uncertain and variable. Third, our experts do not confirm the assumption that microbial applications can be a reliable solution to alleviate diseases. Nonetheless, there are two main advantages. The effect of microbial applications on environmental sustainability is expected to be positive, indicated by almost 60% lower CO_2 emissions and 6.6% fewer active substances. Additionally, microbial applications are expected to increase yield by 3.73%.

Our research has limitations, leading to routes for further research. A major weakness of this study is the limited amount of experts who participated in the two Delphi rounds. Even though there are sixteen experts, we only record five and ten answers in the two Delphi iterations respectively. Nonetheless, we have not invited additional experts. The panel has been coherent and an increase in group size could have lead to compromises. For example, we did not want to invite experts that do not fit the group and/or do not have sufficient expertise (Pashaei Kamali et al., 2017). Further, we acknowledge the potential for a selection bias as all experts are partners in the SIMBA project. While not randomly selected, the experts have been chosen for their high levels of knowledge, expertise, and diverse range of judgements on the subject. Their participation has been voluntary, and measures have been taken to reduce the effects of a potential selection bias, such as extensively discussing validation literature and taking confirmation rates into account to compute parameters. The study's overall results show that despite the potential for bias, the evaluation of microbial applications remains objective and reasonable. Future research can benefit from similar measures to ensure diverse and unbiased expert opinions. A natural progression of this work would be to repeat the Delphi study with another group of experts, if other experts are available.

There are three more limitations to this research and routes for further research. First, the system boundary of the model, the farm gate, does not allow a comprehensive cradle-to-grave analysis. Once further information is available, the system boundary should be widened because the environmental footprint of the large-scale production of microbial applications is expected to be substantial. However, even when life cycle greenhouse gas emissions of microbial application production are as high as the emissions of producing PPP and fertilisers, microbial applications have the potential to improve the sustainability of primary production systems.

Second, we introduce uncertainty distributions on the parameters, but we do not model interaction effects due to a lack of knowledge as to how the variables exactly interact. It is unknown how microbial applications biophysically affect plant growth and resilience. Therefore, a bio-economic modelling approach could not be implemented. Our suggestion for further research is to investigate the biophysical pathways of microbial applications affecting plant growth and resilience. This knowledge would enable a bio-economic modelling approach by integrating microbial application effects, and economic and social indicators into crop models such as LINTUL (Haverkort et al., 2015), WOFOST (Den et al., 2022) or FAO Aqua Crop (Razzaghi et al., 2017). In such an extended model, the survival time of microbial applications in the soil, among others, could be taken into account to turn the model into a dynamic model. With the survival time of microbial applications long-term effects of microbial applications on ecosystem services and biodiversity can be modelled.

A third route for further research is the inclusion of different production scenarios. In addition to comparing the microbial application with the baseline scenario, it could also be investigated how the two production systems behave under different climate change regimes or under salt stress. For instance, the study of Raymundo et al. (2018) provides valuable information for modelling a baseline saline potato production scenario. In this extension route, a clean control baseline scenario could be introduced, too.

All in all, our study suggests that to date microbial applications cannot contribute to reach the Farm-to-Fork reduction goals. Our study suggests potential environmental gains upon the use of microbial applications, albeit at a high economic cost. This study emphasises the importance of considering the economic feasibility of sustainable practices to encourage farmers' adoption. Technological advancements are required to further reduce the costs per unit of production and increase environmental sustainability. In this way, microbial applications can be part of the solution to enable the sustainable transformation of agri-food systems. Further research needs to be directed towards developing more cost-effective microbial applications which are able to prevent potato diseases and we provide four routes for further research on microbial applications.

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Disclaimer

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Code is available in Supplemenatry Material

Acknowledgement

We thank the experts from the SIMBA consortium for their participation and the industry partners for providing information.

Appendix A. Calculating Dutch Farm-to-Fork goals

Table A1
Calculating baseline use of fertilisers and PPP in Dutch arable farming and Farm-to-Fork reduction goal.

Use of active substances	
year	*kg ha^{-1}*
2015	8.19
2016	9.4
2017	8.6
average	8.73
Farm-to-Fork goal	4.36
2020	9

N fertilization	
year	*Kg N ha^{-1}*
2015	124
2016	122
2017	115
average	120.33
Farm-to-Fork goal	96.26
2020	101

Phosphate fertilization		
year	*kg P ha^{-1}*	
	Kunstmest	Dierlijke mest
2015	10	42
2016	10	42
2017	9	43
average	9.67	42.33
Farm-to-Fork goal	7.73	33.87
2020	8	40

All data from Wageningen Economic Research (WEcR) (2022) on arable farming in the Netherlands.

Appendix B. Literature review

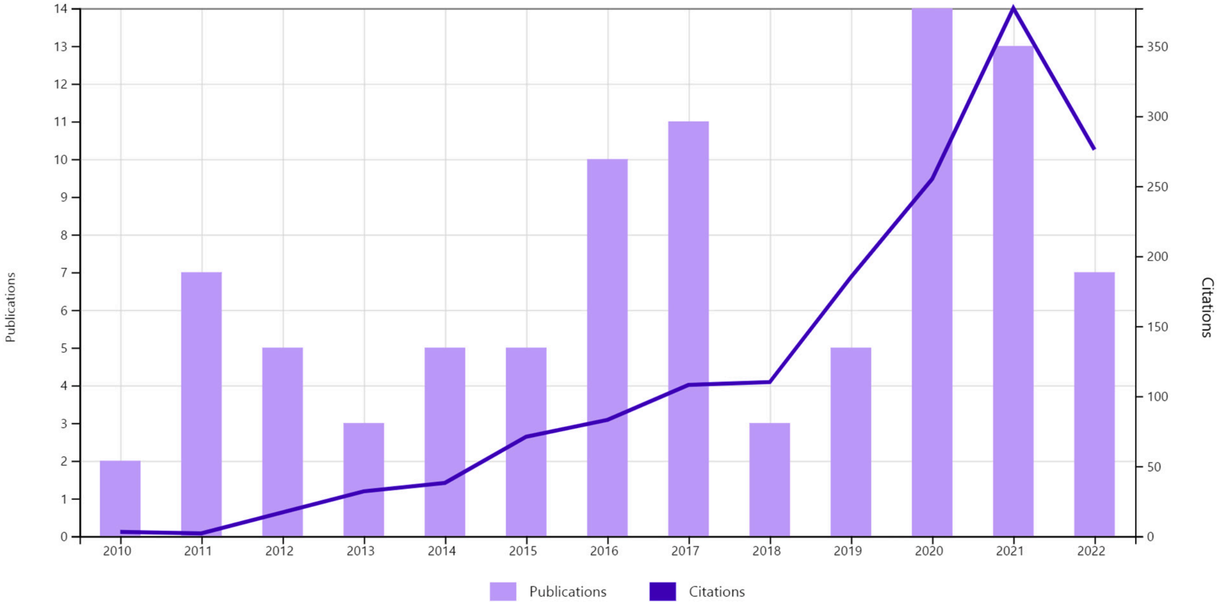

Fig. B1. Number of citations in Web-of-Science with search term.

In the Web-of-Science literature review, we used the following search term for the time-frame from 2010-01-01 to 2022-11-01:

> AB = (potato) AND AB = (plant growth promoting rhizobacteria) NOT PUBL = (Mdpi) NOT ALL = (processing) NOT ALL = (pakistan) NOT ALL = (india) NOT ALL = (china) NOT ALL = (sweet)
>
> OR
>
> AB = (potato) AND AB = (microbial applications) NOT PUBL = (Mdpi) NOT ALL = (processing) NOT ALL = (pakistan) NOT ALL = (india) NOT ALL = (china) NOT ALL = (sweet)

In the Google Scholar literature review, we used the following search terms for the same time-frame as above:

> potato "microbial applications" -processing -pakistan -india -china -sweet source: -MDPI
>
> potato "plant growth promoting rhizobacteria" -processing -pakistan -india -china -sweet source: -MDPI

We excluded studies that have been published in MDPI journals because it is already difficult to judge which studies on microbial applications we can trust (Kołodziejczyk,2014), and "[s]tudies published in predatory journals often have a lower quality and are more likely to be impacted by fraud and error compared to studies published in traditional journals" (Munn et al., 2021). Predatory journals are characterised, amongst others, by deviating from best editorial and publication practices and false or misleading information (Grudniewicz et al., 2019), and MDPI is identified as such a predatory journal (Ángeles Oviedo-Garciá, 2021).

In total, the search delivered 90 publications that have been cited 1,559 times. The publications have an H-Index of 21. When MDPI has been excluded in the search, there have been ten publications more. When MDPI and the countries have not been excluded, we obtained 149 publications.

Appendix C. Details on the Composite Index

The economic dimension is represented by the single indicators revenue and costs. The environmental dimension is represented by the single indicators active substances and CO_2 emissions. The social dimension is represented by the single indicators working hours and satisfaction.

We use two different weighting methods. First, we use the weights provided by the experts in the survey. We compute the average weight for each dimension, which could – in theory – exceed 100% in total and we assume that each single indicator contributes equally to its respective sustainability dimension. The composite expert index ci is computed as $c\hat{i} = \sum_{i=1}^{I}\frac{w_p}{2}i_s$, where w_p is the average dimension specific weight provided by the experts. Second, we use the Benefit-of-the-Doubt (BoD) approach (Cherchye et al., 2007). The BoD approach is based on an input-oriented Data Envelopment Analysis (DEA) model. DEA is a linear program optimization method. The formulas are provided in the text.

We pool the simulated data from both scenarios to compute the BoD ci of each observation. Thereby, we compare each observation with all observations in both scenarios. In addition, we have three robustness checks in place in which we pool the simulated data differently before computing the BoD. First, we pool all observations from the baseline and microbial application scenario and all sensitivity analyses and then compute the BoD ci. Second, we only pool the microbial application scenario and its sensitivity analyses and then compute the BoD ci. Third, we compute the indicator weights for each observation in the baseline scenario and use these weights to compute the sustainability indices for the microbial application scenario.

Comparing the two different weighting methods to aggregate the sustainability index (the BoD approach and expert weighting) shows that the BoD ci is more favourable than the subjective expert-weighted index.

Appendix D. Summary Statistics First Delphi Round

Table D1

Summary Statistics of each PERT estimate provided in the first Delphi round.

Variable	PERT point	Mean	SD	Min	Max
Microbial applications					
Dosage (in kg ha^{-1})	lower bound	36.500	44.710	1	500
Dosage (in kg ha^{-1})	most likely	76.750	116.572	2	250
Dosage (in kg ha^{-1})	upper bound	142. 500	238.904	5	500
Price (in €/kg)	lower bound	256.252	495.904	0.010	1,000
Price (in €/kg)	most likely	285.005	543.473	0.020	1,100
Price (in €/kg)	upper bound	513.763	990.962	0.050	2,000
Future price (in €/kg)	lower bound	132.502	245.236	0.010	500
Future price (in €/kg)	most likely	160.502	293.388	0.010	600
Future price (in €/kg)	upper bound	264.752	490.648	0.010	1,000
Fertiliser usage (expected change in%)					
N	lower bound	−11	16.360	−40	0
N	most likely	−18.200	23.480	−60	−5
N	upper bound	−38.200	27.500	−80	−11
P	lower bound	−5	3.540	−10	0

(*continued on next page*)

Table D1 (*continued*)

Variable	PERT point	Mean	SD	Min	Max
P	most likely	−10.200	5.930	−20	−5
P	upper bound	−28.200	14.530	−50	−11
K	lower bound	−12	21.320	−50	0
K	most likely	−23.600	42.920	−100	2
K	upper bound	−47	61.200	−150	5
PPP usage (expected change in%)					
Fungicides	lower bound	−5.600	8.320	−20	0
Fungicides	most likely	−8.600	10.710	−25	2
Fungicides	upper bound	−32	41.020	−100	5
Insecticides	lower bound	−21.600	43.880	−100	0
Insecticides	most likely	−3.800	5.760	−10	2
Insecticides	upper bound	−7	13.510	−30	5
Herbicides	lower bound	0.200	1.790	−2	3
Herbicides	most likely	−2.600	4.880	−10	2
Herbicides	upper bound	−22	44.240	−100	5
Irrigation (expected change in%)	lower bound	−1.600	2.300	−5	0
Irrigation (expected change in%)	most likely	0.800	2.950	−3	5
Irrigation (expected change in%)	upper bound	3	10.950	−10	20
Effect on ecosystem health (in%)	lower bound	2	5.700	−5	10
Effect on ecosystem health (in%)	most likely	6.800	10.060	−6	20
Effect on ecosystem health (in%)	upper bound	12.800	16.020	−11	30
Potato yield change (in%)					
Consumption	lower bound	−4.600	8.710	−20	0
Consumption	most likely	3.800	3.900	0	10
Consumption	upper bound	13	9.080	5	25
Seed	lower bound	−4.600	8.710	−20	0
Seed	most likely	3.800	3.900	0	10
Seed	upper bound	13	9.080	5	25
Starch	lower bound	−4.600	8.710	−20	0
Starch	most likely	3.800	3.900	0	10
Starch	upper bound	13	9.080	5	25
Potato price change (in%)					
Consumption	lower bound	1.250	2.500	0	5
Consumption	most likely	5.500	3.320	2	10
Consumption	upper bound	11.750	9.070	5	25
Seed	lower bound	1.250	2.500	0	5
Seed	most likely	5.500	3.320	2	10
Seed	upper bound	11.750	9.070	5	25
Starch	lower bound	1.250	2.500	0	5
Starch	most likely	5.500	3.320	2	10
Starch	upper bound	11.750	9.070	5	25
Prevalence of diseases (in %)					
Phytophthora infestans	lower bound	−7	8.370	−20	0
Phytophthora infestans	most likely	−0.200	1.790	−3	2
Phytophthora infestans	upper bound	6	11.940	−10	20
Nematodes	lower bound	−7	8.370	−20	0
Nematodes	most likely	−0.200	1.790	−3	2
Nematodes	upper bound	6	11.940	−10	20
Working hours (expected change in%)					
Application of PPP	lower bound	−3.750	2.500	−5	0
Application of PPP	most likely	−6.500	4.730	−10	0
Application of PPP	upper bound	−11.500	8.500	−20	0
Fertilisation	lower bound	−3.750	2.500	−5	0
Fertilisation	most likely	−6.500	4.730	−10	0
Fertilisation	upper bound	−11.500	8.500	−20	0
Tilling	lower bound	−3	2.450	−5	0
Tilling	most likely	−5.250	4.110	−10	0
Tilling	upper bound	−9	6.380	−15	0
Application of microbes (in hrs)	lower bound	5	4.760	0	10
Application of microbes (in hrs)	most likely	10.750	11.240	0	24
Application of microbes (in hrs)	upper bound	19.250	21.780	0	48
Farmer Satisfaction (on a scale 1-10)	lower bound	0	4.080	−5	5
Farmer Satisfaction (on a scale 1-10)	most likely	5.750	8.100	−2	15
Farmer Satisfaction (on a scale 1-10)	upper bound	15	14.720	0	30
Sustainability dimension weights					
Economic		36	11.400	20	50
Social		27	4.470	20	30
Environmental		37	9.750	25	50

Appendix E. Qualitative Results Farmer Satisfaction

In the second expert elicitation round, we asked the experts to explain why and how they think farmers' satisfaction might change upon the adoption of microbial applications. The raw qualitative answers are provided below.

- The farmers are satisfied when using microbial application either as biofertilizers or biopesticides compared to the baseline, but the inconsistent efficacy of such products impacts their larger adoption. Unfortunately, the farmers usually use the easily accessible agrochemicals to obtain more stable results.
- May be better yiel[d] and quality
- The feeling of doing something better for the environment - and presumably
- better performance
- Obtaining a higher yield with a reduction of inputs
- Improving soil quality in the long term
- Contribute to sustainable agriculture and environment care
- The farmer no longer uses pesticides and produces healthier food
- Farmers are more aware of the "negative" impact of traditional, non biological farming (e.g. using fertilizers and herbicides) on nature and how it resonates in EU policies. In that respect they surely are looking for improvements and change and I think they will be willing to try novel, improved methods as long as it is profitable. Being able to be not part of the problem but part of the solution will lead to greater satisfaction.
- Farmers are more receptive to the use of inoculants mainly because high quality products available at the market, improving yields at low cost in comparison to chemical fertilizers.

Appendix F. Supplementary data

R code with robustness checks; Expert Elicitation Survey, Delphi iteration I; Expert Elicitation Survey, Delphi iteration II. Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2023.103797.

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