# Environmental impacts of cultivation of new potato varieties

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Environmental Life Cycle Assessment of the cultivation of ware potato varieties propagated from True Potato Seed with stacked resistance against Phytophthora infestans

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Abstract: This research investigates the differences in environmental impacts between the cultivation of conventional ware potatoes and the cultivation of PI-resistant ware potato varieties, which are propagated either conventionally or from True Potato Seed (TPS). It was concluded that environmental impacts of new varieties are not significantly different from conventional ware potato cultivation. LCA has been used to assess the environmental impact of the 3 scenarios. The current environmental impact assessment focused on three scenarios: 1) Archetypical conventional ware potato cultivation; 2) PI-resistant ware potato cultivation with conventional propagation; 3) PI-resistant ware potato cultivation with TPS-based propagation.

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Key words: life cycle assessment, LCA, potato, diploid true potato seeds, late blight, Phyophthora infestans, environmental impact, true potato seed

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# Preface

The Public Private Partnership ResPot, short for "Towards a RESilient POTato cropping system" started in 2021 with the aim to facilitate the transformation of potato production towards a better balance between agronomic inputs and the economic and environmental benefits. This is pursued through the development of varieties with stacked resistances against *Phytophthora infestans* and the optimisation of agronomy during their early growth stages. Such varieties are developed through diploid hybrid potato breeding. This type of breeding generates pathogen free True Potato Seeds and allows for faster introduction of crop traits. This report presents the final environmental impact assessment of the cultivation of the *Phytophthora infestans* resistant TPS-based varieties available during the project. In 2022, a screening LCA was conducted to inform the project partners and prioritise input data improvements and methodological choices. The main efforts in the public-private partnership focused on 1) optimising the agronomic resilience of seedling, transplant and seed tuber cultivation and 2) improving disease monitoring and management for the new potato varieties in field cultivation. Another task was dedicated to project result communication and dissemination as well as studying the adoption dynamics of the innovations. The author would like to thank Maarten Kik, Bert Evenhuis, Olivia Kacheyo, Lennert van Puffelen, Auke Greijdanus, Coert Bregman, Roline Broekema and Edwin van der Vossen for providing their advice and data.

# Summary


## S.1 Environmental impact differences between conventional ware potatoes and new *Phytophthora infestans*-resistant varieties from conventional propagation or True Potato Seed (TPS)

New potato varieties that are resistant to *Phytophthora infestans* (PI), promise a new protection strategy against PI, conserving current yield levels. These varieties, which are propagated either conventionally or from True Potato Seeds (TPS), potentially have lower environmental impacts, but these impacts had not yet been compared robustly to conventional potato cultivation, despite a screening LCA that was conducted in 2022. Without insights on the environmental impacts, agronomic optimisation of potato cultivation as well as development of new traits and varieties cannot be targeted at environmental impact reduction. The main research question is: "What are the differences in environmental impacts between the cultivation of conventional ware potatoes and the cultivation of PI-resistant ware potato varieties, which are propagated either conventionally or from True Potato Seed (TPS)?"

## S.2 Environmental impacts of new varieties are not significantly different from conventional ware potato

This study concludes that most of the environmental impacts of cultivating new varieties with PI resistance are not significantly different from cultivating varieties with a normal susceptibility to PI. This conclusion is valid for both conventional propagation and for the TPS-based propagation route studied in this report (with 2 cycles of seed tuber cultivation). It is highly uncertain to what extent other TPS-based propagation routes without seed tuber cultivation will increase or reduce environmental impacts. The following additional conclusions, regarding the sub-questions, are drawn:

- Climate change impacts of the scenarios are not differentiated by the PI resistance or the propagation route, but through the main contributors of N fertilisation and diesel use.
- Freshwater ecotoxicity impacts of PI-resistant varieties will be lower than freshwater ecotoxicity impacts of conventional varieties, thanks to less fungicide application and fungicide production, but the extent to which cannot be quantified with certainty.
- The effect of the PI resistance or the TPS-based propagation on most other environmental impacts than climate change and freshwater ecotoxicity will be limited, because they follow trends of either climate change or freshwater ecotoxicity.
- Climate change impacts and most of the other environmental impacts are strongly coupled to actual variations in nitrogen fertilisation (both animal manure and chemical fertiliser) and to diesel use.

## S.3 Methodology: Life Cycle Assessment (LCA)

LCA has been used to assess the environmental impact of the 3 scenarios. The current environmental impact assessment focused on three scenarios:

1. Archetypical conventional ware potato cultivation
2. PI-resistant ware potato cultivation with conventional propagation
3. PI-resistant ware potato cultivation with TPS-based propagation

Compared to the screening LCA in 2022, the underlying data of the assessment has been improved and a variability analysis has been included: Diesel use, N fertilisation from animal manure and chemical fertiliser, and crop protection data now include field data from experts and statistical databases. System boundaries are set from cradle to ware potato farm gate, including the cultivation of all propagation material. All relevant input data is provided in the Appendices. Common, up-to-date background databases, emission models and impact characterisation methods were employed.

# 1 Robust environmental impact assessment of new resistant potato varieties needed

## 1.1 Currently, environmental impacts of new potato varieties are unclear

Potato late blight (*Phytophthora infestans*, PI) is a predominant disease, which puts potato growers at risk of losing yield or their entire harvest. To prevent the impact of this disease, conventional farmers follow an intensive disease control strategy, relying on very frequent applications of fungicides (Kessel et al., 2018). Across Northwestern Europe, resistant varieties are under development, so that fungicide use can be limited or reduced (Haverkort et al., 2009).

PI-resistant varieties are developed as True Potato Seeds (TPS, seeds from potato berries/fruits) at Solynta, because it has several benefits (Kacheyo et al., 2024). The diploid nature of TPS allows for faster introduction of new traits and better yield potential through hybridisation. TPS also allow for a faster scale-up to commercial quantities of starting material, since potato plants yield much more seed than seed tubers per mother plant. It is also claimed that TPS are less sensitive to diseases during storage than seed potatoes, can be stored longer and are more efficient to transport compared to seed potatoes (Solynta, 2024). Three propagation routes are envisioned for commercial cultivation (Kacheyo et al., 2024):

1. Propagation Route 1: Currently, TPS are sown into substrate-filled tray wells to produce seedlings, which are transplanted to the open field to yield seed tubers. This seed tuber is planted in a second year to yield more seed tubers. In a third year, these are cultivated to yield ware potatoes.
2. Propagation Route 2: The seedlings could be optimised to produce a ware potato directly with a sufficient yield.
3. Propagation Route 3: TPS can be sown in the open field early in the season where they emerge under controlled conditions, and are cultivated to yield a ware potato directly. Initial field trials provide promising results (Kacheyo & van der Vossen, 2024).

The environmental impact of PI-resistant varieties based on conventional and TPS-based propagation methods is not clear and has not been compared robustly to conventional potato cultivation. A first screening assessment of the environmental impacts in 2022 showed that the differences in impact were likely to be small and were uncertain. Without more robust insights on the environmental impacts, agronomic optimisation of potato cultivation as well as development of new traits and varieties cannot be targeted at environmental impact reduction.

## 1.2 Improved comparison of the environmental impacts of cultivating new potato varieties is needed

The comparison of environmental impacts between conventional potato cultivation and cultivation of new PI-resistant varieties should be improved compared to the 2022 screening study. Only then environmental impact reduction could play a role in agronomic and genetic optimisation. Several requirements can be defined for this improved comparison. The comparison is informative if the identified scenarios focus on the most applicable propagation route and the most relevant environmental impacts. The comparison can be made more robust if most of the underlying data is improved. The comparison also becomes more informative and robust if it it is put in perspective of the variability in environmental impacts due to current agronomic practices. The selection of environmental impacts and the efforts to make the comparison more robust are elaborated in Section 2.2, Default approach to Life Cycle Impact Assessment.

The relevant scenarios should allow separation of the effects of PI resistance and TPS-based propagation:

1. Scenario 1: Archetypical conventional ware potato cultivation
2. Scenario 2: PI-resistant ware potato cultivation with conventional propagation
3. Scenario 3: PI-resistant ware potato cultivation with TPS-based propagation (propagation route 1).

A non-resistant TPS-based potato variety exists but is not relevant for this analysis.

Scenario 3 will address propagation route 1 (from Figure 1: Seedling cultivation, followed by 2 years of seedling cultivation). This route is the focus of the RESPOT project and requires strong transplants that grow well under relatively normal seed tuber cultivation conditions, in two cycles of seed tuber cultivation prior to ware potato production. This also implies that the in-field cultivation remains similar to the current practice. In contrast, little is known about the optimal agronomy of newer propagation routes 2 and 3, in which ware potatoes are cultivated directly from seedling- or true potato seed-based. The environmental impact of these propagation routes is more uncertain and are out of scope. They will be addressed in the discussion.

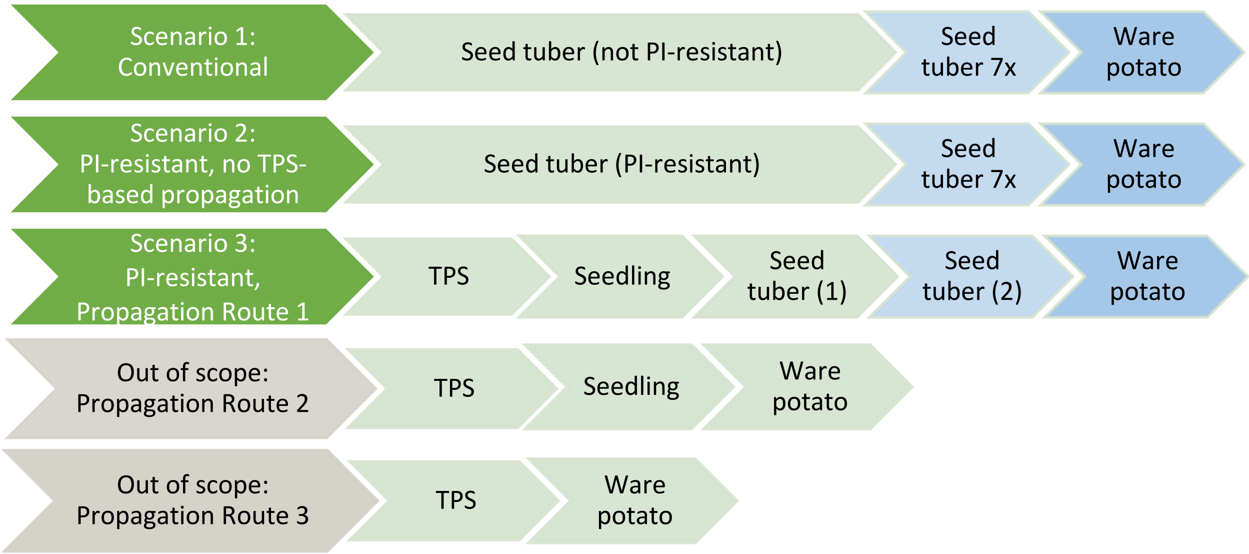


***Figure 1*** *Scenarios for comparison in this study. Light green indicates first year and blue shades indicate later years.*

## 1.3 Research question: What is the effect of the innovations in new potato varieties on the environmental impacts

The main research question for this report is: "What are the differences in environmental impacts between the cultivation of conventional ware potato and the cultivation of PI-resistant ware potato varieties, which are propagated either conventionally or from True Potato Seeds (TPS)?" PI resistance and TPS-based propagation will be described as "the innovations".

The sub-questions will be:

1. What is the climate change impact of ware potato cultivation without and with the innovations?
2. What is the freshwater ecotoxicity impact of ware potato cultivation without and with the innovations?
3. What are other environmental impacts of ware potato cultivation without and with the innovations?
4. What is the variability in the environmental impacts of ware potato cultivation due to current agronomic practices (without the innovations)?

# 2 Improved methods and data for the environmental impact assessment

## 2.1 General approach and scope

**The general approach focuses on ware potatoes**

The current environmental impact assessment focuses on three assessment scenarios:

1. Scenario 1: Archetypical conventional ware potato cultivation (the default)
2. Scenario 2: PI-resistant ware potato cultivation with conventional propagation
3. Scenario 3: PI-resistant ware potato cultivation with TPS-based propagation (propagation route 1).

The underlying data of the assessment has been improved compared to the 2022 screening study and a variability analysis on diesel use, N fertilisation has been included for scenario 1 on conventional cultivation. The reference unit of analysis in this assessment is 1 tonne of ware potatoes at harvest. The quality of the potatoes (flouriness, size, colour, protein, moisture content, etc.) has been assumed the same for all scenarios. The geographical scope is the Netherlands. Most of the data items have been improved since the screening LCA in 2022 by including better data from the Dutch Farmer Accountancy Data Network or from observations by experts, which also supported the variability analysis. The software tool SimaPro 9.6 was used for modelling and impact assessment (Pré Sustainability, 2024).

**System boundaries are set from resource extraction to ware potato farm gate**

The system boundaries include the following (for both seed and ware potato, as well as TPS seed and seedlings unless stated otherwise, see Figure 3 on next page):

- Production, packaging and transport of chemical fertiliser, lime and crop protection products
- Production and transport of fuels and electricity
- Production and maintenance of production infrastructure (sheds, tractors, etc.)
- The cultivation stage
    - Carbon, nitrogen and phosphorous emissions from fertilisation with animal manure and chemical fertiliser, as well as liming
    - Emissions from fuel combustion for mechanised labour or heating and irrigation
    - Emissions from crop protection application
    - Water use irrigation?
- Transport and storage of seed potatoes

The system boundaries exclude the following:

- Production and transport of animal manure, since this is allocated to animal production
- All transport after harvest of the ware potato and storage of the ware potato
- Potato processing and packaging
- Retail, Use, End-of-life
- Commuting and research & development (e.g. breeding)
- All emissions from crop residues and carbon sequestrations anywhere in the life cycle were excluded because it was assumed the biogenic cycles results in no net global warming potential.[1]
- Emissions from peat soil were excluded for field cultivation while emissions from peat substrate for seedling and seed cultivation were included.[2]
- Emissions of mineral oils were excluded because they are very hard to quantify.
- Heavy metal emissions from animal manure are allocated to the animal production.

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[1] Thus it is assumed $CO_2$ absorbed in crop residues and the crop itself is released as $CO_2$ and not as $CH_4$ or $N_2O$. Carbon fixed in the soil in a rotation that includes potato cultivation remains in the soil shorter than 20 years and does not affect the longer term $CO_2$ balance. Crops (productive and cover crops) other than potato were not in scope.

[2] There is hardly cultivation of potatoes on peat soils or on soils with some peat, while peat substrate is commonly used. Therefore this approach is most pragmatic.

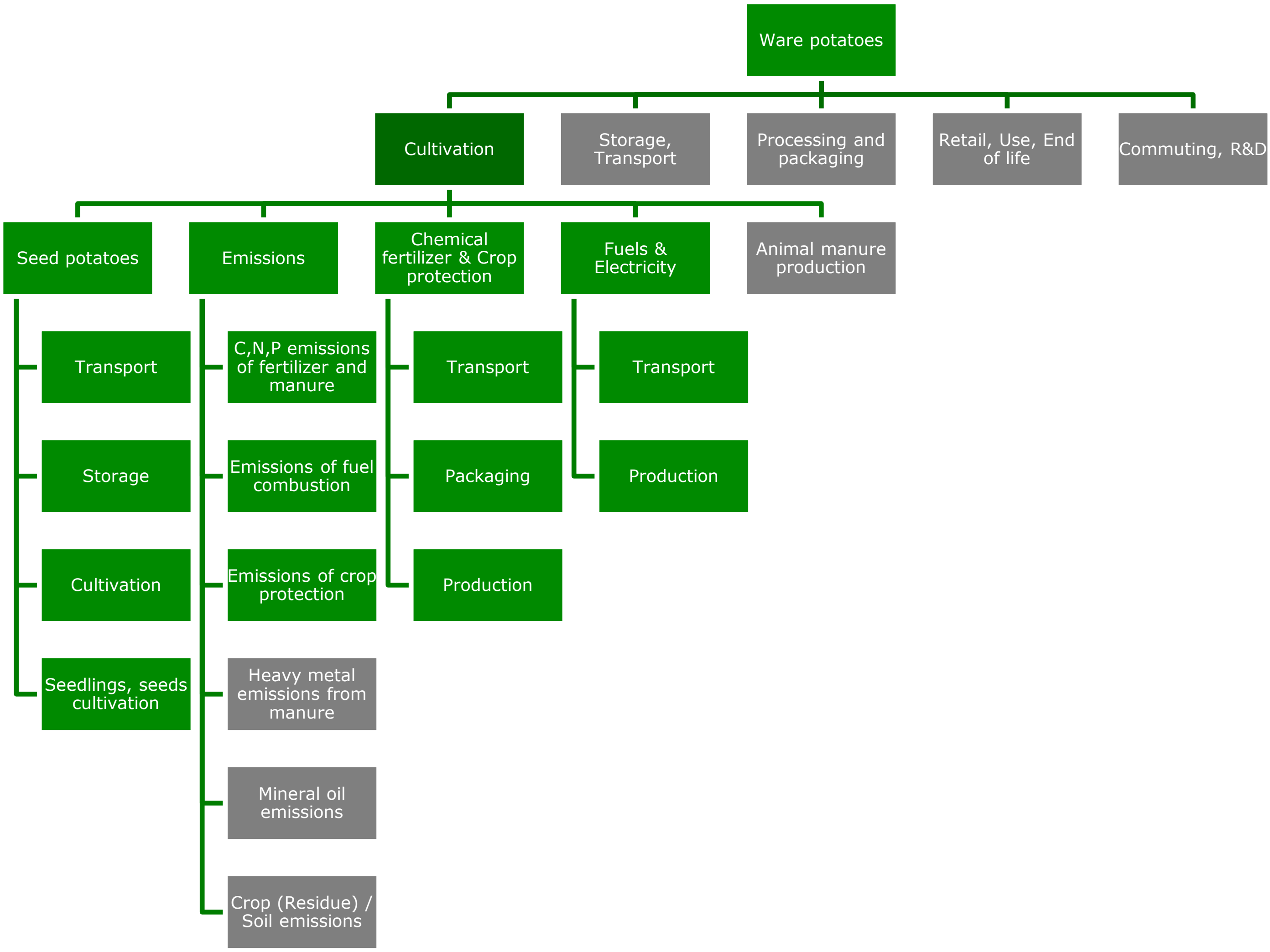


***Figure 2*** *System boundaries Green is included in the scope, grey is excluded; Cultivation of seed potatoes and cultivation of seedlings and seeds also include the items under "Cultivation" (marked darker green).*

**A default approach to allocation**

The harvested potatoes are assumed to be homogenous in quality. Allocating impact crop residues are not relevant for potatoes, since they have no function off field and are not harvested (unlike e.g. wheat straw). Upstream processes may include multifunctionality: we used Agri-footprint 6 economic (Blonk et al., 2022) and ecoinvent 3.9 cut-off processes (Wernet et al., 2016) for these, which means that generally economic allocation is applied, in line with common practice (Pant & Zampori, 2019).

## 2.2 Default approach to Life Cycle Impact Assessment

The emissions and resource extractions calculated from all activities in the scoped life cycle of ware potato cultivation are characterised into environmental impacts. The "EF Method" (Bassi et al., 2023) was used, since it contains well-established and up-to-date characterisation methods for several environmental impacts than method used in the screening study of 2022, that applied the life cycle assessment method ReCiPe 2016 (Huijbregts et al, 2016). Climate change, freshwater ecotoxicity were selected as environmental impact of focus. Climate change is regarded as an important environmental impact ) and many environmental impacts[3] correlate with it because of emission patterns in agriculture and energy consumption (Bassi et al., 2023; Huijbregts et al., 2016). Freshwater ecotoxicity is selected because crop protection product emissions are of specific interest in the RESPOT project and its correlation with climate change is unclear (Kessel et al., 2018; Solynta, 2024). Land use is relevant because the effects of shortened propagation cycle are of specific interest (Kacheyo et al., 2024). Other environmental impacts will be discussed briefly.

[3] Acidification, eutrophication, fossil resource depletion and particulate matter formation

## 2.3 Improvement of data collection

**Basic approach for generic data such as yield and the use of propagation materials**
All data is summarised in Appendix 1 Core input data. Yield and seeding rate for ware and seed potatoes were taken from so-called KWIN data[4] (van der Voort, 2022), as well as the electricity use for seed potato storage. Infrastructure use is taken from AgriFootprint 6.3 (Blonk et al., 2022). Transport and irrigation data were based on assumptions after discussions with experts (Kacheyo & van der Vossen, 2024; Kik, 2023). Seed tuber transportation distance was assumed to be 20 km, transportation distance of other inputs was assumed to be 100 km. In addition, an on-farm transportation distance was assumed for those inputs of 2 km. Only a limited share of transportation of manure was allocated to the potato cultivation (2 km) to consider some contribution of manure transport to crop cultivation.

Yield ($Y_S$, t/ha) and seedling rate ($SR_S$, t/ha) for seed tubers were used to calculate a multiplication fraction ($MF_S$, -). The time-integrated seeding rate for ware potatoes ($TISR_W$, t/ha) was determined as how much seed tubers are produced over all propagation years (r,-) for the cultivation of ware potatoes. This depends on the seeding rates for seed potatoes and ware potatoes, and the multiplication fraction. The net seedling rate for seed potatoes ($NSLR_S$, seedlings/ha) was also determined as how many seedlings are required to cultivate seed potatoes on 1 ha in the year before ware potato cultivation. This is a function of the number of propagation years, the multiplication fraction and the seedling rate for seed potatoes ($SLR_S$, seedling/ha). Equations 1-3 are used.

$$MF_S = \frac{SR_S}{Y_S} \tag{1}$$

$$TISR_W = SR_W + \ SR_S * \sum_{y=2}^{r} MF_S^{y-1} \tag{2}$$

$$NSLR_S = SLR_S * MF_S^r \tag{3}$$

The seed tuber demand of the last year before ware potato cultivation is reflected by $SR_W$ in equation (2) and the seed tuber demand of years before that are reflected by the second term. y starts with 2 indicating the fore last seed tuber year and counts up to r. (r=8 for scenario 2 and r=2 for scenario 3).

With an $MF_S$ in the current range around 0.135, corresponding to Dutch practice, $TISR_W$ and $NSLR_S$ are not very sensitive to a number of multiplication years larger than two.

**Diesel usage was re-modelled including experience from the field**
The total diesel usages for seed and ware potatoes from the KWIN data (van der Voort, 2022), which were used in 2022, were reconstructed with improved detail. First, the minimum and maximum diesel use for each field operation (tillage, irrigation, fertilising, planting, etc.) were taken from all potato cultivation datasets in the KWIN data. These were adjusted by expert interviews who brought their own field data on the average Dutch practices (Kik, 2023) and Solynta field trials (Kacheyo & van der Vossen, 2024). The average was taken for each field operation and added up to represent the diesel use for the three assessment scenarios. The minimums and maximums were added up to represent the low and high diesel use for the variability analysis. The diesel use for crop protection product applications was informed by the number of applications in non-resistant (scenario 1) and resistant (scenario 2 and 3) scenarios (Evenhuis, 2024).

**Fertilisation data for animal manure & chemical fertiliser includes Dutch representative dataset**
Both manure and chemical fertiliser application were derived from the LMM dataset (Greijdanus & Hoogeveen, 2024) (instead of the KWIN data in 2022). This dataset contained nitrogen (N) and phosphorus (P) data for 2019-2021, for conventional and organic cultivation, for ware and seed cultivation and different soil types. Organic cultivation was excluded, ware and seed potato cultivation were analysed separately and no discrimination was made according to soil types and years.

High and low values were taken from the dataset based on fixed percentiles (see Appendix 2 Fertilisation data). These values were validated and sometimes adjusted and rounded using Kik (2023), Ravensbergen (2024) and Kacheyo & van der Vossen (2024). This was done to exclude the extreme end of the distributions, these contain both errors and real extremes, which neither represent a realistic minimum and

[4] https://www.wur.nl/nl/show/kwin-agv.htm: In KWIN-Arable Farming and Field Vegetables (AGV) an overview of the costs and yield per hectare per crop is given, supported by use data of all agronomic inputs.

maximum fertiliser or manure application. For the archetypical values required for the assessment scenarios, the dataset was regarded as less representative than for extreme values. Therefore, the highest total N application norm from RVO (2024) was taken as benchmark, and contributions from manure and chemical fertiliser were derived using the LMM dataset (See also Appendix 2).

The fertiliser total N application was distributed over different chemical fertiliser types using the distributions from WFLDB (Nemecek et al., 2019) and AgriFootprint 6.3 (Blonk et al., 2022) to estimate the production impacts. The fertiliser use and the total manure use was also used to determine transport amounts. The manure use was split into cattle and pig slurry, and P application from manure was derived from these manure amounts for all scenarios. The total P application was derived from KWIN (van der Voort, 2022) for the assessment scenarios and from the LMM dataset (Greijdanus & Hoogeveen, 2024) for the variability analysis. Next, the fertiliser P application was the difference between the total P application and the manure P application. Liming was included in the LCA based on KWIN data.

**Fertiliser emissions calculations were updated**

Field emissions from application of the different fertiliser types and manure types were calculated following (Broekema et al., 2024), which is consistent with or is more advanced than Pant & Zampori (2019) and Tier I modelling from IPCC (Masson-Delmotte et al., 2022) compared to the 2022 study. This implies a number of changes compared to 2022: Ammonia emissions are calculated with volatilisation fractions that were differentiated per fertiliser type, causing an increase. Nitrate emissions are more realistic thanks to a more explicit nitrogen mass balance and the separate inclusion of leaching and runoff, resulting in a decrease. Nitrous oxide emissions are modelled in a simpler and less conservative way, and decrease. Input data for the field emission calculation consist of the manure application, distributed over cattle and pig slurry according to a ratio from LMM data (Greijdanus & Hoogeveen, 2024) and the application of the different fertiliser types, as well as basic soil and climate characteristics.

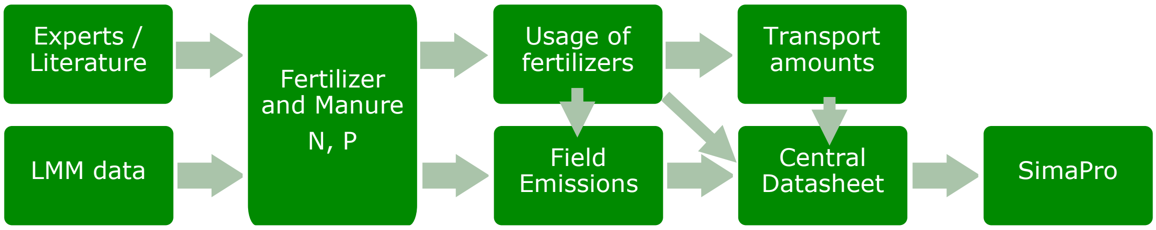


***Figure 3*** *Basic depiction of data flows and calculation steps for fertiliser and manure use and field emissions.*

**Crop protection use derived from field trial planning and only high-impact products were included**

The crop protection use was determined as all PI treatments Evenhuis (2024) as planned for 2024 in ResPot field trials and other experiments by Wageningen Plant Research shared by Evenhuis (2024), augmented with the herbicide and insecticide application from KWIN (van der Voort, 2022). ResPot field trials from 2021-2023 showed that the stacked resistance in the new varieties require at least half of the fungicide applications (Evenhuis, 2024). Thus resistance scenarios consist of the first half of the treatments against *Phytophthora infestans*, and the default weed and insect control applications, for both seed and ware potatoes. This contrasts with the assumption no fungicide use from 2022. In addition, the fungicides used in the spray schemes differ radically compared to the assessment of 2022, which used KWIN data; the current protection strategy considers better the present-day prohibitions and reduced effectiveness of several active ingredients. Halving the number of PI treatments leads to a 48% lower fungicide use in resistant scenarios (2 and 3) than in the conventional scenario (1).

The active ingredient usages of individual treatments were aggregated to total active ingredient usages. A selection of active ingredients for inclusion in the final LCA model was made to limit modelling effort within SimaPro. A preliminary analysis was done for this purpose, as follows:

1. Each active ingredient usage received a matching characterisation factor from excel overviews of USETOX 2.12 (Fantke et al., n.d.) or OLCApest (Nemecek et al., 2022) for the different compartments.[5] These factors have the same units but follow different modelling approaches.
2. Each characterisation factor was multiplied with the corresponding emission factor.

[5] Proxies for sulfoxaflor and amisulbrom and exclusion of potassium phosphonates.

3. The "emission-factor-weighted characterisation factor" were aggregated for each active ingredient into a single factor reflecting the emission factor and the potential toxic impact.
4. Each active ingredient usage was multiplied with its corresponding factor and the 8 most impactful active ingredients were selected for implementation in SimaPro, which covered the 2 to 3 orders of magnitude of the highest impact.[6]

***Table 1*** *Active ingredients used in the crop protection strategy*

| Active ingredient | In SP | Type | unit | a.i. m Ware NR | a.i. m Ware R | a.i. m Seed NR | a.i. m Seed R |
|---|---|---|---|---|---|---|---|
| **oxamyl** | **y** | Ins | kg | 0.00 | 0.00 | 1.00 | 1.00 |
| **maleic hydrazide** | **y** | PGR | kg | 3.00 | 3.00 | 3.00 | 3.00 |
| **prosulfocarb** | **y** | Hrb-pre | kg | 4.00 | 4.00 | 0.00 | 0.00 |
| **pyraflufen-ethyl** | n | Hrb-post | kg | 0.02 | 0.02 | 0.02 | 0.02 |
| **carfentrazone-ethyl** | n | Hrb-post | kg | 0.03 | 0.03 | 0.03 | 0.03 |
| **metribuzin** | **y** | Hrb-pre | kg | 0.30 | 0.30 | 0.30 | 0.30 |
| **clomazone** | n | Hrb-pre | kg | 0.09 | 0.09 | 0.09 | 0.09 |
| **sulfoxaflor** | n | Ins | kg | 0.02 | 0.02 | 0.02 | 0.02 |
| **acetamiprid** | n | Ins | kg | 0.00 | 0.00 | 0.05 | 0.05 |
| **propamocarb hcl** | n | Fun | kg | 5.05 | 3.03 | 1.01 | 0.00 |
| **ametoctradin** | **y** | Fun | kg | 0.96 | 0.48 | 0.48 | 0.48 |
| **amisulbrom** | n | Fun | kg | 0.16 | 0.08 | 0.16 | 0.16 |
| **cyazofamid** | n | Fun | kg | 0.24 | 0.08 | 0.32 | 0.08 |
| **fluazinam** | **y** | Fun | kg | 0.70 | 0.20 | 0.00 | 0.00 |
| **mandipropamid** | n | Fun | kg | 0.15 | 0.15 | 0.00 | 0.00 |
| **fluopicolide** | **y** | Fun | kg | 0.00 | 0.00 | 0.31 | 0.16 |
| **azoxystrobin** | **y** | Fun | kg | 0.05 | 0.00 | 0.00 | 0.00 |
| **potassium phosphonates** | n | Fun | kg | 0.38 | 0.00 | 0.00 | 0.00 |

The column "In SP" indicates if they have been implemented in the LCA model in SimaPro. fungicides are marked as type "Fun", pre- and post-emergence herbicides are marked Hrb-pre and Hrb-post respectively, and insecticides are marked Ins, while plant growth regulator is marked with PGR. "Ware" indicates the consumption for ware potatoes and "Seed" indicates the consumption for seed potatoes; "NR" indicates the non-resistant scenario and "R" indicates the resistant scenario. The emission fractions for oxamyl were considered as pre-emergence application, since it is applied on the planting date.

In 2022, 12 out of 21 used active ingredients had a characterisation factor, while now 14 out of 17 did, and the others could receive a proxy factor. In 2022, it was observed none of the high-impact active ingredients were fungicides. Since only the fungicides vary between the non-resistant and resistant scenario, little variation in ecotoxicity was observed in 2022. Because the current preliminary analysis is more reliable, thanks to new characterisation factors, 8 instead of all active ingredients were implemented in SimaPro. Among these active ingredients were 4 fungicides, so it is expected ecotoxicity will vary across the scenarios.

**Seedling and seed cultivation data was enhanced with field trial data**

The data for seedling cultivation was updated significantly compared to 2022. Primary data (Kacheyo & van der Vossen, 2024) replaced most of the data from van Dijk et al. (2021). All data is summarised in Appendix 3 Seedling and seed data. Compared to 2022, the electricity use was over six times lower and gas use was lowered by a third, while fertiliser application increased strongly. Calculation errors from 2022 were corrected so that nitrous oxide emissions from fertilisation reduced by a factor of 500 and carbon dioxide emissions from peat in substrate doubled. A scenario for optimised seedling cultivation was composed with expert estimates and assumptions (Kacheyo & van der Vossen, 2024).

[6] The human toxicity impact of the selected ingredients ranges from 9E-6 down to 1E-6 DALY (per active ingredient application), while the other ingredients' impacts range from 9E-8 down to 5E-9 DALY; the total ecotoxicity impact ranges from 1E+3 down to 7E+1 PDF.m3.d (per active ingredient application) while the other ingredients' impacts range from 9E+1 down to 1E-1 PDF.m3.d

The impact of seed production was not considered in 2022 for two reasons, but has now been modelled. First, a very large number of seeds is produced on a small greenhouse area with a limited gas and electricity use. In addition, the impact of the seed production is limited by the two cultivation years of seed tubers: a single seedling would yield 55 ware potato plants in the current propagation route.[7] All data is summarised in Appendix 3. Electricity use, gas use and productivity were primary data (Kacheyo & van der Vossen, 2024). The fertigation regime was based on the same primary data as well as some assumptions stated in Appendix 3 (winter irrigation frequency, fertiliser concentration). Substrate composition was assumed to be identical to the seedling cultivation.

[7] Using the seeding rate of 5,180 kg/ha and the yield of 38,500 kg/ha from KWIN (REF), under the assumption that seed tuber for ware potato cultivation weigh as much as seed tubers for seed tuber cultivation.

# 3 Results: Diesel and N fertilisation drive environmental impacts of all potato cultivation

## 3.1 Climate change impact hardly affected by PI resistance and not by TPS-based propagation

Climate change impacts are shown in Figure 5. Across scenarios, field emissions (due to fertilisation by animal manure and chemical fertilisers) contribute 44-45% and the production of chemical fertilisers contributes 10-11%. The impacts due to fertilisation thus contribute more than half of the climate change impact (54-56%). Diesel production and combustion (due to mechanised labour in the field) contributes 29-30%. Seed potato cultivation (of all preceding years) contributes 8% and minor contributions are infrastructure, pesticide production, transportation of all inputs and seedling production. Within seed potato cultivation, fertilisation and mechanised labour have the same large contributions (not shown in figure).

The climate change impact of the resistant scenario (2, with conventional propagation) is 3% lower than the conventional scenario (1), thanks to less pesticide production and less diesel use for fungicide application. The climate change impact of the resistant scenario with TPS-based propagation (3) has approximately the same impact as the resistant scenario (2), because differentiating contributions are small: the seedling production has a very low impact and the amount of avoided seed potatoes from propagation year 8 to 3 is very low. This is better visible in the detail of Figure 5b.

There are limitations in data and methods that provide a considerable range of variability and uncertainty. The effect variability of key input data on the climate change impacts (N fertilisation and diesel use) is assessed in Section 3.4, data limitations in Section 4.1 and methodological limitations in Section 4.2.

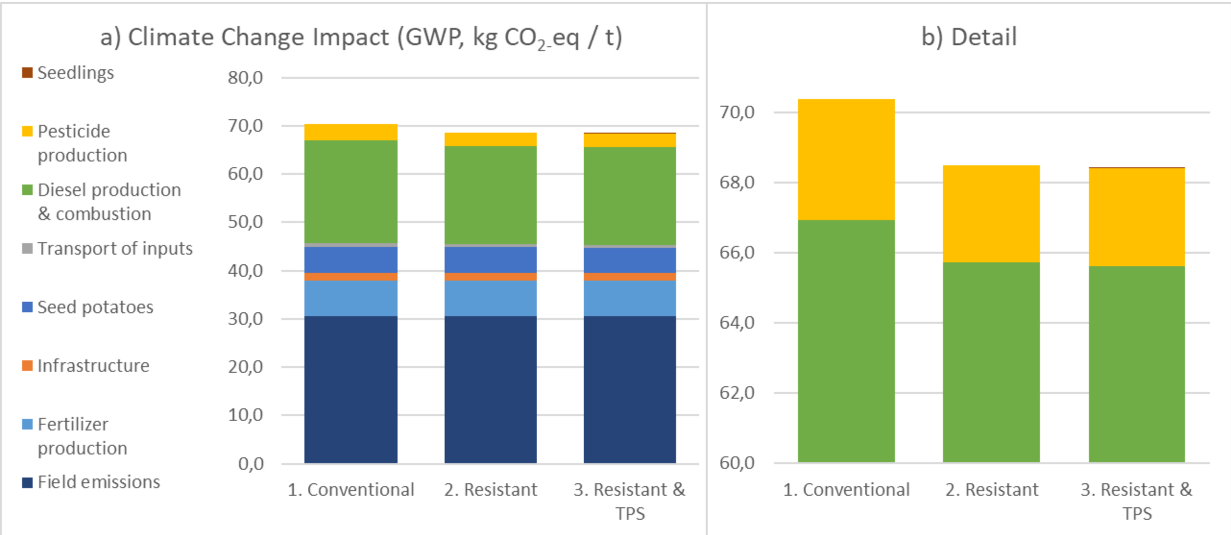


***Figure 4*** *Climate change impacts (global warming potential, GWP100) of ware potato cultivation in kg CO2eq/tonne of ware potato at farm gate of 3 scenarios; frame a) shows all contributions, frame b) shows in more detail the contributions that change: Diesel production & consumption, Pesticide production and Seedlings; all contributions are included in the total impact in frame b).*

## 3.2 Freshwater ecotoxicity impacts co-determined by N fertilisation, diesel and crop protection

Freshwater ecotoxicity impacts are shown in Figure 6 with all contributions shown in part (a). Across scenarios, field emissions and the production of fertiliser contribute 34-37% together. Diesel production & combustion (mechanised labour) contributes 17%. Pesticide emissions contribute 29-31% and their production contributes 7-8% (totalling 36-39%). Hence, these three agronomic practices (fertilisation, mechanised labour and crop protection) are the major contributions to ecotoxicity impact. Smaller contributions are seed potato cultivation (of all preceeding years), infrastructure and transportation of all inputs while seedling production have a negligible ecotoxicity impact.

The freshwater ecotoxicity impact of the resistant scenario (2., with conventional propagation) is 8% lower than the conventional scenario (1), thanks to less pesticide production in the factory and application on the field (See frame b) Detail Figure 6) and a minor reduction in diesel use. The freshwater ecotoxicity impact of the resistant scenario with TPS-based propagation (3.) has the same impact as the resistant scenario (2), because the differentiating contributions are very small: both seedling production (in 3.) and seed tuber propagation in years -7 to -3 (in 2) contribute less than 1%.

There are limitations in data and methods that provide a considerable range of variability and uncertainty. Data limitations in Section 4.1, including the potential variability in crop protection use, and methodological limitations in section 4.2.

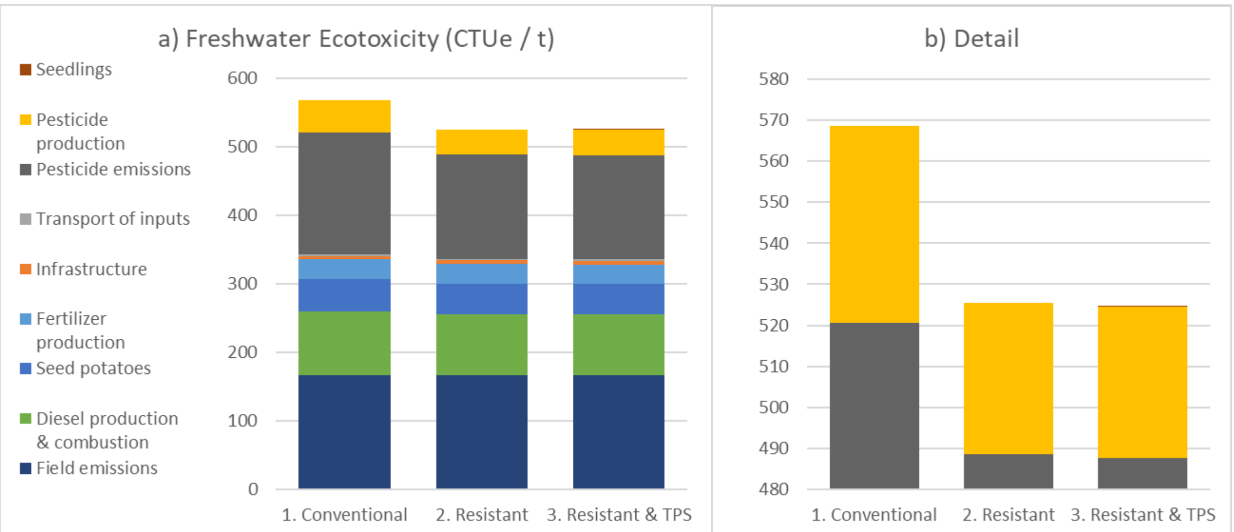


***Figure 5*** *Freshwater ecotoxicity impacts of ware potato cultivation in Cumulative Toxic Units (CTU)/tonne of ware potato at farm gate for 3 scenarios for different contributions; frame a) shows all contributions, frame b) shows in more detail the contributions that change: Pesticide production, pesticide emissions, and seedlings; all contributions are included in the total impact in frame b).*

Which emissions cause the ecotoxicity impact of the different contributions is illustrated in Figure 7(a) on the next page. The field emissions are determined by ammonia and ammonium caused by the nitrogen fertilisation (contributing 30-33%). Diesel combustion during field operations and transport cause a range of toxic emissions, among others hydrogen sulfide, unspecified oils and heavy metals (contributing 9%). A range of other emissions occurs during production of diesel, fertiliser and all other resources (contributing 17%). Pesticides are also emitted during their production, which contributes 7-8%. The pesticide emissions from application during both ware and seed potato production contribute 34-36%.

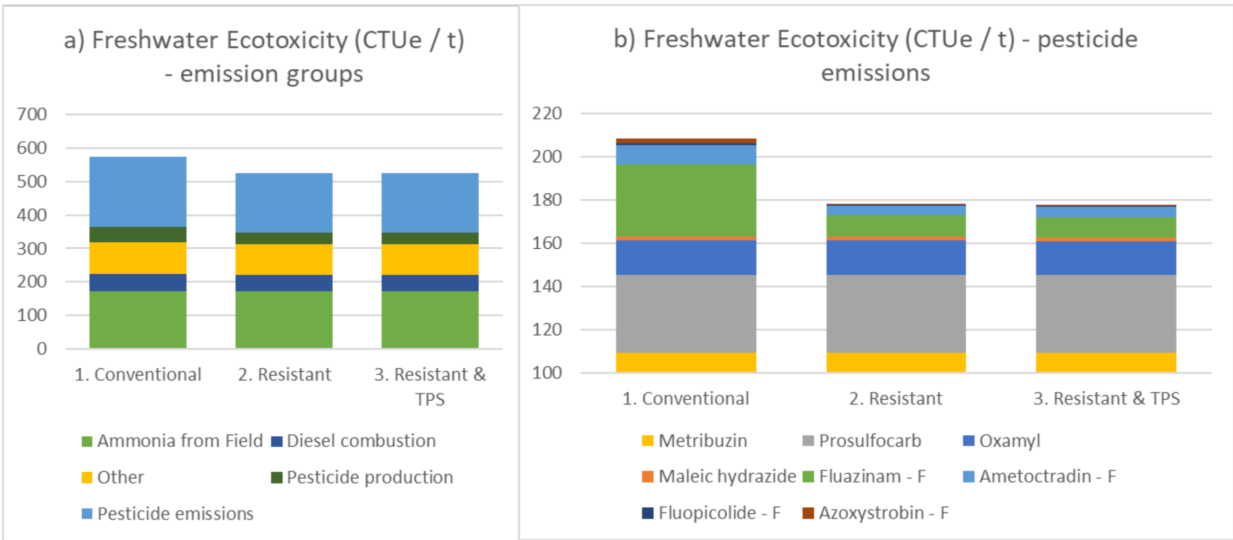


***Figure 6*** *Freshwater ecotoxicity impacts of ware potato cultivation for different emissions for 3 scenarios. (in Cumulative Toxic Units (CTU)/tonne of ware potato at farm gate); frame a) shows total impact of emission groups: emissions linked to a specified activity or source, frame b) shows in detail the contributions of different pesticides; fungicides are indicated with F on a cut-off axis.*

The contributions of the eight selected pesticides are specified in Figure 7 (b). Going from pesticide application to toxicity impacts shows a skewed trend, because differences in the fate behaviour and inherent toxicity of individual pesticides:

- Fungicide use: Halving the number of PI treatments leads to a 48% lower fungicide use in resistant scenarios (2 and 3) than in the conventional scenario (1).
- Total pesticide use: This reduction in fungicide use leads to a 24% reduction in total use of pesticides, because the amounts of herbicides applied remain constant across scenarios.[8]
- Total pesticide emissions: The reduction in total pesticide use results in a smaller reduction in total emissions (4%). This is because a smaller fraction of fungicides goes to the environment, compared to herbicides.
- However, this smaller reduction in total emissions leads to a larger reduction in total freshwater ecotoxicity impact. The four selected fungicides contribute 45 CTUe (22%) in the conventional scenario and 15 CTUe (8%) in the resistant scenarios: a reduction in the freshwater ecotoxicity impact of crop protection of 14%.

Among the fungicides, fluazinam contributes by far most to the ecotoxicity impact. Three of the pesticides are herbicides and maleic hydrazide is a plant growth regulator. These do not change between the conventional and resistant scenarios and contribute 162 CTUe, representing 78-92% of the freshwater ecotoxicity impact from pesticides. Metribuzin contributes by far most to the freshwater ecotoxicity impact. These results will not change if more pesticides, including all fungicides, would be implemented in the LCA model, because additional pesticides have far lower toxicity (more than 100 times).

[8] The amount of pesticides implemented in the LCA model is 11% lower in resistant scenarios, because the pesticides were selected that could have an impact of >0.1% of the total impact (see Section 2.2).

## 3.3 Other environmental impacts follow trends of climate change or freshwater ecotoxicity

Land use impacts are shown in Figure 8. There is no clear difference between scenarios with conventional propagation (1 and 2) and TPS-based propagation (3). The differentiating contributions are very small: seedling production contributes less than 1%, and the amount of avoided seed potatoes from propagation years 8 to 3 is so small that it has a very small impact. The seed potato cultivation in all scenarios (propagation years 1 and 2) contributes 8% to the land use. The ware potato cultivation contributes 92% to the total land use impact. Other contributions are negligible.

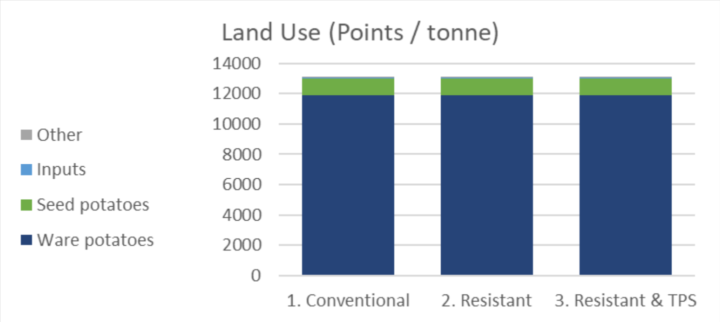


***Figure 7*** *Land use impacts of ware potato cultivation in Points/tonne of ware potato at farm gate for 3 scenarios for different contributions.*

Effects on other environmental impacts are limited, and are summarised in Table 2. There is hardly any difference between the three scenarios for acidification, particulate matter formation, three types of eutrophication (marine, terrestrial, freshwater) and photochemical ozone depletion. This is because these are determined by emissions from nitrogen fertilization and diesel use. Thus their contributions and relative impacts are very similar to that of climate change. The effect variability of key input data on the climate change impacts in section 3.4 gives an impression of the variability in other the impacts driven by N fertilisation and diesel use.
The two human toxicity impacts (cancer and non-cancer) are slightly lower for the PI-resistant scenarios than the default scenario, because they are influenced by the reduction in fungicide use. However, they are more affected by heavy metal emissions so that the trends is less clear and more uncertain than for freshwater ecotoxicity. There is hardly any difference between the three scenarios for fossil and mineral resource use impacts. This is because they are determined by diesel consumption and the use of production infrastructure, respectively, which do not change much between scenarios. Data limitations in Section 4.1, including the potential variability in crop protection use, and methodological limitations in Section 4.2.

***Table 2*** *Qualitive indications of drivers of all environmental impacts (italic = discussed in report)*

| **Impact Category** | **Drivers** | **Difference between scenario 1 (default) and scenarios 2 and 3** |
|---|---|---|
| *Climate Change* | *N fertilisation, Diesel Use* | *Lower or the same* |
| Acidification | N fertilisation, Diesel Use | Lower or the same |
| Particulate Matter | N fertilisation, Diesel Use | Lower or the same |
| Eutrophication (marine, terrestrial, freshwater) | N fertilisation, Diesel Use | Lower or the same |
| Photochemical ozone depletion | N fertilisation, Diesel Use | Lower or the same |
| *Freshwater ecotoxicity* | *N fertilisation, Diesel Use, Crop protection* | *Lower* |
| Human toxicity – cancer | N fertilisation, Diesel Use, Heavy metal emissions | Slightly lower |
| Human toxicity – non-cancer | N fertilisation, Diesel Use, Heavy metal emissions | Slightly lower |
| Fossil Resource Use | Diesel Use | Lower or the same |
| Mineral Resource Use | Production Infrastructure Use | Lower or the same |
| *Land Use* | *Ware potato cultivation* | *Lower or the same* |

## 3.4 Highly variable N fertilisation and diesel use cause high variability in all environmental impacts

The most important input data points were varied and the effect on the environmental impacts was studied for the default scenario (scenario 1). The major contributions to all environmental impact categories are field emissions and diesel production & combustion for mechanised labour. Thus, the total N application and the diesel use in the field were varied in the variability analysis, according to the sections "Diesel Usage" and "Fertilisation: Animal Manure & Chemical Fertiliser" in Section 2.2. The current dataset on fertilisation and diesel is a hybrid of national statistics and field experiences, aimed at identifying realistic upper and lower limits of actual practices across the whole of the Netherlands, under the same yield. The climate change impact is discussed below since this impact is more strongly differentiated due to diesel and N application variation than ecotoxicity and this impact represents trends in other environmental impacts.

The variation in animal manure application results in highly variable climate change impact of the typical conventional ware potato cultivation. Animal manure applications were estimated and rounded to range and additional chemical fertiliser was derived (see Table 3). This results in -21% and +23% differences for ware potatoes against the climate change impact of the default scenario (scenario 1) (see Figure 9). Impact of field emissions range and fertiliser production impacts show a very wide range. Because their limited relative contribution, variation in manure and chemical fertilisation in seed potato cultivation does not significantly affect the climate change impact of ware potato cultivation.

***Table 3*** *Summarised overview of scenarios used in the variability analysis*

| Variable (kg N/ha and L/ha) | Cultivation | Typical (scenario 1.) | High Animal Manure | Low Animal Manure | High Fertiliser | Low Fertiliser | High Diesel | Low Diesel |
|---|---|---|---|---|---|---|---|---|
| Animal N | Ware | 185 | 300 | 200 | 100 | 0 | 185 | 185 |
| Fertiliser N | Ware | 90 | 100 | 0 | 300 | 200 | 90 | 90 |
| Animal N | Seed | 0 | 200 | 100 | 50 | 0 | 0 | 0 |
| Fertiliser N | Seed | 140 | 50 | 0 | 200 | 100 | 140 | 140 |
| Diesel | Ware | 304 | 304 | 304 | 304 | 304 | 410 | 192 |
| Diesel | Seed | 295 | 295 | 295 | 295 | 295 | 419 | 198 |

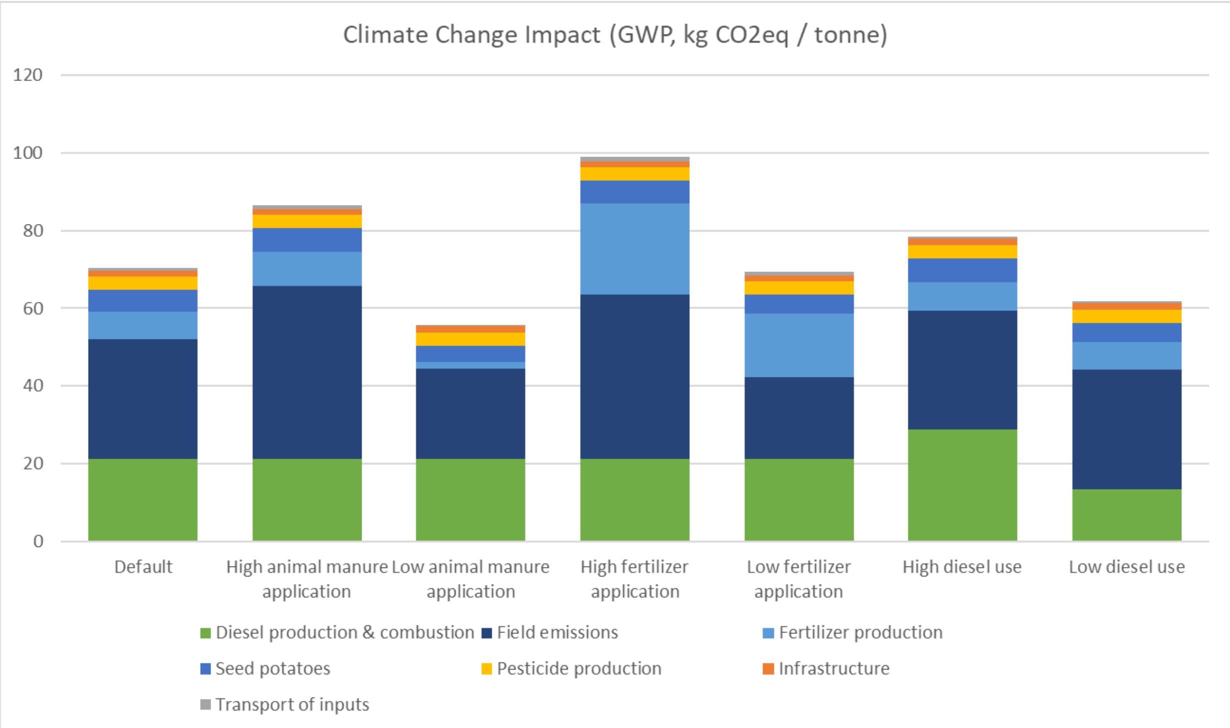


***Figure 8*** *Climate change impacts (global warming potential, GWP) of ware potato cultivation in kg CO2-eq/tonne of ware potato at farm gate for the variability scenarios*

The variation in chemical fertiliser application results in highly variable climate change impacts relative to the typical scenario, similar to the range due to variation in animal manure application (see Figure 9). The high and low fertiliser scenario are the mirror image of the high and low manure scenario (see Table 2). Both low and high fertiliser use imply that the total amount of fertiliser increases at the expense of manure use, relative to the typical scenario. The range of the total climate change impact is very large too. The impact of fertiliser production ranges from +125% to +223% compared to the default scenario 1. Impact of field emissions range less. The contribution of seed potatoes ranges even less because only fertiliser is used in the typical seed tuber scenario.

The variation in diesel usage results in substantial variation in the climate change impact of the default scenario 1 (+/-12%, see Figure 9). This range is smaller than for the fertilisation scenarios. The diesel usage is approximately one third higher or lower for both ware and seed potato cultivation (see Table 2). The contribution of the diesel production and combustion varies accordingly for ware potato diesel use and to a lesser extent for seed potato diesel use.

# 4 Discussion of limitations and possible extrapolations

## 4.1 Key input data is reasonably representative but highly variable

In general, the current LCA study of potato cultivation in the Netherlands has significantly improved compared to the previous LCA screening study from 2022, thanks to the improved data on fertilisation, diesel use and crop protection. The significant variability in the results can be regarded as the sensitivity of the environmental impact to varying farming practices in response to contextual factors, such as weather, financial costs, soil type, individual preferences. The variability can also be regarded as the uncertainty of the environmental impact across a population of farmers, partly due to natural variability and partly due to other uncertainties. The quality, uncertainty and the sensitivity of the different types of input data will be discussed in the order of importance.

**Fertilisation and diesel use are variable but reasonably certain**
Fertilisation practices in the Netherlands were found to be highly variable and strongly influential on the environmental impacts, with reasonable certainty. The fertiliser data for both the benchmark and the variability scenarios is reasonably representative of the average practice in the Netherlands. The initial KWIN data for fertilisation rather reflected the archetypical situation with a normative perspective. Hence, this data was replaced by a more representative estimation based on LMM data, fertilisation norms and expert data. Ravensbergen (2024) indicated that farmers use up to 500 and 350 kg *effective* N/hectare, for clay and sandy soils respectively, which is above our estimates of the high N use scenarios at 400 kg *total* N/hectare. The average effective nitrogen use from this study likely corresponds with our estimates of total nitrogen use, supporting our findings.

The diesel data is more strongly based on KWIN than the fertilisation data, so that it reflects an archetypical situation. Quantitative inputs from experts' field experience were included, thus eliminating the normative perspective from KWIN. Overall, the diesel use data is sufficiently reliable and both the variability and the contribution in the environmental impacts due to diesel use are reasonably certain. The higher diesel use might occur on clay soil due to heavier tillage or on sandy soil due to higher irrigation demand.

**Crop protection use is highly variable and less certain**
While crop protection use might be under- or overestimated, it is hard to characterise input data variability in order to translate this to environmental impact. The crop protection applications were based on a planned strategy, and under- and overestimations are likely for all three scenarios.

It was assumed for the default scenario 1 all planned treatments were executed. The resulting total crop protection use might be underestimated because the strategy is based on the more effective products that are actually allowed on the market, while in practice higher quantities and phased-out products might be used. The total crop protection use might also be overestimated, because not all treatments may be executed: the field expert decided to do less treatments supported by a decision support system driven by weather conditions, even in the rainy summer of 2024 with high PI pressure. In practice, a substantial share of farmers use a decision support system.

The crop protection data for the PI-resistant scenarios 2 and 3 are an imprecise but accurate representation of the expected effect of the resistance on fungicide use: After the 2024 season of field trials, the difference in number of fungicide treatments between non-resistant and resistant varieties turned out to be 18-100%, while the estimate was 50%.

**Yield and other input data is reasonably robust**
The yield taken directly from KWIN may not be fully representative of the Dutch average: The LMM dataset did not allow determination of a representative average yield but it indicated significant variability does exist. Yield was not included in the variability analysis because the independent variation could not be isolated from the variation dependent on fertiliser and diesel use. Moreover, the effect of independent variation is trivial: a 10% decrease in yield increases all environmental impacts by 10%. It is not likely high fertilisation and diesel use result in higher yields, because yields in the Netherlands are high already. Nor is it likely low fertilisation and diesel use would limit yields, since the low fertilisation estimates were above or close to the N application level critical for a good yield from Ravensbergen (2024).

The contributions to the environmental impacts of infrastructure, pesticide production, transport and seedling production (including seed production) are relatively small. The data on these themes is less certain but the environmental impacts are not sensitive to variation in these inputs. Manure transport would have a small but significant impact if all of the transport would be allocated to the potato production. The impact of alternative propagation scenarios is described in the third paragraph of the discussion.

## 4.2 Methodological limitations influence environmental impacts, but less strongly than variability in input data

In addition to limitations in the input data, there are methodological limitations in the current study, which are discussed below, in order of importance.

**Fertiliser emission calculations**
Fertiliser emission calculations are determined by the nitrogen application of different types of manure and chemical fertiliser and by the default parameterisation chosen in Broekema et al. (2024). This method results in structural uncertainty because soil type is not sufficiently considered and weather conditions and farming practices are not considered, but it is compliant to widely accepted methods and the input data is usually available.

**Characterisation methods**
The robustness of the characterisation method for different environmental impacts is variable. Climate change impacts are widely researched so that the relation between the emissions and the impact of climate change is robust and state-of-art. Furthermore, land occupation and land transformation can be transformed to a net land use impact, but this impact is not a good proxy for the total impact on biodiversity. Freshwater ecotoxicity impact cannot be quantified robustly because the causal chain between emission and eventual impact remains challenging to model, because of several uncertain factors: the distribution of a pesticide application over the emission compartments (soil, water, air), the fate behaviour of any chemical in the environment, the inherent toxicity of chemicals and ecosystem level dose-response relationships.

**Metal emissions**
In contrast to commonly used databases such as AgriFootprint (Blonk et al., 2022), heavy metal emissions from manure application were allocated to animal production. This allocation choice is currently under debate in the LCA community. If the seven major heavy metal emissions to soil and waterdue to manure application from AgriFootprint were included, the freshwater ecotoxicity impact would increase by 35% in the default scenario and human toxicity would increase by a factor of 20-50. This indicates human toxicity is much more strongly affected by heavy metal emissions. It also indicates heavy metal emissions are relevant for ecotoxicity and that a fungicide use reduction would have an even lower effect on the total ecotoxicity impact. In addition to the uncertainty due to the allocation choice, it is moreover hard to estimate the metal contents and emissions specifically for the manure considered in this study.

## 4.3 Substantial uncertainty in the effect of propagation routes that eliminate seed tuber cultivation

The current LCA studied the most feasible propagation route on the short term: route 1 from Section 1.1 (i.e., grow a transplant from true potato seed in year -2 and produce seed tubers, grow seed tubers from these seed tubers in year -1 and grow ware potatoes from these seed tubers in year 0). The results showed that there is at most a small difference in climate change, freshwater ecotoxicity and land use impacts between this propagation route and conventional propagation. However, there are various perspectives on the propagation system. It should be noted that the phytosanitary and logistic benefits of True Potato Seeds would also be more relevant if seed tuber cultivation would be eliminated like in propagation routes 2 and 3. It is discussed below how the propagation routes would affect the environmental impact of ware potato cultivation.

**Sufficient robustness of propagation route 1**

The studied propagation route 1 is quite robust in terms of data and results for the seeds and seedlings used. Only the final year of seed tuber cultivation has a significant contribution. The contribution to the climate change impact of the fore last round of seed potato cultivation scenarios is <1%, and the round before that <0.1%, etc. This also supports the robustness of the current results regarding the propagation system: if 1 or more rounds of seed tuber cultivation are included in the scenario, the environmental impacts will not be sensitive to the impact of seed or seedling cultivation or to the eventual number of years of seed tuber cultivation (the parameter r in Section 2.1). Moreover, the environmental impacts will not be sensitive to realistic variations in the seeding rate of seed potatoes.

**Indications on the effect of propagation route 2 and 3**

The climate change impacts and ecotoxicity impacts of ware potato cultivation would increase under propagation route 2 with seedlings and decrease under propagation route 3 with seeds. Land use would decrease under both scenarios. In contrast to route 1, the contribution of seed potato cultivation would be eliminated (8-9% to climate change, freshwater ecotoxicity and land use),[9] but the alternative propagation would have a substituting impact. Around 100 times more seedlings or seeds are needed per hectare of ware potato for routes 2 and 3, compared to route 1, in which two years of seed tuber cultivation limit the number of seeds and seedlings required at the start of the propagation.[10] A rough sensitivity analysis shows that using seedlings (route 2) might increase the climate change impact of ware potato cultivation by 10-15%, compared propagation route 1. This is because seedlings have a relatively high impact due to electricity use and direct emissions from fertilisation and substrate use. Another sensitivity analysis shows that using seeds (route 3) results in a smaller impact of ware potato cultivation compared to route 1, because seeds have a relatively low impact.

**Limited robustness of the effects of propagation route 2 and 3**

These predicted changes are highly uncertain due to uncertainties for both propagation and in-field cultivation. The contribution of seedlings and seeds in alternative propagation routes would be larger, while the data quality is limited and future developments are hard to predict. During the research, stakeholders mentioned that seedling cultivation could be optimised with regards to lighting, the growing cycle and the seedling density. It is not clear if such optimisation is critical or merely beneficial for direct cultivation of ware potatoes from seedlings. A sensitivity analysis shows that such optimisation seems to result in a strong net increase of the environmental impacts of seedling cultivation. Furthermore, it has not been possible to quantify realistic scenarios for the in-field cultivation from seedlings or seeds. For both alternative propagation routes, the in-field cultivation would require more water and higher or lower levels of fertilisation and diesel use, and probably more manual and/or chemical weed control.

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[9] Eventually, the avoided land and the environmental impact from avoided seed tuber cultivation should materialize into a regional impact reduction on ecosystems and human health. This is not certain: seed tuber cultivation would most likely be replaced by another arable crop, and the space that the arable crop frees elsewhere will be replaced by another crop, etc. A substantial analysis should be done to determine whether actual reductions are achieved. Such analysis can be done with an economic equilibrium model or a consequential LCA, which were not in the scope of this study.

[10] 3,000 kg of seed tubers are required for 1 ha of ware potato cultivation (KWIN data); 5,180 kg of seed tubers would yield 38,500 kg of seed tubers (KWIN data); 66,667 potato plants are grown on 1 ha, requiring this number of either seed tubers, seedlings or seeds. 3,000/38,500 = 0.078 ha of seed tuber cultivation is required for the ware potato cultivation in year -1, and 0.078*5,180/38,500 = 0.010 ha of seed tuber cultivation is required in year -2. On this area, 0.010*66,667 = 699 plants are planted.

## 4.4 More variable environmental impacts outside the Netherlands indicate a larger optimisation potential

It will be discussed below how the new potato varieties and variations in agronomy can influence the environmental impacts outside the specific context of this study, according to climate change impact as a proxy for all environmental impacts. Europe as a whole serves as the region outside the geographical scope of this study for which extrapolation is discussed.

**Agronomic practices vary more widely outside the Netherlands**
Practices differ widely across Europe, because it is a larger area with different climates and soil types. As a consequence of this variability in context and practices, yield and agronomic factors vary strongly across Europe (see Table 4). In Northwestern Europe, potatoes are grown in a favourable season with long days and nearly ideal temperatures and usually plenty of rainfall, with a high degree of mechanisation and irrigation technology (Goffart et al., 2022). In Northeastern Europe, the growing season is shorter due to colder winters and rainfall is sufficient, with a variable level of technology and limited irrigation (Geling, 2024). In Southwestern Europe, potatoes are planted in winter and harvested late spring because of the mediterranean climate with the yields being limited by irrigation (Geling, 2024; Pedersen et al., 2005). In Southeastern Europe, soils and the low rainfall due to the local climates seem to be limiting yields while a low degree of irrigation and mechanisation may occur (Pedersen et al., 2005; Ştefan et al., 2023). Some sources indicate that fungal diseases and their treatments are more frequent in Southern Europe (Adekanmbi et al., 2023; Kroschel et al., 2020).

***Table 4*** *Key agronomic variables for ware potato cultivation across Europe, composed from different sources.*

| | Yield (t/ha) / Geography | Animal manure (kg N/ha) / Geography | Chemical fertiliser / Geography | Diesel use / Geography |
|---|---|---|---|---|
| Lowest estimate | 16, Bulgaria[1] | 0, Italy, Denmark[3] | 60, Cyprus[5] | 124, minimum[6] Northeast |
| Lowest regional average | 26, Southeast | Not sufficient data | 100, Northeast | 196, Northeast[6] |
| Highest regional average | 43, Northwest | Not sufficient data | 130, Northwest | 320, Southeast[6] |
| Highest estimate | 51, Netherlands[2] | 185, Netherlands[4] | 165, Greece[5] | 414, maximum Southeast[6] |

Some sources are uncertain and averaging has been done across different sources, so numbers should be taken with caution. (1) Eurostat (2024), (2) (van der Voort, 2022), (3)(Köninger et al., 2021), (4)(Kik, 2023), (5)(IFAstat, 2024), (6) calculated according to section 2.2

**Environmental impacts will be more variable outside the Netherlands**
Given this range in agronomic practices, the environmental impacts and their improvement potential will also be highly variable outside the Netherlands. The variability in the estimated usages in animal manure, chemical fertiliser and diesel across European regions is similar to the variability in these usages within the farmer population in the Netherlands. Furthermore, the yields across Europe are variable but usually lower than in the Netherlands, so that the environmental impacts across Europe will be higher. The variability in environmental impacts of potato cultivation across European regions will be similar in magnitude as the variability in impacts shown in this study's variability assessment.

**A wider range of innovations could optimise environmental impacts outside the Netherlands**
For Europe as a whole, there could be more potential than for the Netherlands to optimise yield, fertilisation and diesel use. One could think of precision agriculture techniques such as variable rate technology (Bohman et al., 2019), irrigation management (Dubois et al., 2021) and yield mapping (Tang et al., 2020). Innovations like those may have a stronger effect on environmental impacts than the introduction of TPS or of PI-resistant varieties. It should be noted TPS introduction through seedlings or seeds (propagation routes 2 and 3) might be challenging in more demanding climates outside Northwestern Europe, while the introduction of PI-resistant seed tubers (route 1) is less challenging. On the other hand, in regions where fungal diseases or fungicide applications are indeed more frequent, PI-resistant varieties will have a stronger effect than shown in this study. Moreover, the introduction of new varieties and agronomic optimisation could actually go hand in hand.

## 4.5 Results are sufficiently valid to draw conclusions, despite limitations

First, it should be noted that the input data is sufficiently robust and the environmental impacts are reasonably in line with previous studies. Notably, Haverkort & Hillier (2011) estimate a climate change impact of 77 kg $CO_2$-eq per tonne of ware potatoes. Because of some differences in source data and methods, specifically N-fertilisation and background data, the results cannot be used for a trend analysis. Trends that influenced the climate change impact over more than a decade, are the increased use of cover crops which maintain N in the soil in the spring and provide N in spring, and the reduction in animal manure use. The use of animal manure seems to be underestimated for ware potatoes in Haverkort & Hillier, while cover crops were out of scope in both studies.

The limitations listed in Sections 4.1 and 4.2 are such that this assessment cannot be regarded as compliant with the general ISO standards for LCA (14040/44:2006). No external review for ISO compliance has been pursued. On the positive side regarding ISO compliance, the variability analysis serves as a sensitivity analysis and the interpretation step has been sufficiently thorough with the current and previous paragraph.

In summary, while limitations remain, the results are a good basis to draw conclusions on the research questions. The uncertainty and the representativeness in the most impactful input data, fertilisation and diesel use (Section 4.1), are the most important limitations. The methodological limitations (Section 4.2) are of secondary importance. Because of the uncertainty on the other two propagation routes (Section 4.3), it has been kept out of scope. The variability assessment (Section 3.4) in this study supports the validity of the conclusions within the Netherlands. The discussion on agronomic practices outside the Netherlands (Section 4.4) indicates some points of attention but also a potential for extrapolation of these conclusions.

# 5 Conclusion & Recommendations

## 5.1 Conclusion: resistance to *Phytophthora infestans* and TPS-based propagation do not significantly affect most of the environmental impacts of ware potato cultivation

Three scenarios were analysed in this study: the default scenario of conventional cultivation (1), and two scenarios considering the innovations of PI-resistance and TPS-based propagation: cultivation of a PI-resistant resistant variety with (PI-resistant) conventional propagation (2), and cultivation of a PI-resistant variety with TPS-based propagation with two years of seed tuber cultivation (3). Conclusions on the research questions are drawn below.

**Main research question: What are the differences in environmental impacts between the cultivation of conventional ware potato and the cultivation of PI-resistant ware potato varieties, which are propagated either conventionally or from True Potato Seeds (TPS)?**
It can be concluded both innovations scenarios do not significantly influence most of the environmental impacts. PI resistance will lead to a lower freshwater ecotoxicity impact, but the extent of this reduction cannot be quantified. The studied route of TPS-based propagation will not eliminate seed tuber propagation and hence not influence environmental impacts. It is highly uncertain to what extent newer, shorter, TPS-based propagation routes will increase or reduce environmental impacts. PI resistance and TPS-based propagation do not strongly affect nitrogen fertilisation and diesel use, while variation in potato cultivation across the Netherlands does. This variation implies that optimisation of the agronomic practices would more strongly influence the environmental impacts than the innovations.

1. **What is the climate change impact of ware potato cultivation without and with the innovations?**

The average climate change impact of ware potatoes is around 70 kg $CO_2$-eq per tonne for all three scenarios. Field emissions due to nitrogen fertilisation and diesel production & combustion contribute most to the climate change impact. The use of fertilisation and diesel is not strongly affected by the PI resistance or the TPS-based propagation. Therefore, these innovations will probably not affect climate change impact.

2. **What is the freshwater ecotoxicity impact of ware potato cultivation without and with the innovations?**

The freshwater ecotoxicity impact of ware potatoes ranges around 550 CTUe per tonne for all three scenarios. Field emissions due to nitrogen fertiliser and diesel production & combustion contribute are major contributors, which are hardly affected by the innovations. The cultivation scenarios of PI-resistant varieties, through either conventional or TPS-based propagation, indicate a small decrease in freshwater ecotoxicity impact due to less fungicide application and fungicide production.

3. **What are other environmental impacts of ware potato cultivation without and with the innovations?**

The effect of the innovations on other environmental impacts will be limited. Many of the environmental impacts are driven by nitrogen fertilisation and diesel use, like climate change impact, and will not be strongly affected by the innovations. The innovation of PI resistance reduces fungicide use and diesel use; it slightly affects toxicity impacts. The innovation of TPS-based propagation reduces the number of years for seed tuber cultivation but does not eliminate seed tuber cultivation altogether; its effect is negligible across all impacts.

4. **What is the variability in the environmental impacts of ware potato cultivation due to current agronomic practices (without the innovations)?**

Climate change impacts and most of the other environmental impacts are very sensitive to real variations in the of nitrogen fertilisation (both animal manure and chemical fertiliser) and to diesel use across the Netherlands. Climate change impact of the benchmark scenario (scenario 1) can range from 55 to 100 kg

$CO_2$-eq per tonne due to single effects of fertilisation or diesel use. A similar variability in the average climate change impact of ware potatoes is suspected across Europe.
Freshwater ecotoxicity impacts are sensitive to the crop protection strategy against all diseases, both *Phytophthora infestans* and others. Furthermore, the crop protection strategy is variable across farmers and the amount of avoided fungicide thanks to the resistance is uncertain. The methods to estimate emissions from crop protection applications and to convert these emissions into toxicity impacts are relatively uncertain.

## 5.2 Recommendations on agronomic optimisation and more broadly informed environmental assessment

Given the concluding remarks, it is recommended that the use of manure, fertiliser and diesel are optimised across potato farmers in the Netherlands. Optimisation and intensification in potato farming are driven by farm economics and national policy on manure and crop protection, and farmers indicate that efficiency might increase and yields might be lower in the future (Ravensbergen, 2024). The significant variation in agronomic practices implies that a large share of the arable farmers could improve their environmental impacts by learning from their more efficient peers. For example, the archetypical total nitrogen application is 275 kg N/ha and a realistic maximum is 400 kg N/ha according to this study, while this could be reduced to 200 kg *effective* N/ha in the Netherlands (Ravensbergen, 2024). For a share of these farmers this means taking more risk in terms of fertilisation, irrigation, crop protection and soil preparation.

In the context of intensive potato cultivation in the Netherlands, innovations like disease resistance, new propagation and precision farming may have a small but significant potential. There are three current challenges in disease management in potato cultivation (Evenhuis, 2024): 1) Crop protection products are taken from the market; 2) Pathogens become resistant against commonly used crop protection products; 3) In practice, a part of the yield gap is caused by disease.

Given these challenges, stacked disease resistance is a good way to maintain yield levels and potentially increase them. Under the same yields, the freshwater toxicity impact will be reduced to some extent and other environmental impacts of potato cultivation will stay the same. Increased yields will reduce the environmental impacts per mass unit of potato cultivation. In addition to disease management, sustainable soil management, a broader rotation could increase yields or support current yield levels (Kik, 2023; Ravensbergen, 2024).

There are interactions between the in-field agronomy, the genetics of a new variety and the propagation route so that efficiency improvements and innovations could be a mix of interventions. Therefore the optimisation of technical, commercial and environmental factors should be integrated with the introduction of new varieties and propagation routes. Acknowledging the differences in the natural, economic and technical context of potato cultivation, there is a bigger potential for optimisation and innovation across Europe than within the Netherlands.

Despite the significant improvements in this study compared to first LCA from 2022, several improvements can be prioritised regarding the environmental assessment itself. For a start, the integration of the newest LCI and LCIA methods would improve the general quality of this LCA. This can only happen if collection and validation of field data for all agronomic inputs become more detailed. Furthermore, including different crop protection strategies from practice would make results more informative.

Given the general limitations in input data collection and LCA methodology, broader recommendations regarding future research can be defined. It is recommended to enhance the variability analysis, by collecting variability information on all input data and to separate actual uncertainty and natural variability. On top of that, with this variability information a structured uncertainty propagation could focus input data collection and the interpretation of the results. Moreover, a broader effort in constructing a larger number of more detailed innovation scenarios, integrating more practical knowledge from farmers, as well as from academic and industrial researchers could provide some deeper insights to the potato breeders, farmers and processors. Such a broader study would ideally consider the innovation adoption dynamics and techno-economic factors in its assessment.

# Sources and literature


Adekanmbi, T., Wang, X., Basheer, S., Nawaz, R.A., Pang, T., Hu, Y., & Liu, S. (2023). Assessing Future Climate Change Impacts on Potato Yields — A Case Study for Prince Edward Island, Canada. *Foods*, *12*(6), 1176. https://doi.org/10.3390/foods12061176

Bassi, A., Biganzoli, S., Ferrara, F., Amadei, N., Valente, A., Sala, A., & Ardente, S. (2023). *Updated characterisation and normalisation factors for the Environmental Footprint 3.1 method*. https://doi.org/10.2760/798894

Blonk, H., Tyszler, M., Van Paassen, M., Braconi, N., Draijer, N., & Van Rijn, J. (2022). *Agri-footprint 6 Methodology Report Part 1: Methodology and basic principles About us Title Agri-footprint 6 Methodology Report*. www.blonksustainability.nl

Bohman, B.J., Rosen, C.J., & Mulla, D.J. (2019). Evaluation of Variable Rate Nitrogen and Reduced Irrigation Management for Potato Production. *Agronomy Journal*, *111*(4), 2005–2017. https://doi.org/10.2134/agronj2018.09.0566

Broekema, R., Helmes, R., Vieira, M., Hopman, M., Gual Rojas, P., Ponsioen, T., Weststrate, J., & Verweij-Novikova, I. (2024). *Product environmental footprint category rules for cut flowers and potted plants : Final version*. https://doi.org/10.18174/549543

Dubois, A., Teytaud, F., & Verel, S. (2021). Short term soil moisture forecasts for potato crop farming: A machine learning approach. *Computers and Electronics in Agriculture*, *180*, 105902. https://doi.org/10.1016/j.compag.2020.105902

Eurostat. (2024). Yield data on potato cultivation across Europe. In *https://ec.europa.eu/eurostat/databrowser/view/tag00103/default/table?lang=en&category=t_agr.t_apro.t_apro_cp*.

Evenhuis, B. (2024). *Crop protection strategy against phytphthora infestans for Dutch field trials by WUR in 2024*. Wageningen University & Research.

Fantke, E.P., Huijbregts, M., Margni, M., Hauschild, M., Jolliet, O., Mckone, T., Rosenbaum, R., & Van De Meent, D. (n.d.). *USEtox ® User Manual USEtox ® User Manual USEtox ® 2.0 User Manual (Version 2)*. http://usetox.org

Geling, E. (2024). *Yield gap analysis of potato in the major production areas of Europe MSc thesis, Plant Production Systems*.

Goffart, J.P., Haverkort, A., Storey, M., Haase, N., Martin, M., Lebrun, P., Ryckmans, D., Florins, D., & Demeulemeester, K. (2022). Potato Production in Northwestern Europe (Germany, France, the Netherlands, United Kingdom, Belgium): Characteristics, Issues, Challenges and Opportunities. In *Potato Research* (Vol. 65, Issue 3, pp. 503–547). Springer Science and Business Media B.V. https://doi.org/10.1007/s11540-021-09535-8

Greijdanus, A., & Hoogeveen, M. (2024). *"LMM data extract": confidential and processed data extract from the National Monitoring system Manure Policy (Landelijk Meetnet Mestbeleid, LMM), subset of the Dutch FADN*. Wageningen University & Research.

Haverkort, A.J., & Hillier, J.G. (2011). Cool Farm Tool - Potato: Model Description and Performance of Four Production Systems. *Potato Research*, *54*(4), 355–369. https://doi.org/10.1007/s11540-011-9194-1

Haverkort, A.J., Struik, P.C., Visser, R.G.F., & Jacobsen, E. (2009). Applied Biotechnology to Combat Late Blight in Potato Caused by Phytophthora Infestans. *Potato Research*, *52*(3), 249–264. https://doi.org/10.1007/s11540-009-9136-3

Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F., Stam, G., Verones, F., Vieira, M.D.M., Hollander, A., Zijp, M., & van Zelm, R. (2016). *ReCiPe 2016 A harmonized life cycle impact assessment method at midpoint and endpoint level Report I: Characterization*.

IFAstat. (2024). Data on chemical fertilizer for potato cultivation across Europe. In *https://www.ifastat.org/databases/plant-nutrition*.

Kacheyo, O.C., de Vries, M.E., van Dijk, L.C.M., Schneider, H.M., & Struik, P.C. (2024). Agronomic consequences of growing field-transplanted hybrid potato seedlings. In *Crop Science* (Vol. 64, Issue 3, pp. 1093–1111). John Wiley and Sons Inc. https://doi.org/10.1002/csc2.20997

Kacheyo, O.C., & van der Vossen, E. (2024). *Personal Communication on diesel use and fertilizer use during the cultivation of True Potato Seed (TPS) and derived seedlings and tubers*.

Kessel, G.J.T., Mullins, E., Evenhuis, A., Stellingwerf, J., Cortes, V.O., Phelan, S., van den Bosch, T., Förch, M.G., Goedhart, P., van der Voet, H., & Lotz, L.A.P. (2018). Development and validation of IPM strategies for the cultivation of cisgenically modified late blight resistant potato. *European Journal of Agronomy*, *96*, 146–155. https://doi.org/10.1016/j.eja.2018.01.012

Kik, M. (2023). *The economic value of sustainable soil management* [Wageningen University]. https://doi.org/10.18174/639907

Köninger, J., Lugato, E., Panagos, P., Kochupillai, M., Orgiazzi, A., & Briones, M. J. I. (2021). Manure management and soil biodiversity: Towards more sustainable food systems in the EU. *Agricultural Systems*, *194*, 103251. https://doi.org/10.1016/j.agsy.2021.103251

Kroschel, J., Mujica, N., Okonya, J., & Alyokhin, A. (2020). Insect Pests Affecting Potatoes in Tropical, Subtropical, and Temperate Regions. In *The Potato Crop* (pp. 251–306). Springer International Publishing. https://doi.org/10.1007/978-3-030-28683-5_8

Masson-Delmotte, V., Pörtner, H.O., Skea, J., Slade, R., Ferrat, M., Neogi, S., Pereira, J.P., Kissick, K., Buendía, E.C., Connors, S., Haughey, E., Pathak, M., Vyas, P., Belkacemi, M., Zhai, P., Roberts, D., Shukla, P. R., van Diemen, R., Luz, S., … Malley, J. (2022). Climate Change and Land: An IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. In *Climate Change and Land: An IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*. Cambridge University Press. https://doi.org/10.1017/9781009157988

Nemecek, T., Antón, A., Basset-Mens, C., Gentil-Sergent, C., Renaud-Gentié, C., Melero, C., Naviaux, P., Peña, N., Roux, P., & Fantke, P. (2022). Operationalising emission and toxicity modelling of pesticides in LCA: the OLCA-Pest project contribution. *International Journal of Life Cycle Assessment*, *27*(4), 527–542. https://doi.org/10.1007/s11367-022-02048-7

Nemecek, T., Bengoa, X., Lansche, J., Roesch, A., Faist-Emmenegger, M., Rossi, V., Sébastien, H., & Agroscope, ). (2019). *World Food LCA Database Methodological Guidelines for the Life Cycle Inventory of Agricultural Products With contributions from Patrik Mouron (1) and Eliane Riedener (1) (up to version 3.0) 2*. www.agroscope.admin.ch

Pant, R. ., & Zampori, L. (2019). *Suggestions for updating the organisation environmental footprint (OEF) method*. Publications Office of the European Union.

Pedersen, S.M., Bizik, J., Costa, L.D., Coutinho, J., Dolezal, F., & Gluska, A. (2005). Production of Table Potatoes in Europe - A Multinational Gross Margin Analysis. *International Farm Management Association (IFMA) > 15th Congress, Campinas SP, Brazil, August 14-19, 2005*, 246–254.

Pré Sustainability. (2024, September 30). *SimaPro 9.5 software description*. Www.Simapro.Com/.

Ravensbergen, P. (2024). *Exploring variability in yield, resource use efficiency and environmental impact of ware potato production in the Netherlands* [Wageningen University]. https://doi.org/10.18174/646034

RVO. (2024). Tabel 2 Stikstof landbouwgrond. In *https://www.rvo.nl/sites/default/files/2023-02/Tabel-2-Stikstof-landbouwgrond-2023.pdf*. Rijksdienst Voor Ondernemend Nederland.

Solynta. (2024, September 30). *Website of Solynta*. Www.Solynta.Com.

Ştefan, F.M., Chiru, S.C., Iliev, P., Ilieva, I., Zhevora, S.V., Oves, E.V., Polgar, Z., & Balogh, S. (2023). Potato production in Eastern Europe (Romania, Republic of Moldova, Russia and Hungary). In *Potato Production Worldwide* (pp. 381–395). Elsevier. https://doi.org/10.1016/B978-0-12-822925-5.00005-0

Tang, S., Farooque, A.A., Bos, M., & Abbas, F. (2020). Modelling DUALEM-2 measured soil conductivity as a function of measuring depth to correlate with soil moisture content and potato tuber yield. *Precision Agriculture*, *21*(3), 484–502. https://doi.org/10.1007/s11119-019-09678-2

van der Voort, M.P.J. (2022). *KWIN-AVG 2022: Kwantitatieve Informatie Akkerbouw en Vollegrondsgroenteteelt*. Wageningen University & Research, Business unit Open Teelten.

van Dijk, L.C.M., Lommen, W.J.M., de Vries, M.E., Kacheyo, O.C., & Struik, P.C. (2021). Hilling of Transplanted Seedlings from Novel Hybrid True Potato Seeds Does Not Enhance Tuber Yield but Can Affect Tuber Size Distribution. *Potato Research*, *64*(3), 353–374. https://doi.org/10.1007/s11540-020-09481-x

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2016). The ecoinvent database version 3 (part I): overview and methodology. *The International Journal of Life Cycle Assessment*, *21*(9), 1218–1230. https://doi.org/10.1007/s11367-016-1087-8

# Appendix 1 Core input data

***Table 5*** *Core data used for the 3 scenarios in the LCA, for ware potatoes and the seed potatoes used as propagation material in each scenario. If a cell is left blank, the value to the left is used. Sources are indicated in the notes*

| Variable | Unit | Scen. 1 Ware | Scen. 2 Ware | Scen. 3 Ware | Scen. 1 Seed | Scen. 2 Seed | Scen. 3 Seed | Notes |
|---|---|---|---|---|---|---|---|---|
| Yield | kg | 50500 | | | 38500 | | | (1) |
| Seeding rate, the integral over all rounds, only for ware | kg / ha | 3466 | 3466 | 3404 | N/A | | | (1),(2) |
| Net number of seedlings used | n | N/A | | | 0 | 0 | 699 | (2) |
| Basic infrastructure | ha | 1.0 | | | 1.0 | | | |
| Irrigation volume | m3 / ha | 600 | | | 600 | | | (1),(3) |
| Total diesel use for field operations | MJ / ha | 10937 | 10401 | 10401 | 10615 | 9972 | 9972 | (1),(2), (3) |
| Electricity, mostly for storage | kWh / ha | 0 | | | 943 | | | (1) |
| **Fertilisation** | | | | | | | | |
| N from all Manure | kg N / ha | 185 | | | 0 | | | (2),(4) |
| Mass of Cattle Manure | kg wet mass / ha | 28675 | | | 0 | | | (2),(4) |
| Mass of Pig Manure | kg wet mass / ha | 10493 | | | 0 | | | (2),(4) |
| N from all chemical fertiliser | kg N / ha | 90 | | | 140 | | | (2),(4) |
| Mass of all N Fertiliser | kg / ha | 314 | | | 488 | | | (2) |
| Ammonium sulphate | kg /ha | 12 | | | 19 | | | (2) |
| Urea | kg /ha | 32 | | | 49 | | | (2) |
| Liquid urea-ammonium nitrate solution | kg /ha | 34 | | | 52 | | | (2) |
| Calcium ammonium nitrate | kg /ha | 236 | | | 368 | | | (2) |
| P from all P fertiliser: Triple superphosphate | kg /ha | 0 | | | 83 | | | (2) |
| Total K added (partial total for ref data) | kg /ha | 306 | | | 306 | | | (2) |
| Potassium chloride | kg /ha | 272 | | | 272 | | | (2) |
| Potassium sulfate | kg /ha | 33 | | | 33 | | | (2) |
| Limestone | kg /ha | 100 | | | 100 | | | (2) |
| Mass of all Fertiliser (N, P, K, Lime) | kg /ha | 619 | | | 877 | | | (2) |
| **Emission Calculation Results** | | | | | | | | |
| $NH_3$ emissions | kg $NH_3$/ha | 62.3 | | | 10.24 | | | (2) |
| Total $CO_2$ emission | kg $CO_2$/ha | 67.1 | | | 79.98 | | | (2) |
| Total $N_2O$ emissions (dinitrogen monooxide) | kg $N_2O$/ha | 5.42 | | | 2.48 | | | (2) |
| NOx emissions | kg $NO_x$/ha | 36.1 | | | 18.40 | | | (2) |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **$NO_3$ emissions to water - total** | kg $NO_3$/ha | 72.6 | | | 29.24 | | | (2) |
| **P emission to freshwater** | kg $PO_4$/ha | 35.9 | | | 17.46 | | | (2) |
| **Crop protection use** | | | | | | | | |
| **Fungicide input** | kg a.i./ ha | 7.68 | 4.02 | 4.02 | 5.41 | 2.44 | 2.44 | (2),(5) |
| **Herbicide input** | kg a.i./ ha | 7.44 | | | 4.44 | | | (2),(5) |
| **Insecticide input** | kg a.i./ ha | 0.32 | 0.02 | 0.02 | 0.02 | 0.07 | 0.07 | (2),(5) |
| **Total liquid pesticide** | kg a.i./ ha | 3.00 | | | 4.05 | | | (2),(5) |
| **Total solid pesticide** | kg a.i./ ha | 12.15 | 8.49 | 8.49 | 5.87 | 2.90 | 2.90 | (2),(5) |
| **Crop protection emissions to soil** | | | | | | | | (6) |
| **oxamyl - H** | g | 0.0 | | | 900 | | | (2),(5) |
| **maleic hydrazide - P** | g | 1499 | | | 1499 | | | (2),(5) |
| **prosulfocarb - H** | g | 3599 | | | 0.0 | | | (2),(5) |
| **metribuzin - H** | g | 270 | | | 270 | | | (2),(5) |
| **ametoctradin - F** | g | 181 | | | 91 | | | (2),(5) |
| **fluazinam - F** | g | 131 | 38 | 38 | 0.0 | | | (2),(5) |
| **fluopicolide - F** | g | 0.0 | | | 59 | 30 | 30 | (2),(5) |
| **azoxystrobin - F** | g | 8.5 | 0.0 | 0.0 | 0.0 | | | (2),(5) |
| **Transport and packaging** | | | | | | | | |
| ***Packaging, for solid fertilisers or pesticides*** | kg | 698 | 694 | 694 | 931 | 928 | 928 | (2) |
| ***Packaging, for liquid fertilisers or pesticides*** | kg | 37 | | | 56 | | | (2) |
| **Seed tuber transport distance to farm or to field** | km | 20 | | | N/A | | | (2) |
| **Transport distance to farm** | km | 100 | | | | | | (2) |
| **Transport distance on farm to field(s)** | km | 2 | | | | | | (2) |
| **Total mass added (inbound transport mass)** | kg | 735 | 731 | 731 | 987 | 984 | 984.0 | (2) |
| **Manure transport distance** | km | 2 | | | | | | (2) |
| **Total mass of manure transported** | kg | 39168 | | | 0 | | | (2) |

1. KWIN data (van der Voort, 2022)
2. Assumptions or calculations explained in 2.2 Data collection, or aggregated numbers
3. Expert estimate (Kik, 2023)
4. LMM Data (Greijdanus & Hoogeveen, 2024)
5. Crop protection strategy (Evenhuis, 2024)
6. Soil emissions shown as illustration, emissions to freshwater and air are also included in the model

# Appendix 2 Fertilisation data

***Table 6*** *Derivation of nitrogen fertilisation input data for the three default scenarios and the variability scenarios (without the rounding in the scenarios in Table 2 and Table 3)*

| **Scenarios and steps** | | **Ware potato** | | **Seed potato** | |
|---|---|---|---|---|---|
| **High Animal Manure scenario** | | **kg N/ha** | **Note** | **kg N/ha** | **Note** |
| **1** | Determine realistic maximum animal manure N application | 300 | (1,2); 96th pct | 200 | (1,2,3); 98.5th pct |
| **2** | Take average fertiliser N application from a range around value from step 1 | 104 | +/-50 range; (1) | 55 | +/-100 range; (1) |
| **High Fertiliser scenario** | | | | | |
| **3** | Use percentile of step 1 to determine maximum fertiliser N application | 315 | 96th pct; (1) | 204 | 98.5th pct; (1) |
| **4** | Take average manure N application from a range around value from step 3 | 77 | +/-50 range; (1) | 34 | 100-max range; (1) |
| **Low Animal Manure and Fertiliser scenarios** | | | | | |
| **5** | Determine absolute minimum of total N application | 150 | (1,3) | 100 | (1,3) |
| **6 for Ware** | Use percentile of step 1 to determine realistic minimum total N application | 186 | 4th pct; (1,4) | - | - |
| **6 for Seed** | Check minimum in LMM data | - | - | 100 | 33th pct; (1) |
| **7** | Check LMM data if fertiliser is applied | 0 | (1,2) | 0 | (1,2) |
| **Medium Animal Manure and Fertiliser scenario** | | | | | |
| **8** | Assume highest norm for total N application in NL is the total N application under "average practice" | 275 | (5) | 140 | (5) |
| **9** | Determine the maximum total N application from the LMM data under "average practice" | 372 | (1,6) | 180 | (1,6) |
| **10** | Determine the median fertiliser N application from the "average practice" range | 90 | 150-372 range;(1) | 140 | (1,2) |
| **11** | Derive the animal manure application from step 8 and 10 | 185 | (1) | 0 | (1,2) |

1. LMM dataset (Greijdanus & Hoogeveen, 2024)
2. Expert estimate (Kik, 2023)
3. Expert estimate (Kacheyo & van der Vossen, 2024)
4. Yield curve (Ravensbergen, 2024)
5. Dutch N fertilisation norms (RVO, 2024)
6. By taking the abovementioned norm as the median and the minimum total N application as minimum, the maximum can be determined from the distribution

*Table 7 Derivation of P fertilisation input data for the three default scenarios and the variability scenarios*

| Scenarios and steps | | Ware potato | | Seed potato | |
|---|---|---|---|---|---|
| **High Animal Manure scenario** | | **kg P2O5/ha** | **Note** | **kg P2O5/ha** | **Note** |
| **1** | Determine maximum P application | 171 | (1,2); 96th pct | 129 | (1,2); 98.5th pct |
| **2** | Calculate P application from manure based on results for N application | 136 | (1) | 91 | (1) |
| **3** | If result step 1 > result step 2, augment with fertiliser P application | 34 | step 1 and 2 | 39 | step 1 and 2 |
| **High Fertiliser scenario** | | | | | |
| **4** | Calculate P application from manure based on results for N application | 45 | (1) | 23 | (1) |
| **5** | If result step 1 > result step 4, augment with fertiliser P application | 125 | step 1 and 4 | 107 | step 1 and 4 |
| **Low Animal Manure scenario** | | | | | |
| **6** | Calculate P application from manure | 91 | (1) | 45 | (1) |
| **7** | Determine recommended P application | 40 | (3) | 40 | (3) |
| **8** | If result step 7 > result step 6, augment with fertiliser P application | 0 | step 6 and 7 | 0 | step 6 and 7 |
| **Low Fertiliser Scenario** | | | | | |
| **9** | P application from fertiliser is taken from P application from manure from step 6 | 91 | step 6 | 45 | step 6 |
| **Medium Animal Manure and Fertiliser scenario** | | | | | |
| **10** | Calculate P application from manure | 84 | (1) | 0 | - |
| **12** | If result step 7 > result step 10, augment with fertiliser P application | 0 | step 7 and 10 | 40 | step 7 and 10 |

1. Fertiliser emission calculations contain N and P contents for different types of wet animal manure, these are used to convert the N application from manure to the P application
2. LMM data (Greijdanus & Hoogeveen, 2024)
3. KWIN data (van der Voort, 2022)

# Appendix 3 Seedling and seed data

*Table 8* *Data on seedling and seed production in greenhouses, explanation on next page.*

| Variable | Unit per reference unit | Seedlings | Notes Seedlings | Seed production | Notes Seeds |
|---|---|---|---|---|---|
| **Productivity** | | | | | |
| Number of products | Number | 104 | (1) | 6700 | (1),(15) |
| Product | - | Seedlings | | Seeds | |
| Reference unit | - | Tray | | m2 | |
| **Materials and energy use** | | | | | |
| Electricity | kWh | 1.7 | (1),(2) | 22.5 | (1),(16) |
| Natural gas | Nm3 | 0.47 | (1),(3) | 17 | (1),(16) |
| Seeds consumed | Number | 104 | (1) | 3.4 | (1),(15) |
| Peat moss | g | 615 | (4) | 5651 | (17) |
| Coconut coir | g | 1024 | (4) | 9419 | (17) |
| Perlite | g | 410 | (4) | 3768 | (17) |
| Water | L | 8.1 | (5) | 43 | (1),(15),(17),(18) |
| PG mix 12-14-2 | g | 4.03 | (6) | 22 | (6) |
| Calcium nitrate | g | 0 | (1) | 0 | (1) |
| Greenhouse construction | m2a | 0.0217 | (7) | 0.50 | (16) |
| **Emissions to air** | | | | | |
| Dinitrogen monoxide | g | 0.008 | (8) | 0.020 | (8) |
| Carbon dioxide, peat oxidation | g | 541 | (8) | 4973 | (8) |
| **Emissions to freshwater** | | | | | |
| Nitrate | g | 1.14 | (8),(9) | 3.05 | (8),(9) |
| Phosphate | g | 0.38 | (10) | 2.59 | (10) |
| **Auxiliary variables (not per reference unit)** | | | | | |
| occupation fraction of trays of floor area | - | 0.85 | (1),(11) | 0.8 | (19) |
| PG mix concentration of N in irrigation water | g/L | 1 | (12),(1) | 1 | (1) |
| N content Fertiliser mix | kg/kg | 0.12 | (1) | 0.06 | (1) |
| P content Fertiliser mix | kg/kg | 0.14 | (1) | 0.18 | (1) |
| Volume Substrate | ml/plug and mL/m2 | 19.7 | (12),(1),(13) | 18838 | (16) |
| fraction_peat | ml/ml | 0.3 | (1),(14) | 0.3 | (1),(14) |
| fraction_coir | ml/ml | 0.5 | (1),(14) | 0.5 | (1),(14) |
| fraction_perlite | ml/ml | 0.2 | (1),(14) | 0.2 | (1),(14) |
| weeks | week | 6 | (1) | 26 | (1),(16) |

1. Kacheyo & van der Vossen (2024)
2. Current scenario: energy bill Feb-May; divided by 4 months and department area; Optimised scenario: energy use = weeks*daysweek*nrhoursday_on*watt_lamps*width_tray*length_tray
3. Gas use for april and may in normal scenario, 8 weeks, conservative; reduced by 1/6 in optimised scenario to go from 6 to 5 weeks seedling cultivation duration
4. Calculated: volume of substrate component = volume of tray well * fraction of substrate component * number of seedlings
5. Assumptions: substrate volume absorbs its own volume of water (i.e. half of the tray volume is water) and 1/8 is evaporated every day, inefficiency of irrigation: 1.5 times more water is given than required; Irrigation volume [L] = Number of seedlings [#] * volume of tray well [L] * irrigation frequency [-] * evaporation fraction [day-1] * seedling cultivation duration [days] * irrigation efficiency factor [-]
6. Calculated: mass of PG mix = irrigation volume * fertigation frequency (half of the irrigation turns) * PG mix concentration in irrigation water
7. Calculated: area-time occupied = (Plugs per tray [number] / Plugs per m2 (number / m2] ) * (Cultivation duration [weeks] / duration of year [weeks]) * Fraction trays on greenhouse floor [-]
8. Calculated with PEF-compliant IPCC Tier I method, corrected an error from 2022 (REF to PEF & IPCC Tier I)
9. Assumed that 1/3 is leached directly and 2/3 leaches with the IPCC-factor 0.3
10. Assuming al P2O5 applied is leached as PO4, very conservative
11. Conservative assumption, higher than from primary data in default scenario
12. van Dijk et al. (2021)
13. No plug size reduction in optimised scenario, not realistic according to (REF later manuscript Olivia)
14. Assuming same ratio for seed cultivation, better ratio for optimised scenario
15. 2.9 plants on 1 m2 in spring, summer and fall, contributing 3/4 to the average and 4.7 pots on 1 m2 in winter, contributing 1/4 to the average; 2000 seeds per plant
16. Cultivation cycle is 26-30 weeks, 26 was assumed, equalling half a year, and annual use was halved to estimate average use per cultivation cycle
17. Calculated: volume of substrate component = volume of substrate per m2 * fraction of substrate component
18. Kacheyo & van der Vossen (2024) indicated 5 irrigation rounds per week in summer. Hence it was assumed: 4 irrigation rounds for spring, summer and fall cultivation and 2 irrigation rounds for winter. 150 mL given per pot per irrigation round. Irrigation volume [L] = SUMover4seasons{season’s averaging factor [-] * irrigation frequency in season [week-1] * number of pots per area in season [m-2]} * seed cultivation duration [weeks] * irrigation volume per pot [mL*week-1]/1000
19. Calculated by dividing net plant density over gross plant density (numbers of pots per m2)

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