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Review

Knowledge gaps on how to adapt crop production under changing saline circumstances in the Netherlands

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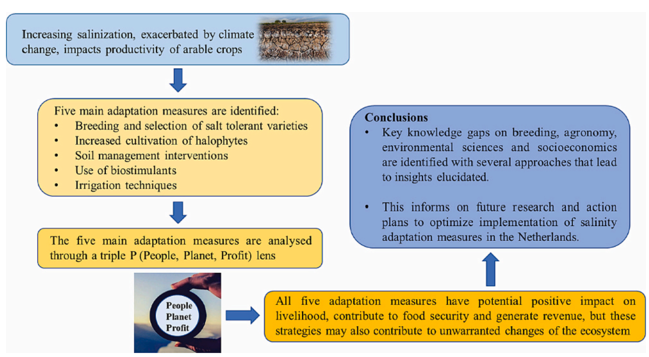
HIGHLIGHTS

- The Netherlands currently suffers from increasing salinization.
- Five salinity adaptation measures of the crop-soil-water continuum were assessed.
- A triple P assessment showed their potential to improve local livelihood and income.
- On the other hand, the measures' environmental impact was not always be positive.
- Core research in breeding, agronomy, environmental and socioeconomics were deduced.

GRAPHICAL ABSTRACT



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ABSTRACT

Salinization, the increase and accumulation of salts in water and soil, impacts productivity of arable crops and is exacerbated by climate change. The Netherlands, like several other deltas and semi-arid regions, faces increasing salinization that negatively impacts agriculture and freshwater availability. Although a lot of salinity expertise exist in the Netherlands, several knowledge gaps on the impact of salinization in the Netherlands, as well as steps to facilitate closing this knowledge gaps to improve saline agriculture in the Netherlands, still exist. This review/opinion article moves beyond existing papers on salinization in bringing together various adaptation measures by thoroughly reviewing the measures through a triple P (People, Planet, Profit) lens. Five main salinity adaptation measures of the crop-soil-water continuum are 1) breeding and selection of salt tolerant varieties, 2) increased cultivation of halophytes, 3) soil management interventions, 4) use of biostimulants, and 5) irrigation techniques. These adaptation measures are described, discussed and analysed for their compliance to the sustainable development elements People, Planet and Profit. All five adaptation measures have potential positive impact on

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livelihood, contribute to food security and generate revenue but on the other hand, these measures may contribute to unwarranted changes of the ecosystem. The paper ends with a concluding chapter in which the bottlenecks and knowledge gaps that need resolving are identified based on the critical, including triple P, assessment of the discussed adaptation measures. Three key knowledge gaps on breeding, agronomy, environmental sciences and socioeconomics are identified with several approaches that lead to insights elucidated. Thereby informing on future research and action plans to optimize implementation of salinity adaptation measures in the Netherlands.

1. Introduction

Salinization, the increase and accumulation of salts in water and soil, can occur either naturally or as a result of anthropogenic activities. Climate change further exacerbates the salinization problem. Predictions indicate a rise in seawater level and extreme weather conditions that promote salt seepage into soil and water bodies resulting in an overall increase of salt-affected soils in the coming years (Hassani et al., 2021). In December 2021, the Food and Agriculture Organization (FAO) of the United Nations issued a warning press release, stating that excess salt in soils put food security at risk (FAO, 2021). This is a serious threat since most food and feed crops are glycophytes that rely on freshwater irrigation whereas the availability of freshwater is declining, and is also threatened by salinization (Cunillera-Montcusí et al., 2022). Moreover, our current crops and cropping systems are extremely sensitive to (soil) salinization.

The increasing world population and associated welfare further increases the demand for food and feed. Salinization of agricultural areas impact productivity of arable crops (Zörb et al., 2019) thereby threatening food security and may finally result in land abandonment and migration (Chen and Mueller, 2018), as well as increased deforestation for agricultural purposes, plus biodiversity loss (Haj-amor et al., 2022). Investigations into the effects of salinization have highlighted that salinization is a global problem. To get insights on the extent of salinization, the FAO launched a universal map of salt-affected soils in 2021 (FAO et al., 2021). Current estimations indicate that 3 % of our total soil resources is salinized and salt-affected land area is increasing at a rate of 2 Mha/yr (FAO et al., 2021; Singh, 2018), projecting a crop yield loss equivalent to ~124 trillion kilocalories which is the daily food requirements for 170 million people each year (Russ et al., 2020). From a European perspective, the European Soil Data Centre (part of the Joint Research Centre of the EU) suggests that salinization is a major cause of desertification and soil degradation (JRC et al., 2009), and indicate that economic loss due to salinization is at least half a billion Euros annually (Ruto et al., 2021).

Irrespective of the projected trends, soil and water salinization will remain an important factor in relation to food security and needs further in-depth attention from both a political and scientific point of view. The Netherlands, like several other deltas and semi-arid regions, also faces increasing salinization that negatively impacts agriculture and freshwater availability due to salt discharge in lakes IJsselmeer and Markermeer (Centre for Climate Adaptation, 2023). Coastal regions such as the Wadden islands, coastal areas of Friesland and Groningen, the South-West delta and North Holland are especially vulnerable to salt intrusion. This has led to development of consortia and projects in the Netherlands that focus on expanding knowledge on how to deal with increasing salinization (NFP and NWP, 2022; Redactie OTAR, 2023; ZZK, 2021). Measures to deal with salinization are either mitigative or adaptative independent of the level or scale. Mitigative measures address the causes of salinization, including measures to change water systems, while adaptative measures aim to adapt agricultural practices in such a way that they can cope with increased salinity. Although much knowledge, including expertise, on salinity has been generated in the Netherlands (Snethlage et al., 2021), there remain knowledge gaps on the impact of salinization in the Netherlands, as well as on steps to facilitate implementation of these measures to improve saline agriculture in the Netherlands. Therefore, in this review paper, we address the following research questions:

1. What is the state-of-the-art on current measures to adapt to salinization?
2. What is the impact of the identified adaptation measures to people, planet and profit?
3. What are the bottlenecks or knowledge gaps that need resolving, and what are future actions to optimize implementation of salinity adaptation measures in the Netherlands?

The review article moves beyond existing papers on salinization in bringing together various adaptation measures by thoroughly reviewing the measures through a triple P (people, planet and profit) lens. The paper concludes with the identification of research needs, and proposes next steps, based on the needs, to influence future research agendas on salinization in the Netherlands.

2. Methods

In answering these research questions, the following stepwise approach was conducted (Fig. 1). Step 1 was the identification of key salinity adaptation measures, including highlighting adaptation measures used at specified locations in the Netherlands (case studies). Next, the adaptation strategies identified were evaluated using the triple P concept People, Planet and Profit (step 2). This evaluation step fuels identification of knowledge gaps in the last step (step 3).

The analysis started with identification of adaptation measures and the systematic collection of literature on the socioeconomic impacts of salinization and of the adaptation strategies. The study team

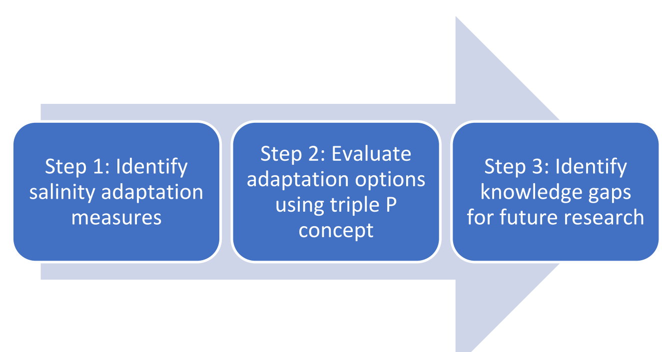

Fig. 1. Stepwise approach taken in the review paper.

experimented with various search queries to retrieve an appropriate number of results. The search query selected[2] resulted in 65 publications. The abstract of these publications was screened, looking for information on the geographical focus of the paper, the causes of salinization mentioned, and the adaptation measures discussed. Eleven publications on socioeconomic impacts were highlighted as being of particular interest for this study and full text were downloaded for in-depth analysis.

The triple P concept (Elkington, 2018) was used to evaluate the adaptation measures along criteria defined for the elements of sustainable development; people, planet, and profit. The concept was chosen because its three elements of assessment facilitate operationalisation of the salinity adaptation measures in business practice. For the identified adaptation measures, we aimed to answer the following questions:

People; impact on farming communities

- What is the impact on livelihood?
- What is the impact on food security (quantitative and qualitative)?
- What are the local benefits?

Planet; impact on environment and ecosystem

- What are the long-term impacts on terrestrial and marine ecosystem?
- What is the life cycle impact on production and transport?

Profit: impact on farmers and the agricultural sector

- What is the impact on revenues for farmers?
- What is the impact on yield?
- What is the business status of the sector?

The answers to these questions were based on the scientific literature review in step 1 which was integrated into a process of interpretation and analysis of selected relevant literature performed by an interdisciplinary group of researchers from economic, plant, marine and environmental sciences. In cases where the information used in the table was mentioned in a scientific report, the documents were referenced. Based on the evaluation of adaptation measures in the triple P approach and case studies describing the use of some of the adaptation measures in the Netherlands, key knowledge gaps relevant for future research in areas of breeding, agronomy, environmental and socioeconomic research were described.

3. Overview of adaptation measures to salinization

Most (domesticated) food crops are glycophytes and therefore their growth and resulting yield are reduced by salinity (FAO, 2021). To counteract soil salinization, promote crop growth and circumvent yield reduction under saline conditions, several adaptation measures have been proposed. Conventional measures like excessive irrigation and deep tillage have been successfully used to mitigate the effects of salinity but create alternative problems such as decreased water tables and soil erosion, respectively (Bilgili et al., 2018; Singh, 2018). Furthermore, climate change has led to prolonged periods of elevated temperatures and reduced water holding capacity due to drought, thereby limiting availability of freshwater for salt flushing. There are several adaptation measures to improve agriculture under saline conditions (Litalien and Zeeb, 2020; Mukhopadhyay et al., 2021; Shahbaz and Ashraf, 2013) that focuses on one or more aspects of the crop-soil-water continuum. Some of the key adaptation measures include breeding and selection of salt tolerant varieties, increased cultivation of halophytes, soil management or interventions, use of biostimulants, and irrigation techniques. These adaptation measures are described and discussed in this section, including examples of their use in three locations experiencing salinity in the Netherlands.

3.1. *Breeding and selection of salt tolerant varieties*

Conventional breeding, new plant breeding techniques (NPBTs) or genetic modification (GM) are ways to introduce salt tolerant traits into crops. Conventional breeding for salt tolerance has been challenging due to the low genetic variation within most domesticated crop species (Flint-Garcia, 2013) since breeding in the past centuries focused on selection for high yield rather than stress tolerance. Moreover, salt tolerance is a complex polygenic trait comprising several physiological and biochemical processes. Analysing the salt tolerant wild relatives of these crops via genome wide association studies and qualitative trait loci studies facilitates identification of important genes or genetic clusters responsible for the observed salinity tolerance phenotype, present in their wild relatives (Choudhary et al., 2019). But conventional breeding is time- and labour intensive and transferring these desirable genes from the wild relative to the domesticated crop varieties is not always possible (Ashraf and Akram, 2009; Ashraf and Foolad, 2013). Speed breeding is a non-GM method that promotes rapid generation advancement in a time and labour-efficient manner (Wanga et al., 2021). An example is a salt tolerant rice F3 population "YNU31–2-4" that was developed in ~1.5 years by speed breeding method in combination with single nucleotide polymorphism (SNP) marker-assisted selection (Rana et al., 2019), reducing the time (10 to 15 years) typically spent when using other conventional breeding techniques. GM tools and techniques may also provide time-, labour- and cost-efficient solutions for successful transfer of desirable genes (Razzaq et al., 2019). Current restrictions on the use of GM tools have rendered this method of developing saline resilient crops unfeasible. Regulations of crop GM may change soon, especially considering the development of CRISPR/Cas9 gene editing technique (Turnbull et al., 2021), which is seen as a NPBT.

Despite all these limitations, some published studies have highlighted salt tolerant varieties of domesticated crops that are commercially available (Ferreira et al., 2019; Hosseini et al., 2021; Khan et al., 2016; Sanwal et al., 2022). In such studies, the crop varieties were selected based on their positive physiological, and agronomic (crop yield and quality) performance under saline conditions. Critical assessment of the case studies showed that crop productivity of the salt tolerant varieties under saline conditions remain lower than yield under non-saline conditions, thus a negative yield gap always remain. Additionally, some salt tolerant varieties still have lower yields than other sensitive varieties under moderately- and non-saline conditions (Cheng et al., 2021; Sanwal et al., 2022). For example, a salt tolerant potato variety K.Thar-2 and a sensitive variety K. Manik produced tubers of ~299 g/ plant and 207 g/ plant respectively under saline conditions compared to production of 322 g/plant and 429 g/plant of the same cultivars respectively, in non-saline conditions (Sanwal et al., 2022). Promoting varieties that already have low productivity may not be easy, especially since soil and water salinity typically fluctuates relative to the available ground water over a growing season. The low crop yield associated with the salt tolerant varieties may not motivate farmers to adopt these varieties except in dire situations where alternative adaptation measures, e.g., switching to halophytes, improving cropping systems or biostimulant application, cannot be easily implemented or do not give positive results.

[2] (((TITLE-ABS-KEY (salinisation OR salinization) AND (netherlands)))) AND (econom*) AND (LIMIT-TO (PUBYEAR, 2022) OR LIMIT-TO (PUBYEAR, 2021) OR LIMIT-TO (PUBYEAR, 2020) OR LIMIT-TO (PUBYEAR, 2019) OR LIMIT-TO (PUBYEAR, 2018) OR LIMIT-TO (PUBYEAR, 2017)) AND (EXCLUDE (SUBJAREA, "BIOC") OR EXCLUDE (SUBJAREA, "CHEM") OR EXCLUDE (SUBJAREA, "ENGI") OR EXCLUDE (SUBJAREA, "ARTS") OR EXCLUDE (SUBJAREA, "ENER") OR EXCLUDE (SUBJAREA, "PHYS") OR EXCLUDE (SUBJAREA, "CENG") OR EXCLUDE (SUBJAREA, "DECI") OR EXCLUDE (SUBJAREA, "MATE") OR EXCLUDE (SUBJAREA, "MEDI"))

3.2. Increased use of halophytes for food

Halophytes are a group of plants that thrive at high salt concentrations and may be utilized in severely salt affected areas. They have potential to extract salts from the soil known as phytoremediation, while producing biomass as food (Sarath et al., 2021). The exposure of halophytes to high salt concentrations may alter some metabolic processes leading to production of phenolic compounds that have high industrial potential (Lopes et al., 2023). Halophytes such as samphire (*Salicornia* sp.) and sea aster (*Aster tripolium*) are consumed as food (Chaturvedi et al., 2022). The plant species originate from coastal areas, often salt marshes, where they live near the sea and are seen as delicacies. However, halophyte species are currently only consumed on a small scale, and its introduction as a substantial part of our everyday diet will not happen soon. Although they have some nutritional benefits, the plant species accumulate high levels of salt (Barreira et al., 2017), therefore making it unpalatable and unsuitable for consumption in high quantities. Additionally, cultivation practices are still poorly developed (Ventura and Sagi, 2013) making large scale production very costly and the yield per hectare is very low relative to staple crops. Both factors limit the market potential of halophytes as food. Therefore, several efforts are needed (Custódio et al., 2021) to make these plant species a common food source and with a competitive price compared to commonly used crops.

3.3. Mechanical and biochemical soil interventions

Moderate levels of salt may have positive effects on the soil by facilitating flocculation (Zhang et al., 2021) but at higher levels, it negatively impacts the soil structure and quality. Sodium ions (Na^+) are abundant in saline and sodic soils and create weak bonds between soil particles resulting in poor soil permeability and low field capacity (Seelig, 2000). Salinity also inhibits microbial activity in the soil leading to a reduction in nutrient cycling and thus, soil nutrient limitation may occur (Yan et al., 2015). Soil interventions to combat salinity include introduction of new cropping systems, bioremediation/phytoremediation and use of amendments.

3.3.1. Adapting and managing crop cultivation systems to improve soil health

Changing the cropping system by crop rotation or intercropping food crops with forage, ornamental and tree crops have positive effect on saline soils. Agroforestry is a regenerative agriculture concept of integrating trees and shrubs with crop cultivation systems. Several tree species including fruit trees, grow deeper roots and can survive on saline soils (Schofield, 1992; Toderich et al., 2013), and play a role in biodrainage and minimizing soil salinity (Singh et al., 2019; Turner and Ward, 2002), thereby improving soil quality. For example, intercropping of *Jatropha curcas,* an ornamental crop, with herbs and cereals stimulated microbial activity and biomass, and improved soil quality (Singh et al., 2016). The forage, ornamental- and tree crops have alternative uses as feed, increase biodiversity, for partial (re)forestation and as a source of timber.

Improved cultivation systems where planting on soil ridges or beds occur instead of flat surfaces, also have a positive effect on crop yield and soil properties in saline conditions. Best results of enhanced soil quality were established when this method was combined with mulching and furrow micro-irrigation due to reduced salt accumulation in the rootzone of crops growing on the raised beds (Dong et al., 2018). Another crop management technique to combat salinity is deep tillage. It involves turning the soil periodically to leach out salt from the topsoil and promote water movement trough the soil, using hand-held or mechanical tools. Although deep tillage has been previously successful, it may lead to soil erosion in the long term (Bilgili et al., 2018), creating new challenges for farmers.

3.3.2. Phytoremediation and bioremediation of salt-stressed soils

Saline soils can be reclaimed by phytoremediation using plants, and bioremediation using microbes. Phytoremediation of salty soils involves cultivating halophytes such as *Acacia ampliceps* and *Atriplex nummularia*, and tree crops such as poplars, that can take up salt from the soil (Toderich et al., 2013). Contrary to glycophytes, halophytes possess mechanisms to counteract high salt concentration. They can actively transport salt to a designated area or compartment in the plant e.g., leaves or fruits, and allow that part containing high salt concentrations die off (Sarath et al., 2021). During plant harvesting, the stored salts in the plant tissues are taken out as well, resulting in a natural salt extraction. Some other halophytes excrete salt from the plant through specialized salt bladders, secretory cells, and salt glands (Litalien and Zeeb, 2020). Model simulations indicated that salt excreted by the plants is atmospherically dispersed over long distances but further research on salt dispersal especially the impact of site-specific factors needs to be considered (Litalien and Zeeb, 2020). Halophytes may accumulate salt concentrations of up to 20 % of their dry weight resulting in excessive amounts of salt i.e., $\geq$ 4000 kg NaCl/ha, removed annually but still saline soil remediation takes a long time (Jesus et al., 2015). For example, it will take at least a decade to reduce soil salinity from 20 dS/m (severe soil salinity) to <4 dS/m (moderate levels of soil salinity). The growth rate and biomass of most halophytes are low which directly limits their salt holding capacity. Therefore, studies on increasing the salt uptake capacity of halophytes may boost remediation potential.

Certain bacteria like cyanobacteria and PGPR (plant growth promoting rhizobacteria) are halophytic and can be used to clean-up saline and sodic soils. Cyanobacteria are involved in nitrogen fixation thereby improving soil flocculation and resulting in enhanced soil permeability and aeration (Bergi and Trivedi, 2020). They also serve as biofertilizers to increase nutrient levels and promote crop growth (Nisha et al., 2018). PGPR co-cultivated with halophytic plants reduced soil salinity by facilitating efficient salt uptake by the plants (Delgado-González et al., 2022). Care should be taken when performing bioremediation activities by first critically assessing that the bacteria do not negatively impact population or activity of the native microbiota.

3.3.3. Application of amendments to the soil

Addition of organic and inorganic amendments to sodic or saline soils is one of the well-established measures used for improving conditions on salty soils. Soil amendments positively enhance the physical, chemical, and biological properties of the soil. Compost, gypsum, zeolite, biochar and biostimulants are examples of soil amendments, with the last two as newer groups of amendments. Gypsum rich in Ca^{2+}, compost derived from organic and inorganic waste, and zeolites leach salt, improve soil physical properties, and increase nutrient availability. Biochar is derived from thermochemical combustion of organic materials under low oxygen supply (Ali et al., 2017), while biostimulants can be sourced from seaweeds, fulvic and humic acids, protein hydrolysates, microbes, and silicon (Rouphael and Colla, 2020). Application of biochar directly improved water holding capacity, aggregate stability, aeration, and microbial activity of the soil while it decreased Na^+ uptake by plants (Ali et al., 2017). Biostimulants work similarly to biochar. Direct application of seaweed- or protein hydrolysate-derived biostimulants to soil stimulated beneficial microbial and enzymatic activity, suppressed nematode activity, enhanced soil holding capacity and improved soil aeration (El Boukhari et al., 2020; Khan et al., 2009).

3.4. Application of biostimulants to crops

Apart from direct application of biostimulants to soil (soil drenching), the products can be applied to crops via foliar spraying, seed coating, or root dipping of nursery plants prior to transplanting. Biostimulants are products that improve crop nutrient use efficiency, crop tolerance to abiotic stress, plant quality, and nutrient availability in the rhizosphere and soil (Rouphael and Colla, 2020). One of the promising classes of biostimulants are those derived from seaweeds and represent the fastest growing biostimulant industry (Carmody et al., 2020). The extracts derived from seaweeds contain a plethora of bioactive compounds such as polysaccharides, pigments, phenolic compounds, proteins and (bioactive) peptides, phytohormones and micro- and macronutrients (El Boukhari et al., 2020). This complex chemical composition could explain the wide range of functionality of these extracts, and more information on the putative mode of action has been reviewed (Deolu-Ajayi et al., 2022). In general, application of biostimulants resulted in increased productivity of crop growth, yield and quality under saline conditions. For example, rapeseed plants treated with seaweed-derived biostimulants showed a significant increase in yield and oil quality under saline stress compared to their corresponding untreated plants (Hashem et al., 2019). However, when comparing these positive results to crop response under the non-saline conditions, it is not always clear-cut. This is because application of plant biostimulants under saline stress does not still close the yield gap created by crops cultivated in optimal non-stressed conditions (Deolu-Ajayi et al., 2022). To better improve crop productivity and potentially close yield gaps under salinity, the synergistic effect of using multiple biostimulants should be tested. Combining biostimulants from diverse sources produced positive results that exceeded independent application of a single biostimulant under the same conditions (Rouphael and Colla, 2018).

3.5. *Irrigation innovations under saline conditions*

Irrigation of agricultural fields is mostly executed by (large) sector sprinklers. Sector sprinklers consume a large amount of water and is not a sustainable irrigation practice due to pressure on freshwater availability. In this context, micro-irrigation systems such as drip and furrow irrigation are more preferred. However, for such irrigation practices both the quantity and quality of water need to be regulated to maintain the soil water table and prevent salinization of topsoil and rooting zones. This is relevant as drought may increase the severity of salinity (Jones and van Vliet, 2018). The addition of a leaching fraction to the water requirements enables salt flushing from plant rootzone. However, whether this is a sustainable option remains unclear especially in cases where groundwater levels are shallow, creating capillary rise of saline water to the surface that would negatively impact crop productivity (Mukhopadhyay et al., 2021). Micro-irrigation systems should be installed together with a (controlled) filtration and drainage system to minimize salt accumulation in the soil.

To overcome freshwater scarcity, water desalinization of brackish and saline water may be performed. Water desalinization use techniques such as reverse osmosis, flash desalination, ion-exchange resin, gas hydration and membrane distillation to separate and remove salts from water (Curto et al., 2021). Although this method is expensive, using renewable energy sources such as wind, solar and biogas may reduce associated costs (Curto et al., 2021). The desalinized water can then be used for agricultural purposes, including cultivation of high value crops (Burn et al., 2015).

3.6. *What current adaptation measures are applied in the Netherlands*

Salinity intrusion is on the rise in the Netherlands, especially in coastal regions, negatively affecting agriculture. Here, we focus on three case studies of Dutch locations experiencing high salinity: Terschelling, Texel and Zeeland, by indicating what adaptation measures have been introduced to deal with salinity.

3.6.1. *Terschelling*

The small Wadden island Terschelling is located North of the Netherlands, bordering the Wadden Sea in the South and the North Sea in the North. Although available anecdotal evidence on salinity is contradictory and the effects differ locally overall, the island suffers from saltwater intrusion and freshwater shortages. Therefore, uncertainties due to increasing salinity intrusion complicates decision-making on coastal adaptation (Haasnoot et al., 2020). Livestock rearing is one of the main agricultural focuses in that area, and 11 out of the 25 agricultural companies located in Terschelling are dairy farms.

Breeding and selection of salt tolerant varieties, and increased use of halophytes for food are two adaptation measures adopted in Terschelling. In the research project "Toekomstperspectief polder Terschelling[3]", one of the dairy farmers facilitated experiments for selection of salt-tolerant grass varieties. The yield of salt-tolerant varieties, its applicability as livestock feed and impact on the business case of dairy farming in Terschelling are key research questions of the project. Additionally, a small plot of halophytes is maintained by Zilte Smaak,[4] a foundation that aims to promote salt-tolerant crops. Marketing of the halophytes and organising the value chain to benefit the local community remains a challenge for the foundation.

3.6.2. *Texel*

Texel is also a Wadden island housing ~175 farmers with ~9000 ha of arable land. Grasslands occupy half of the agricultural area while the other half is used for cultivating beets, potatoes, cereals and flower bulbs.[5] The farmers deal with rising saline groundwater especially since the number of farms have increased in recent decades.

On the island of Texel, awareness on salinization is boosted by the Salt Farm Texel[6] that focused on saline crop production. This company was one of the first in the Netherlands to grow halophytes such as samphire, sea aster, oyster leaf (*Mertensia maritima*), ice plant (*Mesembryanthemum crystallinum*) and sea cabbage (*Crambe maritima*). Apart from halophyte cultivation, salt tolerance of common crop varieties, and seaweed (*Ulva* sp.) cultivation using severely salinized groundwater, have been experimented. Field trials from 2012 to 2018 in an open-air laboratory of Salt Farm Texel tested varieties of potato, cabbage, onion, carrot, lettuce and barley for salt tolerance (de Vos et al., 2016). The set-up consisted of seven different saltwater levels ranging from slightly saline (1.7 dS/ m) to severely saline (35 dS/m) under drip irrigation. Based on the Maas and Hoffman salinity classification on relative decrease in crop yield correlating with the severity of soil salinization (Maas et al., 1977), the experiments showed large variations among the tested crop varieties. The results indicated different thresholds at which decreased production occurs in response to saline irrigation that is applicable for selection of salt tolerant varieties of the common crops (de Vos et al., 2016; van Straten et al., 2021). Unfortunately, the company went bankrupt in August 2020.[7] Nonetheless, awareness on salinization is still been further promoted on the island of Texel resulting in water management changes such as implementation of drainage systems in the channels to facilitate freshwater retention.

3.6.3. *Zeeland*

The province of Zeeland consists of multiple former islands all located in the Southwest of the Netherlands. This area is an estuary surrounded by multiple rivers: the Schelde, Maas and Waal. Delta barriers such as dikes, have been built to circumvent flooding and connect the former islands resulting in the formation of Lakes Grevelingen and Veere. The combined effect of rise in seawater level and land subsidence has enhanced salinization in the Southwest Delta (van Baaren et al., 2016), and the occurrence of less rainfall in summer has further contributed to salinization in Zeeland.

Zeeland comprise a large (90,000 ha) agricultural area due to the presence of highly fertile clayey soil. Increased salinization and freshwater shortages have led to major concerns on the state of agriculture for

[3] https://toekomstperspectiefpolderterschelling.mailchimpsites.com/general
[4] https://www.deziltesmaak.nl/
[5] https://www.boerenklasse.nl/het-boerenleven
[6] https://www.saltfarmtexel.com/
[7] https://www.akkerwijzer.nl/artikel/215327-zilt-proefbedrijf-texel-failliet/

local farmers, but also at higher levels for the local government, agricultural sector representatives and water management institutes. This led to development of the "Deltaplan agrarisch waterbeheer (Delta plan on agricultural water management)[8]", an initiative by agricultural sector representatives and water boards, and supported by the national government, to promote good water management including water desalinization technologies and water storage.[9] Although majority of farmers in Zeeland are aware that their cultivated crops should be salt resilient, they still focus on growing common salt sensitive crops e.g., potato and wheat (Stuyt et al., 2016) and only in a few locations (Emmadorp, Waterdunen and Wolphaarsdijk) are halophytes cultivated. In these locations, farmers cultivate both samphire and sea aster by saline water irrigation on the edges of salt marshes.[10] Sales of halophytes remain low because cultivation is labour intensive and seasonal. Furthermore, the food market for halophytes is small, easily saturated and does not offer a sustainable "market potential" for farmers. Other initiatives that combine saline aquaculture and agriculture such as cultivation of worms/polychaetes, seaweed, or shellfish are ongoing in Waterdunen and are seen as solutions to economically revive saline degraded areas.

Overall, the adaptation measures have potential to reduce the negative impact of salinity on crops, as well as improve the soil conditions. Although positive results have been achieved with these measures, combining multiple measures may proffer better solutions to adapting crops to saline conditions while boosting production. The synergistic effect of combining several measures still needs to be tested for their combined effect in improving crop productivity e.g., the use of amendments to improve salt uptake of halophytes, or closing the yield gap of salt tolerant varieties with the application of biostimulants or other amendments. Factors such as crop type, soil conditions, and climatic conditions may play a role in the effectivity of combined measures and should therefore be considered in such analysis.

4. People-planet-profit evaluation of salinity adaptation measures

The five discussed adaptation strategies were analysed for their compliance to the sustainable development elements People, Plan and Profit based on the outcomes of literature study (Table 1). In general, scientific evidence for Life Cycle Assessment (LCA) is poorly available on the consequences of mitigation and adaptation measures. Although, LCA methodology has been established (Payen et al., 2016) and studies have been performed to qualify impact of activities or alternatives (Warshay et al., 2017), studies on adaptation measures and especially benchmarking impacts of adaptation strategies and scenarios, are less available. A review of the environmental effects of salinization to support policy goals and ambitions concluded that the case studies that are used to validate and reflect the impact of the adaptation methods on livelihood, food security, ecology and socioeconomic impacts do not result in a clear consistent picture (Haj-amor et al., 2022). The scientific and anecdotal base is quite marginal, small scale and experimental by design. On many occasions the case studies focus on the technical aspects of mitigation and adaptation measures, while not considering the outcome of the study in a broader socio-ecological context. While the drivers for the study are usually more acute due to current salinization stress or salinization outlooks. However, the demonstration of the adaptation measures and the consequences for long term, local and regional impacts is complex and multi-dimensional and therefore needs to be analysed by the introduction of multiple factors.

The results indicate that there are many stand-alone adaptation measures. However, the effect of combining adaptation measures have yet to be identified and explored and is also the case in the Netherlands, therefore it raises practical implications.

5. Research areas and knowledge gaps in salinization

In the last decade, publications on salinization have been steadily increasing but several aspects remain relatively unknown therefore requiring further research (Hopmans et al., 2021). There are also several knowledge gaps in the Netherlands that still need attention. Till date, the actual extent of salinization in the Netherlands remains obscure and it may be a priority to indicate the severity of salinity. Mapping of soil salinization in the whole Netherlands using a combination of geographic information system (GIS) data (such as aerial, satellite and thermal imaging), soil sampling and modelling would facilitate this process and proffer a promising first step on dealing with salinization, to stimulate further research on the topic. Another arising issue is that current adaptation measures to salinity in the Netherlands have mainly focused on water management while implementation of measures that involve adapting crops and soil, and the role these interacting components of crop-soil-water play, has not been prevalent. Based on the adaptation measures, case studies, and triple P analysis, a summary of key knowledge gaps on salinization under research lines of breeding, agronomy, environmental sciences and socioeconomics relevant for dealing with salinization in the Netherlands are highlighted in this section.

5.1. Breeding

1. Although breeding for increased salinity tolerance has been somewhat successful, yields of the tolerant varieties are relatively low compared to common high-yielding varieties in non-stress or mild saline stress conditions (Shahbaz and Ashraf, 2013). Thus, indicating a need to also improve the overall productivity of tolerant crop varieties. Breeding to simultaneously increase stress tolerance (both abiotic and biotic stress tolerance) and productivity in crops is also still needed.
2. The use of NPBTs such as CRISP-Cas for abiotic stress tolerance should get more attention. Because it does not have the GM status in many countries (and might be approved in the EU soon), it is much faster and less costly to use the edited plants (Kumar et al., 2023) for food or feed production, compared to genetically modified crops in which (foreign) DNA is inserted.
3. Breeding companies mainly focus on breeding of the major (staple) crops. There is a gap in breeding efforts for higher yield of halophytes that can be used for human consumption or can be used for soil remediation (non-food application).

5.2. Agronomy

1. The current classification of crop tolerance (Maas et al., 1977) needs be updated to include crop response on different soil types since soil structure, water holding capacity or porosity, may impact severity of the stress (Rengasamy, 2016).
2. The synergistic effect of simultaneously using multiple adaptation measures to mitigate salinity still needed to be tested and may proffer solutions to improve crop productivity higher than current observations.
3. Crops are realistically exposed to multiple stresses (both abiotic and biotic stresses) within one growing season. Moreover, salinity shares similar crop responses and underlying mechanisms with other abiotic stresses such as drought, heat or cold (Ahmad et al., 2019; Sah et al., 2016; Zhu, 2016). Therefore, the selected adaptation measures should be adapted for multi-stress resilient systems

[8] https://www.lto.nl/onderwerpen/deltaplan-agrarisch-waterbeheer/
[9] https://www.zeeland.nl/water/zeeuws-deltaplan-zoet-water
[10] https://www.thesaltdoctors.com/zeeland

Table 1
Evaluated effect of the key adaptation measures on People-Planet-Profit analysis. The results mentioned in this table are used for the gap analysis described in Section 5.

Element	Sub-questions on impacts	A. Breeding and selection	B. Halophytes for food	C. Soil interventions	D. Application of biostimulants	E. Irrigation innovations
People	What is the impact on livelihood?	Salt tolerant varieties may positively impact livelihood as a source of food and income for the farmers and society. Impact will depend on the productivity (yield) of the newly introduced salt-tolerant varieties.	Limited impact on livelihood currently since halophyte consumption as food remains limited in most parts of the world.	Simple temporary solutions (e.g., application of amendments or biostimulants) might have adverse effects in the long term with consequence on the entire agricultural sector (Haider and Hossain, 2013), including livelihood of the farmer. For soil remediation, impact on farmers' livelihood will depend on the time required to de-salinize the soil.	Sustained or improved production potential due to biostimulant use may contribute to livelihood and reduce agriculture-dependent migration.	Sustained production which secures farmer income and food under increasing saline conditions.
	What is the impact on food security (quantitative and qualitative)?	Increased or maintained crop yield using salt-tolerant varieties positively impacts food security, but it depends on the effect of multi-stress factors on the selected crop variety.	It has potential impact, but little is known on its overall impact in reducing food insecurity (Cheeseman, 2016). Yield of halophytes is at this moment much lower compared to other known food crops.	Potentially positive impact on food security, especially if the crops used for phytoremediation also have economic value (e.g., as stock-material for bio-based products)	Maintained or increased crop yield positively impacts food security.	Allows maintenance of food production during salinity stress.
	What are the local benefits?	Potential for farmers to keep production at current levels, and location or even increase production levels under saline conditions but also dependent on the cumulative effect of other stresses.	Suitable financial stimulation especially in severely salinized areas to prevent land abandonment. It presents a new option for food production. Additionally, long-term exploitation may occur in cases where halophytes have industrial use.	Less abandonment of salinized soils therefore, preventing expansion of already limited agricultural land.	Potential for farmers to keep production at high current levels, or even increase the production level at relatively low costs associated with biostimulant use (Ginter et al., 2022; Kocira et al., 2020).	Farmers may be able to maintain crop production levels instead of dealing with losses due to salinity.
Planet	What is the long-term impact on terrestrial and marine ecosystem?	The introduction of new tolerant crop varieties may lead to changes in the ecosystem by impacting plant and soil biodiversity in a positive or negative way.	Phytoremediation due to halophyte cultivation may improve long term resilience of production areas, and so prevents biodiversity loss due to newly created agricultural lands via deforestation.	Soil interventions usually result in healthier soils that may support the existing ecosystem. On the other hand, the impact of bioremediation and addition of biochar has on the activity and population of soil (micro) biota may result in (negative) changes of the entire ecosystem.	Long-term continuous application of amendments may change distribution of native species, including insects or even negatively impact crop productivity (for example, via increased salt concentrations). Biostimulants can be effectively produced from more sustainable sources including seaweeds, to avoid resource overexploitation.	Micro-irrigation and water desalinization increases water use efficiency in agriculture resulting in less pressure on local freshwater.
	What is the life cycle impact of adaptation measures?	NPBTs speed up the production process of breeding and selection of salt-resilient cultivars compared to conventional methods. The salt-resilient crops and cultivars obtained from breeding and selection do not necessarily differ from already existing salt-sensitive crops and would not produce additional waste.	Halophytes unlike most glycophytes, do not have established value chains including markets, to minimize waste and increase profit.	Soil amendments still contribute to greenhouse gas emissions from the soil, although not to the extent of synthetic pesticides and fertilizers (Thangarajan et al., 2013).	Biostimulants are typically biodegradable and used in minimal quantities. They can be produced from plant and animal waste streams, and other sustainable resources such as seaweeds, thereby minimizing overall waste.	Irrigation innovations require materials for installation such as drainage pipes and filters which only last for a couple of years. Damaged equipment should be sustainably discarded or re-used.
Profit	What is the impact on revenues?	Cultivating high-yielding salt tolerant crop varieties may allow farmers to close the yield gap and compete with other farmers growing crops under non-stressed	Halophytes could become a new revenue-generating product for farmers, especially those in highly salinized regions, this depends on the final financial benefits per ha	Introduction of most soil interventions require initial knowledge and capital investment by farmers. Therefore, when applying such options pre-investment and depreciation costs need to	Higher yields can increase profit, assuming costs for biostimulants are not exorbitant.	Although micro-irrigation and water desalinization innovations are expensive, it still provides year-round irrigation. A cost-benefit analysis on financial feasibility may promote

(*continued on next page*)

Table 1 (*continued*)

Element	Sub-questions on impacts	A. Breeding and selection	B. Halophytes for food	C. Soil interventions	D. Application of biostimulants	E. Irrigation innovations
		conditions, at a regional, national and global level.	(price per kg x yield per ha). .	be factored into business plans, as the return-on-investment is low in the first years.		installation of these innovations.
	What is the impact on yield?	Most salt tolerant varieties of common food crops have lower yields. Recent focus is on breeding for combined traits of salt tolerance and high yield in crops (Rana et al., 2019).	Most halophytes are low in productivity. Production is mostly small scale since cultivation practices are still poorly developed.	Additions of amendments on salty soils may increase crop yield but this is not always the case e.g., use of biochar in temperate regions (Jeffery et al., 2017)	Empirical evidence on crop yield is dependent on the severity of the salt stress. For example, a 10 to 20 % yield loss may be counteracted by applying biostimulants, but severe losses due to salinity would not be compensated (Deolu-Ajayi et al., 2022)	Micro-irrigation optimizes water supply (quantity and quality) resulting in higher crop yield. However, it requires advanced knowledge on water management.
	What is the Status on the sector of the adaptation measure?	New conventional breeding tools such as speed breeding in combination with marker-assisted breeding, and/or targeted genome editing are available, but the technique is highly specialized and not widespread (Wanga et al., 2021). GM crops are still restricted (including in the Netherlands) and not accepted by the public.	Halophytes production is currently done on small scale and not taken up by main players in agricultural value chains.	Soil interventions are some of the oldest adaptation strategies and the techniques are widespread.	The biostimulant sector is in place but small. Further linkage to other stakeholders in the agricultural value chain is needed.	Irrigation innovations are commercialised, and widespread adoption of these innovations may provide additional market opportunities for private stakeholders specialized in these technologies.

5.3. Environmental sciences

1. The soil biota needs further characterization i.e., identification of organisms residing in the soil (micro)biome, and their role in maintaining soil structure.
2. The functionality of biostimulants on their potential reduction of agrochemicals (fertilizer, pesticide) or impact on soil health should be further assessed. Also, methods that minimize greenhouse gas (GHG) emissions due to application of organic and inorganic amendments should be elucidated.
3. Long-term effects on the continuous use of micro-irrigation innovations (compared to the widely used large sector sprinklers) leads to creation of different soil moisture zones within agricultural fields which may impact soil micro(biota), therefore also requiring further research.

5.4. Socioeconomics

1. There is no commonly used methodology to assess the socioeconomic causes of salinization. Studies point to the importance of socioeconomic drivers of salinization, and the need to include such analysis when implementing adaptation strategies. For example, several case studies outside the Netherlands have indicated how poverty led to the adoption of farming practices that resulted in salinization (Hossain et al., 2018). Therefore, adaptation measures should consider socioeconomic factors to avoid adopting solutions that eventually lead to new problems (Hossain et al., 2018).
2. Solid empirical data on the socioeconomic impact of salinization and the cost and benefits of adaptation measures is lacking. Such analysis should move beyond the farm level and inform regional, national and international policy making regarding salinization. Global and regional economic models can be used, as well as agent-based economic models (such as farm level *Farmdyn* (Mosnier et al., 2019)) for the analysis.
3. The adaptation measures require better description of their economic viability (e.g., capital and operational costs, revenues), to comprehend the economic impact at the farm level. A shift towards halophytes as new food products would require an analysis of the current and future market demand of the bio-based economy in the organization of (global) value chains affected (Gereffi et al., 2005; Ruto et al., 2021) and an understanding of consumer perception of such products (Custódio et al., 2021).

6. Conclusions and future prospects

Salinization of water and soil, that occurs both naturally and as a result of anthropogenic activities, is a global problem that is further exacerbated by climate change. Salinization of agricultural areas has a huge impact on the productivity of arable crops threatening food security and resulting in land abandonment and migration, desertification and soil degradation leading to increased deforestation for agricultural purposes, and biodiversity loss. It is of uttermost importance to study not only different adaptation methods to deal with salinization, but also to critically scrutinise the putative effects of these adaptation strategies. Adapting crop production to salinization is a complex challenge that involves a combination of scientific, technological, and socioeconomic factors. Addressing these knowledge gaps requires interdisciplinary collaboration among researchers, policymakers, farmers, and other stakeholders.

We can learn from other (dry) areas such as Australia, Saudi Arabia, the US and China, as well as deltas that are affected by salinization. Some of these countries have invested significantly in salinity research to facilitate crop production under increasingly saline conditions. To address the salinization issue, the Netherlands may learn from successful and promising initiatives that have been introduced in such areas. Some delta countries e.g., Vietnam, Bangladesh, and Egypt have research institutes that focus on salinity. BRRI[11] in Bangladesh and NWRC[12] in Egypt lead projects including experimental pilots, to showcase applicable local salinity adaptation measures. Farmers in Vietnamese Mekong Delta and the Bangladeshi delta adopt saline-resilient cropping calendars, cultivate alternative climate-resilient crops, or even switch from agriculture to saline aquaculture e.g., shrimp farming (Hossain et al., 2018; Nguyen, 2017). In Egypt, the salinity research agenda focuses on irrigation modernization. These modernizations entail structural improvement of the irrigation system and current water management governance (AbuZeid, 2020). In Western Australia, the government provides up-to-date information on salinization including links on detecting salinity in the field[13] and several options for salinity adaptation.[14] Most of these adaptation measures utilized in these countries have already been discussed in this manuscript. Some measures may be adopted and implemented in the Netherlands on a case-by-case basis although the socioeconomic and environmental cost of large-scale implementation still needs to be thoroughly assessed.

This paper provides an encompassing exploration of the existing adaptation measures employed to address the challenge of salinization. Moreover, it offers a comprehensive assessment of these measures from the perspectives of People, Planet, and Profit. Drawing upon this evaluative analysis, our concluding chapter outlines the critical constraints and areas of limited knowledge that necessitate attention. It is our aspiration that these identified gaps will serve as a foundation for forthcoming action strategies, aimed at enhancing the efficacy of salinity adaptation measures within the Netherlands. For a consolidated view, refer to Table 2, which succinctly outlines the recognized knowledge gaps and suggests potential methodologies to gain insights and resolve these gaps.

6.1. Approaches to improve knowledge on breeding impact on dealing with salinization

Addressing the current gaps in knowledge within the realm of breeding goals to combat salinization highlights the imperative need for increased emphasis on the utilization and advancement of NPBTs. Specifically, the integration of traits related to both abiotic stress tolerance and productivity necessitates heightened attention. Within the domain of halophytes, an underexplored avenue prevails due to their limited recognition as viable "crops" not extensively used for human consumption or livestock feed. This remains an unexplored research area.

While the pursuit of more robust crop varieties remains time-intensive, the application of "speed breeding" methods and directed mutagenesis has notably condensed this timeframe. Simultaneously, there arises a pressing requirement to delve into the rich genetic diversity inherent within existing crops, specifically examining the interplay of abiotic stress tolerance and yield performance across diverse soil types. The overarching goal is to develop a cohort of climate-resilient cultivars adept at navigating an array of (a)biotic stressors.

In this endeavour, an indispensable aspect involves unravelling the distinct mechanisms that plants employ to counteract abiotic stress. This insight bears the potential to unveil pivotal biomarkers capable of forewarning farmers about impending stress-related challenges, thereby enabling timely and informed interventions. As the pursuit of breeding strategies to confront salinization progresses, the horizon broadens towards the realization of agriculture that is both robust and responsive to multifaceted stressors.

Table 2
Approaches to improve knowledge on breeding, agronomy, environmental and socioeconomic impact of salinization in the Netherlands.

Knowledge gap	Method	Insights
How can we breed for multiple traits on improved salt tolerance and yield in crops?	GWAS/ QTL analysis, NPBTs such as speed breeding and targeted gene-editing (e.g., Crispr-Cas).	Identification of genetic clusters that can be used as traits or markers for breeding. NPBTs facilitate generation of varieties that are both high yielding and salt tolerant and can even be tolerant to multiple abiotic and biotic stresses.
How can we improve the awareness and adoption of Crispr-Cas?	Campaigns and interactive workshops to raise awareness on the usefulness (and potential drawbacks) of the NPBTs.	Changing the narrative of the society on the use of non-GM crops (by emphasizing differences between NPBTs and GM).
How can we increase productivity (yield and salt uptake) of halophytes?	The same breeding techniques, and especially NPBTs, as mentioned earlier for existing crops should be used to increase traits in halophytes.	Identification of traits for breeding for improved yield (as a food) or salt uptake (for soil phytoremediation).
What is needed to update the current classification of crop tolerance?	Certain parameters such as the presence of other stresses (e.g., drought, heat, disease infestation), soil type (sandy vs. clayey soils), and cultivar selection impact the severity of salinity stress and should be included as factors for categorizing salt tolerance of crops. Experiments that include these additional factors should be performed to also establish empirical evidence.	Information on salt thresholds that support optimum yield of important crop species and varieties cultivated in the Netherlands
What are the synergistic effects of combining adaptation measures?	Controlled greenhouse experiments supported with field experiments on naturally salinized soils in the Netherlands. Examples of combined adaptation strategies to be tested are increasing soil remediation rate of halophytes by boosting growth via biostimulant application, and applying both biostimulants to crop and soil amendments to salt tolerant varieties to close yield gaps.	Information on the best (combined) adaptation measures per crop group, that would support high yields under saline conditions.
How do we promote multi-stress climate-resilient systems?	Controlled experiments in climatic rooms where different stresses can be introduced to the crops at varying timepoints of their lifecycle, like observations in nature. Salt tolerant species and varieties should also be tested for multi-resilience to drought, heat, cold, weed infestation, pests, and diseases.	Insights into crop responses to multiple stresses and selection of crop varieties that are stress resilient. Generates knowledge that can disseminated into information for signalling early stress disasters for farmers.

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[11] http://brri.gov.bd/site/page/9bf0a9f3-e216-4e85-80b0-10b2e87136c2/-
[12] https://www.nwrc.gov.eg/img/brochure/NWRC%20Brochure.pdf
[13] https://www.agric.wa.gov.au/dryland-salinity-site-assessment
[14] https://www.agric.wa.gov.au/soil-salinity/managing-dryland-salinity-south-west-western-australia

Table 2 (*continued*)

Knowledge gap	Method	Insights
What organisms interact and are responsible for maintaining soil structure under saline conditions?	Soil sampling, enzymatic assays and protein reporter assays.	Characterization of the (micro)organisms give information on how to improve soil structure during salt stress as well as, insights on agricultural inputs that can be applied to boost these organisms thereby preventing collapse of the soil due to high salinity and improving soil quality.
What is the impact of biostimulants and (organic) amendments on agrochemical use, soil health and GHG emissions?	Greenhouse experiments to elucidate fertilizer-biostimulant interaction, Measuring the associated CO_2 emission for both production and use of the products. Modelling the short- and long-term GHG emissions due to product use.	This type of research safeguards against biostimulant and amendments having a negative or counterproductive effect on the ecosystem.
What are the long-term effects of continuous use of micro-irrigation innovations?	Modelling crop-soil-water factors, combined with practical studies on micro-irrigation of salinized fields.	Evaluation on short and long-term impact of micro-irrigation, thereby creating optimal irrigation management regimens for salinized soils.
What are the effects of salinization on global agricultural trade and global food security?	The effects of salinization can be assessed by coupling biophysical and socioeconomic models	Scenarios perspective at regional level on land and water demands to maintain the provision of food, animal feed and fibre.
What is the impact of salinization and implementation of adaptation measures on farmers?	Cost-benefit analysis and agent-based modelling to understand decision making by farmers.	Insight into costs and revenues of adaptation measures. Additionally, insight into ways to change farmer behaviour.
How to create markets for new salt tolerant food products?	(Global) value chain analysis and studies into consumer acceptance of halophytes.	Understanding of consumer perception, as steppingstone towards marketing of halophytes.

6.2. Approaches to improve knowledge on agriculture impact on dealing with salinization

A multitude of adaptation measures has been identified and is currently employed to address various aspects of the crop-soil-water component. These strategies encompass a wide spectrum, ranging from the application of biostimulants during crop growth to the implementation of mechanical and biochemical interventions within the soil, extending even to innovations in irrigation techniques.

A critical trajectory involves the examination of combined adaptation approaches, evaluating their potential to synergistically amplify cumulative impacts and yield outcomes within saline environments. It is essential to subject these combined strategies to rigorous testing to ascertain their capacity for producing enhanced outcomes. However, a notable knowledge gap persists concerning the continuous application of amendments or biostimulants and their consequences on the intricate soil ecosystem and the broader environment. This gap extends to understanding the short-term and long-term implications of such practices on GHG emissions. Resolving these uncertainties becomes pivotal for the development of sustainable and environmentally conscious adaptation methodologies. As the pursuit of salinization adaptation advances, a complete comprehension of the intricate interactions between adaptation strategies, soil dynamics, and environmental repercussions emerges as an essential cornerstone for effective and harmonious agricultural transformation.

6.3. Approaches to improve knowledge on socioeconomic impact of salinization

The current and anticipated socioeconomic factors contributing to and influenced by salinization remain largely uncharted territory. In-depth examinations conducted at the farm level, focusing on the intricate balance of costs and benefits associated with novel agricultural practices, serve as an illuminating vantage point. Such studies not only provide insights into farmer behaviour but also facilitate the identification of suitable adaptation measures customized to the farm-level context. As the projected geographical expanse of salinization gains prominence, there arises a pronounced need for comprehensive analyses spanning broader horizons. It encompasses evaluations of the present and potential future repercussions on both national and international scales of agricultural production. Consequently, the intricate web of stakeholders engaged in the agricultural value chain assumes centre stage, demanding attention to their roles and dynamics. Significantly, these analyses, hinging on both present and forward-looking perspectives, possess the potential to transcend the farm level. By extending their reach, they empower decision-making processes that extend beyond immediate agricultural considerations. This expanded purview pertains to longer timeframes where the interplay of national and international policies significantly shapes the trajectory of forthcoming food systems.

In essence, these comprehensive socioeconomic explorations function as the compass navigating the uncharted waters of salinization's far-reaching impacts. As they illuminate the complex interconnections between agricultural practices, economic implications, and policy landscapes, they equip decision-makers with the insights required for forging sustainable and resilient pathways for our future food systems.

6.4. From people-profit-planet to circular economy

We opted for the triple P approach to evaluate the various adaptation measures. The triple P approach is well-known and widely used in various contexts to assess the sustainability of innovations of developments from people, planet and profit perspectives (Böcker and Meelen, 2017; Ellis et al., 2022; Larivière and Smit, 2022; Liute and De Giacomo, 2022; van den Burg et al., 2021). It has become part of business lexicon and is commonly used in business environmental and social reporting and has changed the way businesses report on their impact (Sherman, 2012). Recent critical assessment suggest that new concepts are needed to systematically evaluate the sustainability of business operations and innovations (Elkington, 2018). Two main lines of argument are given. The first indicate that as numerous businesses report on people, planet and profit, it has become clearer that the triple P concept is increasingly used to greenwash business performance, and a deeper dive into the trade-offs in decision making is lacking (Xu et al., 2023). Others argue that the concept pays insufficient attention to politics (O'Neil, 2018). The authors of this manuscript are of the opinion that the triple P concept provides valuable first insights on the impacts of innovation, in this case salinity adaptation measures, as long as one refrains from making final decisions on overall sustainability from only assessment using the triple P concept.

Another approach to this type of assessment may be to use the concepts of circular economy to review adaptation measures. The concept of circular economy was originally coined to describe how products at the end of their service could be re-purposed (Stahel, 2016). To adopt it to the bioeconomy, a broader set of principles was defined: ***safeguard*** the health of ecosystems to ensure the future availability of natural resources; ***avoid*** the use and production of non-essential bio-based products to minimize waste and preserve natural resources; ***prioritize*** biomass production for essential human needs, e.g., food, pharmaceuticals, and to decarbonize highly pollutant sectors (e.g., energy sector); ***recycle*** existing bio-based waste resources (e.g., residues from the livestock sector) to improve ecosystems; and ***entropy*** for maximizing the use of natural processes and energy within ecosystems (Muscat et al., 2021). These five key principles promote sustainability (including recycling) of products and the environment while meeting the defined broader needs of the society.

A review of salinization adaptation measures based on the principles of the Circular (Bio)economy concept may further provide new insights that are summarized in three points.

- Contribution of the adaptation measures in supporting farming practices that prevent society from crossing planetary boundaries (Muscat et al., 2021) that are currently at risk, including analysis of their contribution to restore the ecosystem (García-Caparrós et al., 2020) should be evaluated.
- Consider the best use of crops produced under saline conditions at the food system level, either for direct consumption or for alternative use as feed and biomaterial resources
- Assess total energy use in the life-cycle energy of crop products under saline conditions vis-à-vis conventional crops and include climate impacts in considering salinization adaptation practices.

Such results from the circular bioeconomy assessment would be complementary to the triple P analysis, specifically by looking into the trade-offs between ecology, economy and social impacts. Together, both analyses can provide a more nuanced insight into the potential contribution of salinization adaptation measures to future food systems.

CRediT authorship contribution statement

Sander van den Burg: Data curation, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing, Conceptualization. **Ayodeji O. Deolu-Ajayi:** Conceptualization, Data curation, Funding acquisition, Investigation, Validation, Visualization, Writing – original draft, Writing – review & editing. **Reinier Nauta:** Conceptualization, Data curation, Validation, Visualization, Writing – original draft, Writing – review & editing. **Walter Rossi Cervi:** Data curation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Adrie van der Werf:** Conceptualization, Visualization, Writing – original draft, Writing – review & editing. **Marnix Poelman:** Conceptualization, Visualization, Writing – original draft, Writing – review & editing. **Gert-Jan Wilbers:** Writing – original draft, Writing – review & editing. **Judit Snethlage:** Writing – original draft, Writing – review & editing. **Monica van Alphen:** Writing – original draft, Writing – review & editing. **Ingrid M. van der Meer:** Conceptualization, Funding acquisition, Investigation, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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