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Knowledge synthesis on foliar nitrogen and phosphorus fertilization

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Preface

This knowledge synthesis on foliar nitrogen and phosphorus fertilization was initiated and financially supported by the Danish Agricultural Agency on behalf of the Ministry of Food, Agriculture and Fisheries, Denmark, grant agreement no. J.nr. 2021-8453. The purpose of the knowledge synthesis is to present the available information about foliar fertilization in a comprehensive report, as well as to describe the agronomic and environmental advantages and potentials, as well as disadvantages and unintended effects, of foliar fertilization. Studies and literature from Denmark and comparable countries, together with literature and experiences from the rest of the world, are included. During the preparation of the report, a thematic meeting on foliar fertilization was organised in order to enable a broad involvement of researchers, theoreticians, practitioners and authorities with the aim of creating a common understanding of the possibilities and weaknesses of foliar fertilization. The knowledge synthesis reflects the views only of the authors, and the Ministry of Food, Agriculture and Fisheries cannot be held responsible for any use, which may be made of the information contained therein.

Scientific assessment and commenting of the report:

Prof. Søren Husted, University of Copenhagen, Department of Plant and Environmental Sciences
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This knowledge report will serve as a basis for a review article that will be submitted to Advances in Agronomy volume 186 (forthcoming), invited by the Editor D.L. Sparks. The current report has been declared in the correspondence with Elsevier.

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Abstract

This review presents a synthesis of the current state of knowledge of the agronomic and environmental impacts of foliar fertilization with nitrogen and phosphorus. The main processes and factors affecting the efficiency of foliar fertilization are discussed along with the advantages and disadvantages compared to the use of conventional solid fertilizers applied to the soil.

Spraying nutrients directly on the leaves of plants provides a possibility for rapid optimization of the nutritional status of crops, because the uptake of the applied nutrients will not be affected by soil processes delaying their availability. Foliar fertilization also implies better possibilities for delaying part of the fertilizer application in order to take the predicted yield potential and nutrient requirement in the specific growing season into account. To serve this purpose, implementation of novel sensors and spraying technologies for precision agriculture will be important.

Urea is the preferred form of nitrogen used for foliar fertilization. This is the case because the uptake rate is faster and the risk of leaf scorch smaller compared to other nitrogen forms. Urea is taken up at a high rates during the first 4 to 8 hours after application. Depending on the urea rate applied, typically 80% will be absorbed within the first 24 hours after application. Only a very small proportion (<1%) of urea may hydrolyze while still being on the leaf surface. Thus, there is no significant ammonia volatilization from urea on the leaf surface. Nevertheless, only a relatively small amount of urea, 10-20 kg N ha^{-1}, should be applied per application event in order to minimize the risk of leaf scorch and washing-off of urea to the soil surface, where it may be lost by ammonia volatilization. Adjuvants (spreading adhesives and humectants) should be added to the solution to reduce surface tension and ensure optimal leaf contact and absorption of nutrients by the leaves. By co-formulating urea solutions with phosphoric acid or sulphuric acid it is possible to lower the pH, which may reduce risks of ammonia volatilization. Urea-ammonium-nitrate (UAN) may be used as an alternative to urea, but seems to have slight lower efficiency and slightly higher risk of causing leaf scorch than urea. Foliar fertilization with 1 to 2 kg P ha^{-1} may increase the phosphorus content of the leaves, but yield responses need to be further documented under field conditions.

A large number of measurements of the recovery of foliar nitrogen applied to different crop species show values ranging from 21 to 99%, reflecting the use of different application methods and experimental conditions. On average, recoveries of 61% for different crop species and 66% for wheat have been obtained by foliar N-fertilization with urea. Based on these average recoveries, it is estimated that the potential N-fertilizer saving without reducing crop yields will be 14%, provided half of the total nitrogen requirement is applied by foliar fertilization. Recent international results

from field experiments with wheat and grassland systems have shown that it is possible to maintain similar crop yields with 25-40% less nitrogen applied by foliar fertilization compared to fully soil-fertilized control plots. In Denmark, field experiments carried out by SEGES Innovation have not shown any advantages of foliar N- fertilization.

It is concluded that if foliar fertilization is carried out in the correct way under carefully optimized conditions, it is possible to obtain higher nutrient efficiencies than is the case for conventional soil-based fertilizer applications. However, successful implementation of foliar fertilization requires careful optimization of the conditions for nutrient uptake across the leaf barriers as affected by the form of nutrient applied, the concentration of salts in the applied solution, the addition of adjuvant and the application time in relation to crop developmental stage and weather conditions. Foliar fertilization should be carried out when there is no forecast of rain in the next few days to prevent nutrients washing down to the soil. Within the day of application, foliar fertilization should not be carried out in the middle of the day, when the sun is shining and the air temperature is relatively high, as this increases the risk of the sprayed solution drying out on the leaves and of leaf scorch. Thus, foliar fertilization is more demanding with respect to technical knowledge and management skills than is the conventional use of solid fertilizers. If not carried out appropriately, foliar fertilization with nitrogen or phosphorus will imply a considerable risk of causing negative yield responses.

Improvement of the nutrient use efficiency by foliar fertilization will have attractive economic and environmental benefits by reducing fertilizers costs, nitrous oxide emissions and nitrate leaching. This will be important for the future sustainability of agriculture in a scenario with carbon dioxide taxation and more strict environmental regulations. However, there is an urgent need for further studies of nutrient uptake efficiencies and crop yield responses in well-designed and well-executed field experiments. This is required in order to provide more detailed and better information about the optimization of foliar fertilization in relation to the complex interactions between crop parameters, application techniques and weather conditions. An important target for future innovation will be development of new nutrient formulations, adjuvants and synergists, that can prolong the duration of the period in which the sprayed solution remains as a liquid on the leaf surface and ensure rapid and efficient nutrient uptake with minimal risks of scorch. In addition, it will be essential to develop new sensor and spraying technologies for precision agriculture, including drone-based systems that may enable frequent applications of relatively low nutrient doses under optimum weather conditions.

Extended abstract

Foliar fertilization denotes a technique in which a liquid fertilizer solution is sprayed on the canopy of crop plants. This provides a possibility for rapid optimization of the nutritional status of crops, because the uptake of the applied nutrients will not be affected by soil processes delaying their availability. Using foliar fertilization, losses of nutrients via gaseous emissions and/or leaching may also be reduced. However, despite the potential advantages, foliar fertilization with nitrogen and phosphorus is not widely implemented in agriculture. This review presents a synthesis of the current state of knowledge of agronomic and environmental impacts of foliar fertilization with nitrogen and phosphorus. The main processes and factors affecting the efficiency of foliar fertilization are discussed along with the advantages and disadvantages compared to conventional solid fertilizers applied to the soil.

The uptake of nutrients by plant leaves occurs along several pathways including the cuticle, stomata and/or trichomes. The cuticle consists of hydrophobic (nonpolar) compounds, but cuticular cracks with water clusters may form a continuous connection between the outer and inner side of the cuticle in which hydrophilic solutes can diffuse across the cuticle. However, there is no experimental evidence documenting that these 'pores' have any quantitative importance in crops. Stomatal uptake of nutrients depends on hydraulic activation, a process in which a water sheet is formed in the stomatal aperture, connecting the solution in the cell walls with the outer surface of the leaf. Hydraulic activation does not take place in all stomata, but seems to be limited to about 10-20% of stomata present in leaves. Trichomes are specialized structures originating from epidermal cells, forming unicellular or multicellular, and branched or unbranched hairy structures. Trichomes are important for the retention of droplets on the leaf surface. In addition, together with fiber cells (sclereides) above leaf veins, the basal cells of the trichomes constitute a potential uptake pathway for nutrients applied to the leaf surface. Properties such as leaf angle, leaf area index, trichome abundance and cuticle hydrophobicity vary among plant species and with the growth stage of the crop. These properties influence the droplet retention by the leaves and, thus, the proportion of the sprayed solution that will stay on the leaves rather than reach the soil.

After nutrients applied to plant leaves have diffused into the apoplastic solution surrounding the leaf cells they need to cross the cell membranes before they can be assimilated or translocated to other plant parts. The uptake of nutrients into the leaf cells is mediated by specific proteins (transporters) in the cell membrane. Several types of transporters have been characterized in plants, including nitrate transporters (NRTs), ammonium transporters (AMTs), urea transporters (DUR3)

and phosphate transporters (PHTs). The role and regulation of these transporters in the uptake of nutrients by plant roots are well described, while much less is known about how the capacity of these transporters affects the uptake and storage of nutrients applied to leaves.

To achieve potential benefits of foliar fertilization, it is important to optimize the conditions for nutrient uptake across the leaf barriers as affected by nutrient form, the concentration of salts in the applied solution, and the application time in relation to crop developmental stage and weather conditions. Optimization of these parameters is also a requirement for avoidance of undesirable effects, e.g., leaf scorch and run-off of nutrient solution to the soil surface. Choosing a nitrogen salt with low point of efflorescence (POE) will, other things being equal, be important in foliar fertilization with nitrogen. Low POE implies that the applied nutrient source will stay in solution on the leaves for a greater period once the relative humidity of the air varies along the day (i.e., higher value close to the sunrise, decreasing by noon and with a slight increase until the evening). Foliar fertilization should be carried out when there is no forecast of rain in the next few days to prevent nutrients washing down to the soil. Within the day of application, foliar fertilization should not be carried out in the middle of the day, when the sun is shining and the air temperature is relatively high, as this increases the risk of the sprayed solution drying out on the leaves and of leaf scorch. In general, the optimal weather conditions for foliar fertilization are air temperatures between 10 and 20°C, relative air humidity greater than 50%, and wind speed below 2 m s^{-1}.

Urea is the preferred form of nitrogen used for foliar fertilization. This is the case because the uptake rate is faster and the risk of leaf scorch less compared to other nitrogen forms. Urea is taken up at a high rates during the first 4 to 8 hours after application. Depending on the urea rate applied, typically 80% will be absorbed within the first 24 hours after application. Only a very small proportion (<1%) of urea may hydrolyze while still being on the leaf surface. Thus, there is no significant ammonia volatilization from urea on the leaf surface. Nevertheless, only a relatively small amount of urea, 10-20 kg N ha^{-1}, should be applied per application event in order to minimize the risk of leaf scorch and washing-off of urea to the soil surface, where it be lost by ammonia volatilization. Adjuvants (spreading adhesives and humectants) should be added to the solution to reduce surface tension and ensure optimal leaf contact and absorption of nutrients by the leaves. By co-formulating urea solutions with phosphoric acid or sulphuric acid it is possible to lower the pH, which may reduce risks of ammonia volatilization. Urea-ammonium-nitrate (UAN) may be used as an alternative to urea, but seems to have slight lower efficiency and slightly higher risk of causing leaf scorch than urea. Foliar fertilization with 1 to 2 kg P ha^{-1} may increase the phosphorus content of the leaves, but yield responses need to be further documented under field conditions.

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Improvement of the nutrient use efficiency by foliar fertilization will have attractive economic and environmental benefits by reducing fertilizers costs, nitrous oxide emissions and nitrate leaching. This will be important for the future sustainability of agriculture in a scenario with carbon dioxide taxation and more strict environmental regulations. However, there is an urgent need for further studies of nutrient uptake efficiencies and crop yield responses in well-designed and well-executed field experiments. These further investigations are required to provide more detailed and better information about the optimization of foliar fertilization in relation to the complex interactions between crop parameters, application techniques and weather conditions. An important target for future innovation will be development of new nutrient formulations, adjuvants and synergists, that can prolong the duration of the period in which the sprayed solution remains as a liquid on the leaf surface and ensure rapid and efficient nutrient uptake with minimal risks of scorch. In addition, it will be essential to develop new sensor and spraying technologies for precision agriculture, including drone-based systems that may enable frequent applications of relatively low nutrient doses under optimum weather conditions.

Dansk resumé

Denne vidensyntese samler den publicerede viden om agronomiske og miljømæssige aspekter ved bladgødskning med kvælstof og fosfor. De vigtigste processer og faktorer, der påvirker effektiviteten af bladgødskning, diskuteres sammen med fordele og ulemper sammenlignet med brugen af faste eller flydende handelsgødninger, der tilføres jorden.

Sprøjtning af næringsstoffer direkte på planters blade giver mulighed for hurtig optimering af afgrødernes ernæringsstatus, fordi optagelsen af de tilførte næringsstoffer ikke bliver påvirket af jordprocesser, der forsinker deres tilgængelighed. Bladgødskning, hvor der typisk gødskes med mindre mængder ad flere gange, indebærer også bedre muligheder for at udskyde en del af gødningstilførslen, så der kan tages højde for afgrødernes udbyttepotentiale og næringsbehov under de aktuelle vækstbetingelser i den specifikke vækstsæson. I denne sammenhæng vil det være centralt at implementere nye sensorer og sprøjteteknologier til præcisionsjordbrug.

Urea er den foretrukne form for kvælstof til bladgødskning, fordi optagelseshastigheden er hurtigere og risikoen for bladsvidning mindre sammenlignet med andre kvælstofformer. Urea optages med høj hastighed i de første 4 til 8 timer efter tilførslen. Afhængigt af den tilførte mængde vil typisk mindst 80% blive absorberet inden for de første 24 timer efter udbringningen. Kun en meget lille andel (<1%) af urea hydrolyserer på bladoverfladen, inden det optages i bladet, hvorfor der ikke er en signifikant risiko for ammoniakfordampning fra urea på bladoverfladen. Ved bladgødskning med urea bør der alligevel kun anvendes en relativt lille mængde kvælstof pr. tilførsel, 10-20 kg N ha^{-1}, således at risikoen for bladsvidning og nedvaskning til jordoverfladen med efterfølgende ammoniaktab minimeres. Overfladeaktive stoffer (sprede-/klæbemidler) bør tilsættes opløsningen for at reducere overfladespændingen og sikre optimal bladkontakt og optagelse af næringsstoffer i bladene. Ved samformulering af ureaopløsninger med fosforsyre eller svovlsyre er det også muligt at sænke opløsningens pH, hvilket vil reducere risikoen for ammoniaktab. Urea-ammonium-nitrat (UAN) kan anvendes som alternative til urea, men synes at være lidt mindre effektiv og indebære lidt større risiko for bladsvidning end urea. Bladgødskning med 1-2 kg fosfor ha^{-1} medfører øget

fosforindhold i bladene, men betydningen af bladgødskning med fosfor for afgrødeudbytter og -kvalitet er endnu ikke tilstrækkeligt belyst under markforhold.

Et stort antal målinger af genfindelsen af kvælstof tilført via bladgødskning af forskellige afgrøder viser værdier fra 21 til 99%, hvor den brede variationen afspejler forskellige forsøgsbetingelser og anvendelsen af forskellige udbringningsmetoder. I gennemsnit er der opnået en genfindelse på 61% for forskellige afgrøder og 66% for hvede efter bladgødskning med urea. Baseret på disse gennemsnitlige værdier vurderes det, at der potentielt kan spares 14% kvælstof uden at reducere afgrødeudbytterne, hvis halvdelen af afgrødernes samlede kvælstofbehov tilføres ved bladgødskning. Resultater fra nye internationale markforsøg med bladgødskning af hvede og græs viser, at der selv efter tilførsel af 25-40% mindre kvælstof blev opnået samme udbytter som i kontrolparceller, der var fuldgødede med faste gødninger tilført jorden. I Danmark har markforsøg udført af SEGES Innovation ikke vist nogen fordele ved bladkvælstofgødskning.

Det konkluderes, at hvis bladgødskning udføres korrekt, vil det være muligt at opnå en højere næringsstofeffektivitet end tilfældet er ved sædvanlig jordbaseret gødskning. Dette kræver dog en omhyggelig optimering af betingelserne for bladenes optagelse af næringsstoffer, som afhænger af den tilførte næringsstofform, koncentrationen af salte i den tilførte opløsning, tilsætning af sprede-/klæbemidler og udbringningstidspunktet i forhold til afgrødens udviklingsstadie og vejrforhold. Bladgødskning er således mere krævende med hensyn til teknisk-biologisk viden og praktisk udførelse end sædvanlig brug af fast gødning. Der er behov for yderligere undersøgelser af effektiviteten af næringsstofoptagelse og udbytterespons i veltilrettelagte og veludførte markforsøg med henblik på at opnå et mere detaljeret og bedre grundlag for anvendelse af bladgødskning som redskab til bedre næringsstofudnyttelse. Et vigtigt mål for fremtidig innovation er udvikling af nye gødningsformuleringer, sprede-klæbemidler og bærestoffer, der forlænger varigheden af den periode, hvor den sprøjtede opløsning forbliver som væske på bladoverfladen og sikrer en hurtig og effektiv optagelse med minimal risiko for bladsvidning. Derudover vil det være centralt at udvikle nye sensor- og sprøjteteknologier til præcisionsjordbrug, herunder dronebaserede systemer, der kan anvendes til hyppige udsprøjtninger af relativt små næringsstofmængder under optimale vejrmæssige forhold.

Den potentielle forbedring af næringsstofeffektiviteten ved bladgødskning sammenlignet med faste gødninger tilført til jorden vil have attraktive økonomiske og miljømæssige fordele i form af reducerede gødningsomkostninger, lattergasemissioner og nitratudvaskning, og dermed kan bladgødskning være relevant for jordbrugets planteproduktion, der i stigende grad mødes med krav om reduktion af klimagasser og miljøpåvirkninger.

Udvidet dansk resumé

Denne vidensyntese samler den publicerede viden om agronomiske og miljømæssige aspekter ved bladgødskning med kvælstof og fosfor. De vigtigste processer og faktorer, der påvirker effektiviteten af bladgødskning, diskuteres sammen med fordele og ulemper sammenlignet med brugen af faste eller flydende handelsgødninger, der tilføres jorden.

Sprøjtning af næringsstoffer direkte på planters blade giver mulighed for hurtig optimering af afgrødernes ernæringsstatus, fordi optagelsen af de tilførte næringsstoffer ikke bliver påvirket af jordprocesser, der forsinker deres tilgængelighed. Bladgødskning, hvor der typisk gødskes med mindre mængder ad flere gange, indebærer også bedre muligheder for at udskyde en del af gødningstilførslen, så der kan tages højde for afgrødernes udbyttepotentiale og næringsbehov under de aktuelle vækstbetingelser i den specifikke vækstsæson. I denne sammenhæng vil det være centralt at implementere nye sensorer og sprøjteteknologier til præcisionsjordbrug.

Optagelsen af næringsstoffer igennem planters blade følger forskellige transportveje. Disse omfatter kutikulaen, spalteåbningerne (stomata) og/eller trikomerne. Kutikulaen består af hydrofobe (non-polære) forbindelser, men vandfyldte revner og sprækker i kutikulaen kan udgøre en kontinuert film, hvorigennem opløste stoffer kan diffundere. Der er dog ikke eksperimentel evidens for, at sådanne kutikulære 'porer' har en betydning i afgrødeplanter. Optagelse af næringsstoffer igennem stomata afhænger af, at disse bliver hydraulisk aktiveret, en proces hvorved der i spalteåbningen dannes en vandfilm, som forbinder cellevæggen med ydersiden af bladet. Hydraulisk aktivering sker ikke i alle stomata, men synes at være begrænset til 10-20% af spalteåbningerne. Trikomer er specialiserede hårlignende strukturer, der dannes af de ydre bladceller (epidermis). Trikomer kan være en- eller flercellede, og være forgrenede eller ugrenede. De basale celler af trikomerne udgør, sammen med fiberceller (sklereider) over bladvenerne, en potentiel transportvej for optagelse af næringsstoffer. Egenskaber som bladvinkel, bladarealindeks, tætheden af trikomer og hydrofobicitet af kutikulaen varierer mellem forskellige plantearter og med planternes udviklingstrin. Disse egenskaber påvirker bladenes evne til opfange og fastholde dråberne i den udsprøjtede næringsstofopløsning og dermed, hvor store en del af den udsprøjtede opløsning, der afsættes på afgrøden fremfor at havne på jorden.

Efter at næringsstoffer udsprøjtet på planteblade er diffunderet ind i den vandige opløsning (apoplasten) i cellevæggene omkring bladcellerne, skal de krydse cellemembranerne, før de kan assimileres eller translokeres til andre plantedele. Optagelsen af næringsstoffer i bladcellerne katalyseres af specifikke proteiner (transportører) i cellemembranen. Flere typer transportører er blevet karakteriseret i planter, herunder transportører for nitrat (NRT'er), ammonium (AMT'er), urea (DUR3) og fosfat (PHT'er). Funktionen og reguleringen af transportproteiner i planterødder er velbeskrevet, mens man ved meget mindre om, hvordan kapaciteten af disse transportører påvirker optagelsen og lagringen af næringsstoffer tilført bladene.

For at udnytte de potentielle fordele ved bladgødskning er det vigtigt at optimere betingelserne for optagelse af næringsstoffer gennem bladoverfladebarrieren. Denne optagelse påvirkes af form og koncentration af næringsstoffet og andre salte i den udsprøjtede opløsning, afgrødens udviklingsstadium og vejrforholdene omkring udbringningstidspunktet. Optimering af disse parametre er også en forudsætning for at undgå uønskede effekter, fx bladsvidning og afstrømning af næringsopløsning til jordoverfladen. Valg af en næringsstofformulering, der ikke krystalliserer, men forbliver i opløsning i en længere periode ved faldende luftfugtighed (lav point of efflorescence, POE), vil alt andet lige være en fordel ved bladgødskning. Bladgødskning bør ikke udføres midt på dagen, hvis solen skinner, lufttemperaturen er forholdsvis høj og luftfugtigheden forholdsvis lav, da dette øger risikoen for, at den udsprøjtede opløsning udtørrer på bladeoverfladen. For at undgå, at de udsprøjtede næringsstoffer nedvaskes fra bladene til jorden, bør bladgødskning endvidere ikke udføres, når der er udsigt til regn den efterfølgende dage. Generelt er de optimale vejrforhold for bladgødskning en lufttemperatur mellem 10 og 20°C, en relativ luftfugtighed over 50% og en vindhastighed under 2 m s^{-1}.

Urea er den foretrukne form for kvælstof til bladgødskning, fordi optagelseshastigheden er hurtigere og risikoen for bladsvidning mindre sammenlignet med andre kvælstofformer. Urea optages med høj hastighed i de første 4 til 8 timer efter tilførslen. Afhængigt af den tilførte mængde vil typisk mindst 80% blive absorberet inden for de første 24 timer efter udbringningen. Kun en meget lille andel (<1%) af urea hydrolyserer på bladoverfladen, inden det optages i bladet, hvorfor der ikke er en signifikant risiko for ammoniakfordampning fra urea på bladoverfladen. Ved bladgødskning med urea bør der alligevel kun anvendes en relativt lille mængde kvælstof pr. tilførsel, 10-20 kg N ha^{-1}, således at risikoen for bladsvidning og nedvaskning til jordoverfladen med efterfølgende ammoniaktab minimeres. Overfladeaktive stoffer (sprede-/klæbemidler) bør tilsættes opløsningen for at reducere overfladespændingen og sikre optimal bladkontakt og optagelse af næringsstoffer i bladene. Ved samformulering af ureaopløsninger med fosforsyre eller svovlsyre er det også muligt at sænke opløsningens pH, hvilket vil reducere risikoen for ammoniaktab. Urea-ammonium-nitrat (UAN) kan anvendes som alternative til urea, men synes at være lidt mindre effektiv og indebære lidt større risiko for bladsvidning end urea. Bladgødskning med 1-2 kg fosfor ha^{-1} medfører øget fosforindhold i bladene, men betydningen af bladgødskning med fosfor for afgrødeudbytter og -kvalitet er endnu ikke tilstrækkeligt belyst under markforhold.

Et stort antal målinger af genfindelsen af kvælstof tilført via bladgødskning af forskellige afgrøder viser værdier fra 21 til 99%, hvor den brede variationen afspejler forskellige forsøgsbetingelser og anvendelsen af forskellige udbringningsmetoder. I gennemsnit er der opnået en genfindelse på 61% for forskellige afgrøder og 66% for hvede efter bladgødskning med urea. Baseret på disse gennemsnitlige værdier vurderes det, at der potentielt kan spares 14% kvælstof uden at reducere afgrødeudbytterne, hvis halvdelen af afgrødernes samlede kvælstofbehov tilføres ved bladgødskning. Resultater fra nye internationale markforsøg med bladgødskning af hvede og græs viser, at der selv efter tilførsel af 25-40% mindre kvælstof blev opnået samme udbytter som i kontrolparceller, der var fuldgødede med faste gødninger tilført jorden. I Danmark har markforsøg udført af SEGES Innovation ikke vist nogen fordele ved bladkvælstofgødskning.

Det konkluderes, at hvis bladgødskning udføres korrekt, vil det være muligt at opnå en højere næringsstofeffektivitet end tilfældet er ved sædvanlig jordbaseret gødskning. Dette kræver dog en omhyggelig optimering af betingelserne for bladenes optagelse af næringsstoffer, som afhænger af den tilførte næringsstofform, koncentrationen af salte i den tilførte opløsning, tilsætning af sprede-/klæbemidler og udbringningstidspunktet i forhold til afgrødens udviklingsstadie og vejrforhold. Bladgødskning er således mere krævende med hensyn til teknisk-biologisk viden og praktisk udførelse end sædvanlig brug af fast gødning. Der er behov for yderligere undersøgelser af effektiviteten af næringsstofoptagelse og udbytterespons i veltilrettelagte og veludførte markforsøg med henblik på at opnå et mere detaljeret og bedre grundlag for anvendelse af bladgødskning som redskab til bedre næringsstofudnyttelse. Et vigtigt mål for fremtidig innovation er udvikling af nye gødningsformuleringer, sprede-klæbemidler og bærestoffer, der forlænger varigheden af den periode, hvor den sprøjtede opløsning forbliver som væske på bladoverfladen og sikrer en hurtig og effektiv optagelse med minimal risiko for bladsvidning. Derudover vil det være centralt at udvikle nye sensor- og sprøjteteknologier til præcisionsjordbrug, herunder dronebaserede systemer, der kan anvendes til hyppige udsprøjtninger af relativt små næringsstofmængder under optimale vejrmæssige forhold.

Den potentielle forbedring af næringsstofeffektiviteten ved bladgødskning sammenlignet med faste gødninger tilført til jorden vil have attraktive økonomiske og miljømæssige fordele i form af reducerede gødningsomkostninger, lattergasemissioner og nitratudvaskning, og dermed kan bladgødskning være relevant for jordbrugets planteproduktion, der i stigende grad mødes med krav om reduktion af klimagasser og miljøpåvirkninger.

1. Introduction

Foliar fertilization denotes a technique in which a liquid fertilizer solution is sprayed directly on the canopy of crop plants. Liquid fertilizers incorporated into the soil or sprayed on plants at high volume rates promoting run-off from the canopy to the soil are not considered to represent foliar fertilization. Foliar fertilization provides a potentially valuable possibility for rapid optimization of the nutritional status of crops, because the uptake of the applied nutrients will not be affected by soil processes delaying their availability. Such delay may, e.g., be the case when solid granular fertilizers are applied to dry soils where lack of ample soil moisture slows down the dissolution of the fertilizer grains and the transport of nutrients to the roots. Delayed nutrient availability may especially be a problem when fertilizers are split so that part of the total crop nutrient requirement is applied relatively late in the growing season. Nitrogen fertilizers applied to winter cereal crops are generally split in three to four dressings in order to obtain high yield and high grain protein content, without increasing lodging risk, attack of fungal pathogens and other problems associated with nitrogen fertilization. In addition, applications later in the growing season have the advantage that fertilizer rates can be adjusted according to plant nutritional status, determined by sensors (e.g., satellite data), and current weather conditions.

Using foliar fertilization, soil processes causing losses of nutrients via gaseous emissions and/or leaching can be reduced or completely avoided. Emission of ammonia (NH_3) and nitrous oxide (N_2O) may occur when nitrogen-containing fertilizers are applied to soil. Nitrous oxide is a potent greenhouse gas, while NH_3 emission leads to eutrophication and acidification of natural ecosystems when the emitted NH_3 subsequently becomes deposited. Leaching of nitrogen to groundwater and surface water bodies takes place in the form of nitrate (NO_3^-), originating either directly from applied fertilizers or formed when soil organic matter is mineralized and the resulting ammonium (NH_4^+) nitrified. In contrast to nitrate, phosphate is strongly adsorbed to soil particles, which limits its availability to plants, causing less than 15-20% of the applied fertilizer to be plant available. Bypassing soil nitrogen immobilization and phosphorus adsorption will actually be one of the main advantages of foliar fertilization, potentially increasing the nutrient use efficiency and reducing losses to the environment (Fageria et al., 2009; Eichert and Fernández, 2012).

Foliar fertilization with micronutrients is carried out as a standard management operation in agriculture and horticulture (Fernández and Brown, 2013; Niu et al., 2021; Ishfaq et al., 2022). However, despite the potential advantages, foliar fertilization with nitrogen and phosphorus is not widely implemented in agriculture. The main reasons are uncertainties about how and when foliar fertilization should be carried out and what the advantages and disadvantages compared to conventional solid fertilizers will be. A major challenge of foliar fertilization is to maximize the nutrient use efficiency without causing crop damages in the form of leaf scorch. A number of crop parameters such as developmental stage and nutrient requirement during the growing season must be taken into account along with the physicochemical properties of the applied fertilizer solution, e.g., pH, electrical conductivity, purity, deliquescence and efflorescence point. Several studies have been carried out focusing on the physical-chemical properties of the solution by addition of adjuvants. These compounds increase the adhesion of the solution to the leaf surface by reducing the surface tension and contact angle of the fertilizer droplets (Hazen, 2000; Zabkiewicz, 2000; Fernández and Eichert, 2009; Peirce et al., 2019). Finally, weather conditions during and shortly after foliar fertilization must be taken into account in order to optimize the uptake of nutrients before the sprayed solution dries out on the leaf surface or becomes washed off by rainfall (Fernández and Brown, 2013; Fernández et al., 2013, 2020; Peirce et al., 2019).

The main objective of the present work is to present the state-of-the-art of foliar fertilization with nitrogen and phosphorus. Emphasis is given to crop and management parameters important for the optimizing the yield response and the nutrient use efficiency of the applied foliar fertilizer. Prospects with respect to using foliar fertilization as a technique to minimize the negative environmental effects associated with the use of fertilizers in agriculture are discussed. Finally, needs for future research are pointed out.

2. Nutrient uptake by leaves

2.1. Uptake pathways and anatomical barriers

The uptake of nutrients by plant leaves occurs along several pathways including the cuticle, stomata and/or trichomes (Fernández and Eichert, 2009; Li et al., 2019; Schreel et al., 2020; Fernández et al., 2021).

The cuticle constitutes part of the outer cell wall covered by epicuticular wax (Figure 1). The composition of the cuticle is diverse, embracing different proportions of hydrophobic (nonpolar) compounds, e.g., wax, cutin, and cutane, as well as hydrophilic (polar) compounds, e.g., polysaccharides such as cellulose, pectin, and hemicellulose (Fernández et al., 2016, 2017). Cuticular waxes are divided into epicuticular and intracuticular waxes, the former consisting of aldehydes, alkanes, primary alcohols, secondary alcohols, and ketones, while the latter is made of terpenoids and sterols. The epicuticular waxes have different crystal shape types including plates, platelets, ribbons, rods, and threads (Bi et al., 2016). The cuticle has a low permeability for gases, solutes, and water, thereby negatively impacting the uptake of nutrients applied to the leaves (Eichert and Fernández, 2012).

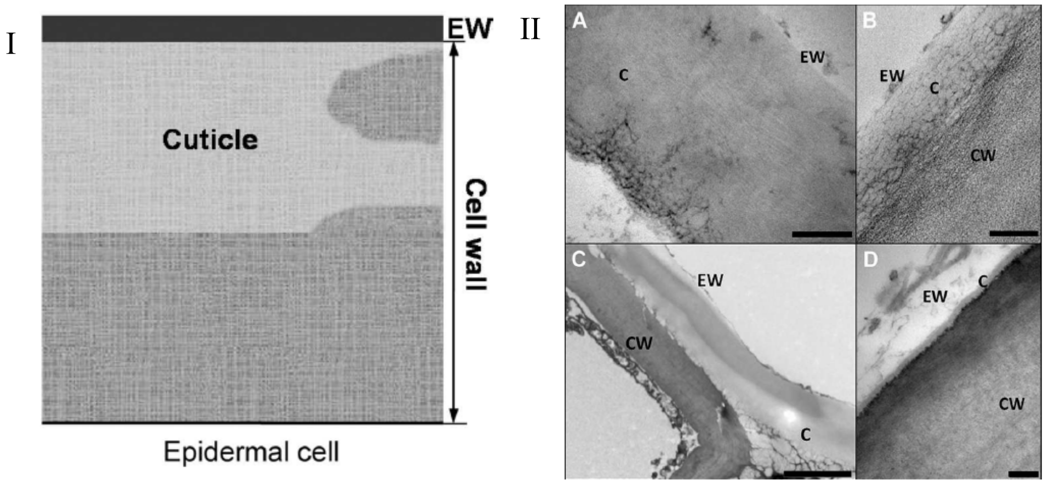

Figure 1. I. The cuticle represented as a lipidized, chemically, and structurally heterogeneous region of the epidermal cell wall; **II.** Structural heterogeneity of plant cuticles, exemplified by transversal Transmission Electron Microscopy (TEM) of leaf cuticle sections of (A) pear (*Pyrus communis*; bar, 200 nm), (B) poplar (*Populus bolleana;* bar, 200 nm), (C) Magellan's beech (*Nothofagus betuloides*; bar, 2 mm), and (D) wheat (*Triticum aestivum*; bar, 50 nm). Abbreviations: C: cuticle, CW: cell wall, and EW: epicuticular waxes. Reprinted from Fernández et al. (2016).

Nutrient transport through the cuticle takes place due to a concentration gradient between the internal and external medium of the leaf, driving nutrients to be transported from the compartment with the highest to the lowest concentration (Riederer and Friedmann, 2006; Bi and Scagel, 2008; Fernández and Brown, 2013). The diffusion rate is controlled by the magnitude of the concentration gradient, the size and charge of the nutrient ion/molecule as well as the chemical composition of the cuticle and cell wall (Khayet and Fernández, 2012). Cuticular diffusion was initially proposed to take place via polar aqueous 'pores' created by clusters of water associated with relatively hydrophilic cell wall compounds such as cellulose, pectin and hemicellulose (Figure 2I) (Schönherr, 2006). The model was modified by Fernández et al. (2017), taking into account variations in the hydration of the cuticle, leading to the concept of a dynamic polar pore (Figure 2 II). The model assumes that under dry atmospheric conditions, only low amounts of water will be absorbed by the outer cuticle. Consequently, only a few functional aqueous connections traversing the cuticle will exist. With increasing air humidity or after leaf surface wetting by foliar spraying, more water will be absorbed by the cuticle from the outer side and cuticular cracks may emerge. This increases the probability that water clusters will form a continuous connection between the outer and inner side of the cuticle

(Figure 2 II) in which hydrophilic solutes can diffuse across the cuticle (Fernández et al., 2017). So far this is all theory and there is no experimental evidence that these 'pores' have any quantitative importance in crops.

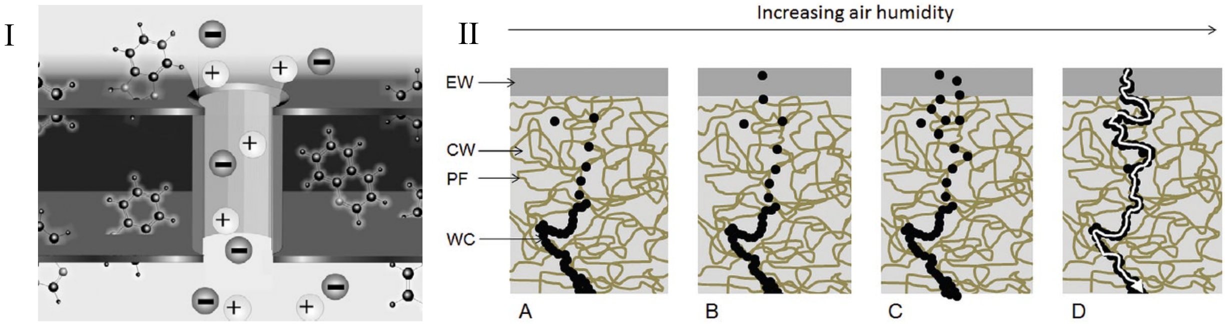

Figure 2. I. Schematic drawing of a membrane traversed by an aqueous pore. Non-charged molecules dissolve in the membrane matrix, while ions are restricted to the aqueous pore. To maintain electroneutrality, cations and anions must penetrate in equivalent amounts; **II.** Model of the formation of an aqueous connection traversing the cuticle. In this simplified model, the cuticle consists of a matrix of cutin and waxes (CW) interspersed with hydrophilic domains provided by polysaccharides fibrils (PC). The overlying layer of epicuticular waxes (EW) facing the outer side is devoid of polysaccharides. Water clusters (WC) are formed by adsorption of water by the hydrophilic domains. If air humidity is low, water clusters mainly originate from the epidermal cells underneath the cuticle (A). With increasing external air humidity, more water is sorbed by the cuticle from the outer surface (A–C). At high humidity, a tortuous connection between the leaf surface and the leaf interior emerges (D). Externally applied solutes may diffuse in these connections through the cuticle (white arrow in D). For clarity, other water clusters in the cuticle adjacent to the depicted emerging connection are not shown. Reprinted from Schönherr (2006) and Fernández et al. (2017).

Stomata offer a potential pathway for the uptake of nutrients applied to the leaves of plants (Burkhardt, 2010; Burkhardt et al., 2012). Initially, the stomatal pathway was thought to be mediated only by mass flow, i.e., movement of water with dissolved nutrients (Eddings and Brown, 1967). This assumption was questioned by Schönherr and Bukovac (1978) and Maier-Maercker (1983), arguing that the wetting required for mass flow is not likely to occur, because the guard cells and accessory cells surrounding the stomatal aperture are covered by hydrophobic cuticle structures. However, wetting of the stomatal pore is indeed possible and it has been shown that the uptake of ionic solutes increases with stomatal density and opening (Eichert and Burkhardt, 2001) and that certain substances can only be absorbed via the stomata (Eichert and Goldbach, 2008; Eichert et al., 2008). Stomatal uptake depends on hydraulic activation of the stomata (Figure 3), a process in which a water sheet is formed in the stomatal aperture, connecting the apoplast and the outer surface of the leaf (Burkhardt et al., 2009; Burkhardt, 2010). Hydraulic activation does not take place in all stomata, but seems to be limited to about 10-20% of stomata present in leaves and seems to be triggered by the deposition of hygroscopic aerosols on the leaf surface (Eichert et al., 2008). Following hydraulic activation, solutes (e.g., nutrient ions) may be absorbed via the stomata by diffusion and mass flow (Figure 3). In addition, uptake of particles may be promoted via Brownian movements in the water continuum, providing a possible route for the uptake of nanoparticle phosphorus fertilizers (Husted et al., 2022). The stomatal density differs among crop species which can influence the efficiency of foliar fertilizers. Crops also differ in their distribution of stomata on the adaxial and abaxial sides. Wheat has a relatively high stomatal density and accordingly an efficient uptake of foliar nutrients (Ishfaq et al., 2022). The uptake of applied phosphate through the adaxial leaf surface of wheat is higher compared to the abaxial due to higher density of stomates and trichomes (Peirce et al., 2014). Conversely, potato has a much larger number of stomates on the abaxial leaf surface compared to the adaxial. In maize, the uptake of phosphorus was similar whether foliar P-fertilizer (KH_2PO_4) was applied to the ad- or abaxial side of the leaf (Görlach and Mühling, 2021).

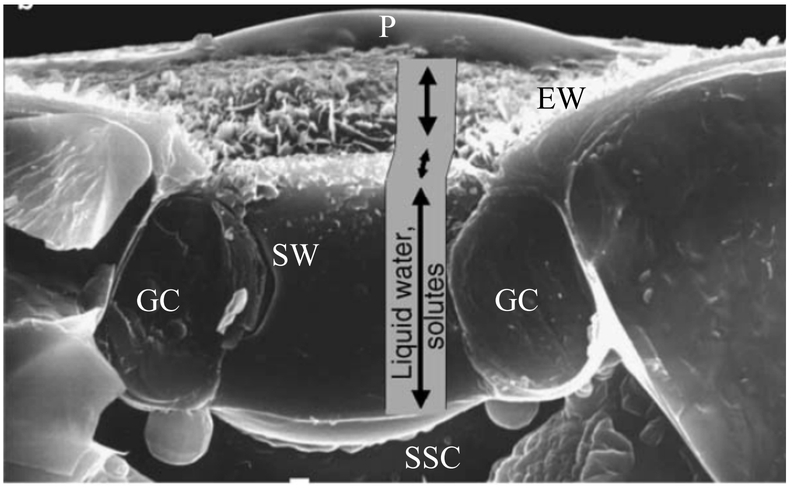

Figure 3. Cryo-scanning electron microscopy image of a stomatal pore of *Allium cepa* with an amorphous salt particle on the surface. The dimension of the pore is about 15 µm. Hydraulic activation of stomata is established, enabling stomatal transport of solutes and liquid water (solid arrows) in either direction. Abbreviations: EW: epicuticular waxes, GC: guard cells, P: particle, SSC: substomatal cavity, and SW: stomatal wall. Reprinted from Burkhardt (2010).

Trichomes are specialized structures on the leaf surface (Watts and Kariyat, 2021). They originate from epidermal cells, forming unicellular or multicellular, and branched or unbranched hairy structures. The type, density, size and composition of trichomes vary among plant species. Trichomes are important for the retention of droplets on the leaf surface (Winkler and Zotz, 2010; Li et al., 2018). In addition, together with fiber cells (sclereides) above leaf veins, the basal cells of the trichomes constitute a potential uptake pathway for nutrients applied to the leaf surface as illustrated in Figure 4 for phosphorus (Arsic et al., 2022) and zinc (Li et al., 2021). Cuticular parameters, including trichome density, wax shape and composition, may be important for differences between wheat genotypes in ability to absorb foliar-applied urea (Kirika, 2021).

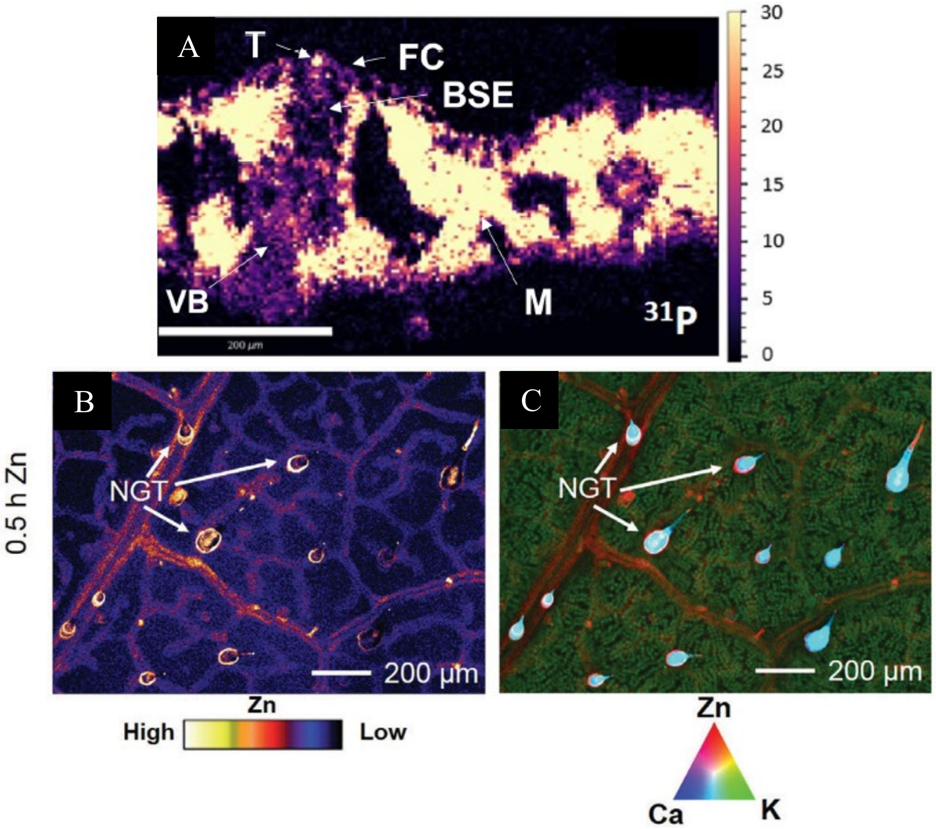

Figure 4. A. LA-ICP-MS scans of P-deficient leaf cross-section at flag leaf emergence showing the ^{31}P elemental distributions. Following foliar phosphorus application, P signal intensities increased throughout the leaf cross-section and were highest in the mesophyll tissue, with a small hotspot identifiable in an adaxial trichome. Elemental scale bars indicate counts (signal intensity). **B** and **C.** X-ray fluorescence microscopy images showing Zn distribution in sunflower leaves after Zn had been applied for 0.5 h before being excised; in (B) brighter colours show higher Zn concentrations and in (C) red shows Zn, green shows K, and blue shows Ca. Abbreviations: BSE: bundle sheath extension, FC: fiber cell, M: mesophyll, NGT: non-glandular trichome, T: trichome, and VB: vascular bundle. Reprinted from Arsic et al. (2022) and Li et al. (2021).

2.2. Physiological regulation

A range of physiological processes, which interact with the nutritional status of plants and the environmental conditions when the foliar fertilization is carried out, affect the uptake of nutrients across the leaf surface and their subsequent assimilation.

2.2.1. Stomatal opening and closure

As described above, nutrients applied to the leaves can be absorbed through the cuticle, stomates and trichomes. Only the stomatal pathway is under dynamic physiological control, while all three pathways will be affected by environmental conditions (see section 3.4).

The opening and closing of stomata are tightly regulated to reduce excess water loss, while maintaining the uptake of carbon dioxide for photosynthesis. Stomatal opening and closure are mediated by multiple pathways (Misra et al., 2015). Influx of K^+ in the guard cells causes a decrease in the osmotic potential leading to water movement into the guard cells and opening of the stomates. Oppositely, stomatal closure is promoted by K^+ and water efflux from the guard cells. In addition, nitrate is an osmotic component contributing to stomatal movements (Wang et al., 2018). The plant hormone abscisic acid (ABA), which accumulates under stress conditions (e.g., drought) is involved in the regulation of the ion fluxes leading to opening or closure of the stomates (Bharath et al., 2021). The guard cells also respond to external factors such as changes in light intensity and relative air humidity (Guzmán-Delgado et al., 2021). These factors may accordingly affect the uptake of foliar-applied nutrients.

2.2.2. Uptake of nutrients into leaf cells

After nutrients applied to plant leaves have diffused into the apoplastic solution surrounding the leaf cells they need to cross the cell membranes before they can be assimilated or translocated to other plant parts. The uptake of nutrients into the leaf cells is mediated by specific proteins (transporters) in the cell membrane. Several types of transporters have been characterized including nitrate transporters (NRTs), ammonium transporters (AMTs), urea transporters (DUR3) and phosphate transporters (PHTs). The role and regulation of these transporters in the uptake of nutrients by plant roots are well described, while much less is known about how the capacity of these transporters affects the uptake and storage of nutrients applied to leaves.

Nitrogen

At the molecular level, nitrogen transporter genes are regulated differently depending on the level and form of nitrogen supply (urea, ammonium, and nitrate). For example, some transporters are specifically induced and upregulated by nitrate while others are nitrate repressible (Hawkesford et al., 2023). Stable-isotope labeling has shown that the foliar uptake of different nitrogen forms by wheat leaves occurs rapidly and efficiently regulating root nitrate uptake (Kirika, 2021) (see section 3.2.2.).

Nitrate uptake and assimilation

In higher plants, there are two types of transporters involved in nitrate transport. These transporters belong to the NPF (NRT1/PTR; Nitrate Transporter 1/Peptide Transporter Family) or the NRT2 (Nitrate Transporter 2) families. It is generally assumed that the NPF (previously named NRT1/PTR) and NRT2 transporters mediate low- and high-affinity transport of nitrate into roots, respectively, except NPF6.3 (NRT1.1) which can exhibit both high- and low-affinity transport (Wang et al., 2018). Low-affinity transporters may significantly contribute to nitrate uptake at external nitrate concentrations in the millimolar range, while high-affinity transporters mediate nitrate uptake at lower external concentrations (Hawkesford et al., 2023).

Several members of the NPF family of nitrate transporters have been found to exert a specific role in terms of controlling nitrate distribution within the shoot (Figure 5). AtNPF7.2 (NRT1.8) is likely to mediate unloading of nitrate from the xylem for uptake into leaf cells in the shoot in addition to its role in the root of unloading nitrate from the xylem. AtNPF6.2 (NRT1.4) is involved in controlling the nitrate content of the leaf petiole (Wang et al., 2018).

The concentration of nitrate in the phloem is generally low (µM) and regulation of nitrate distribution via the phloem has for many years believed to be of limited importance. However, it was recently reported that AtNPF2.13 (NRT1.7) encodes a low-affinity nitrate transporter, which is expressed in the phloem of the minor veins of older leaves and transports nitrate across the plasma membrane into the phloem (Chen et al., 2020). Such a transport step would potentially allow nitrate remobilization from older (source) leaves to N-demanding (sink) tissues under N starvation. Disruption of NPF2.13 increased the accumulation of nitrate in old leaves, while less nitrate was detected in the phloem exudates of old leaves (Chen et al., 2020). Overexpression of OsNRT2.3, a plasma membrane transporter expressed mainly in the phloem, where it switches nitrate transport activity on or off by a pH-sensing mechanism, significantly improved grain yield and nitrogen use efficiency in rice (Fan et al., 2016).

Nitrate must be reduced to ammonium before the nitrogen can be used for protein biosynthesis. Nitrate reduction is catalyzed by two enzymes; nitrate reductase, with an iron (Fe) and molybdenum (Mo) domain (Figure 6A), mainly located in the cytosol of root cells as well as in shoot mesophyll cells, and nitrite reductase, located in the chloroplast of leaves and plastids of roots

(Figure 6B) (Xiong et al., 2012; Hawkesford et al., 2023). Nitrate assimilation by plants is energetically more costly than ammonium assimilation; however, nitrate can be stored in the vacuoles, while ammonium cannot to the same extent (Hawkesford et al., 2023).

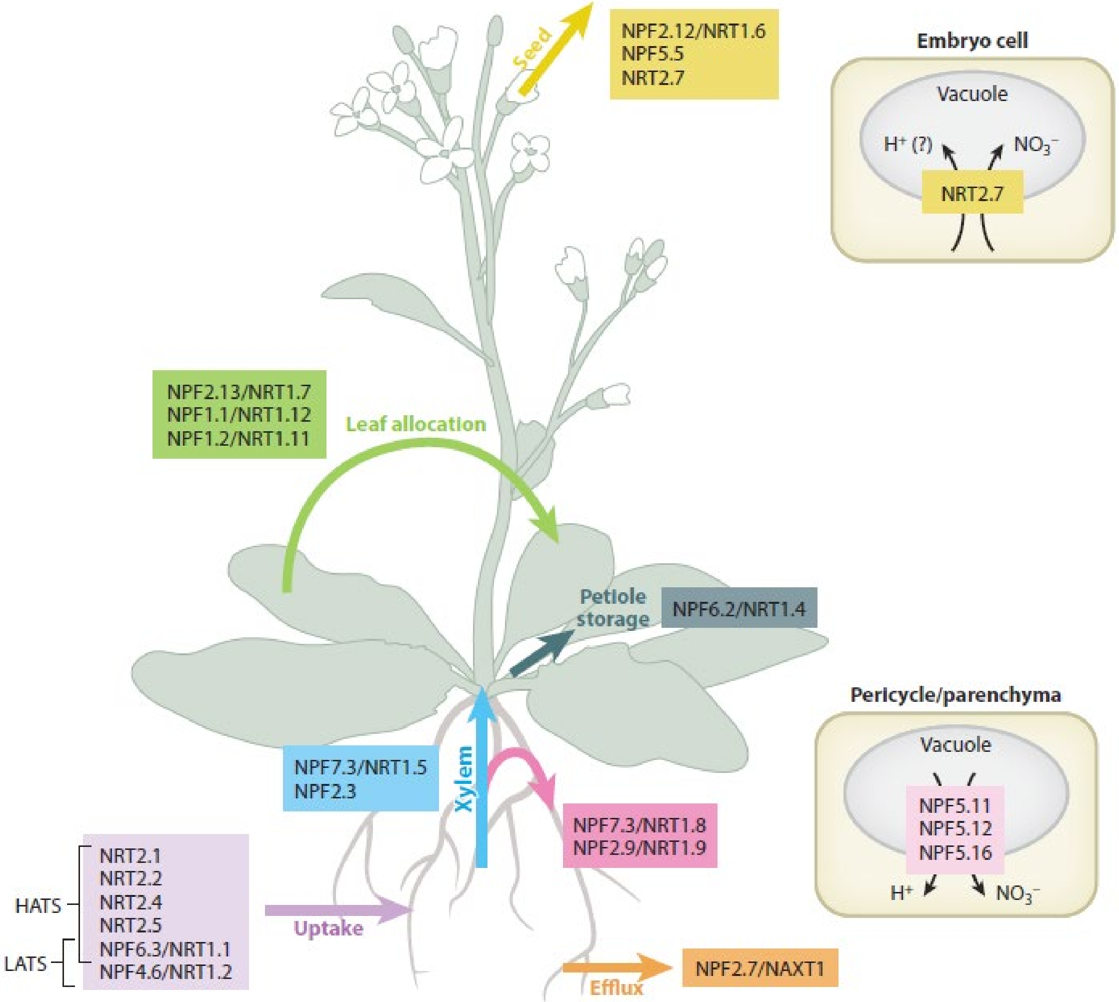

Figure 5. Physiological functions of *Arabidopsis* NPF and NRT nitrate transporters, showing roles in nitrate uptake and efflux from soil, root-to-shoot transport, nitrate allocation among leaves, and seed development. Abbreviations: HATS, high-affinity transport system; LATS, low-affinity transport system; NAXT, Nitrate Excretion Transporter; NPF, Nitrate Transporter 1 (NRT1)/Peptide Transporter (PTR) family; NRT, Nitrate Transporter. Reprinted from Wang et al. (2018).

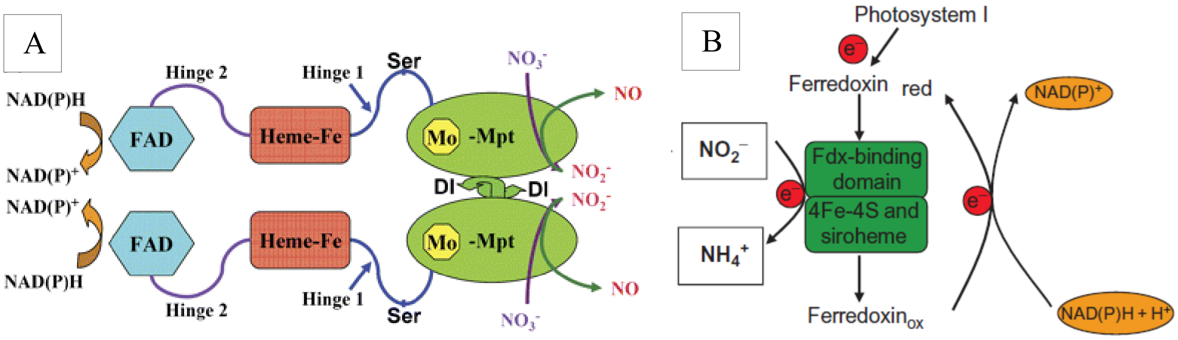

Figure 6. A. Structural and function of nitrate reductase (FAD domain accepts two electrons from NAD(P)H, and then the electrons are transferred via heme-Fe to Mo-Mpt, in which nitrate is reduced to nitrite and then nitrite is reduced to NO. The heme-Fe domain connects the FAD domain with hinge 2 while it connects Mo-Mpt with hinge 1, in which a serine residue is carried. DI indicates the dimer interface domain. FAD: flavine adenine dinucleotide, Ser: serine, Mo: molybdenum, Mpt: molybdopterin, NAD(P)H: nicotinamideadenine dinucleotide phosphate; **B.** Structure and function of nitrite reductase (in green leaves, the electron donor is reduced ferredoxin, generated by photosystem I during photosynthetic electron transport in the light. Electrons from the reduced ferredoxin are passed to nitrite via a ferredoxin-binding domain, an iron–sulphur cluster, and a siroheme co-factor bound to the nitrite reductase enzyme. Reprinted from Xiong et al. (2012) and Hawkesford et al. (2023).

Ammonium transport and assimilation

Foliar fertilization with ammonium or urea leads to a dramatic increase in the concentration of ammonium in the apoplastic solution surrounding the leaf cells (Britto and Kronzucker, 2002; Li et al., 2014). Ammonium uptake into the leaf cells is catalyzed by members of the AMT family of ammonium transporters (Hao et al., 2020). AMT transporters have been identified in many plant species and include the AMT1 sub-family, which transports ammonium via ammonium (NH_4^+) uniport or NH_3/H^+ symport, or the AMT2/MEP sub-family which contains the ammonia channel AmtB. Functional AMT transporters are found in leaves of many crop species and may be upregulated or downregulated spatially or temporarily to deal with different requirements for ammonium transport (Hao et al., 2020). The uptake of ammonium in leaf cells is very rapid (Nielsen and Schjoerring, 1998). After being taken up, ammonium is assimilated or stored in vacuoles. Generally, cytosolic levels of ammonium range from 1 to 30 mM. In vacuoles, the concentration of ammonium in non-stressed plants range from 2 to 45 mM. Cytosolic NH_3 is passively transported across the vacuolar membrane (the tonoplast) where the acidic environment traps NH_3 as NH_4^+. Ammonia and water have similar sizes and polarity. This resemblance allows NH_3 to permeate water channels in some cases. Accordingly, members of the Tonoplast Intrinsic Proteins (TIP) have been shown to play a role in NH_3 import into the vacuole (Loqué et al., 2005). Excessive NH_4^+ accumulation may cause cell damage, promoting leaf scorching (Castro et al., 2022).

Ammonium assimilation in leaves is mainly mediated by glutamine synthetase (GS) and 2-oxoglutarate aminotransferase (GOGAT or glutamate synthase) (Figure 7). This process produces glutamine (Gln) and requires glutamate (Glu) as substrate for the acceptor for ammonium. Subsequentially, Gln is assimilated into glutamate (Glu), due to the reaction with 2-oxoglutarate originating from the tricarboxylic acid cycle (or from the Krebs cycle which is the main source of energy for cells which occurs in the mitochondria). Gln can also be assimilated directly into asparagine, due to the reaction with aspartate catalyzed by asparagine synthetase. Gln and Glu amino acids will be used to produce other nitrogen compounds, e.g., others amino acids, proteins, and nucleotides (Liu et al., 2022).

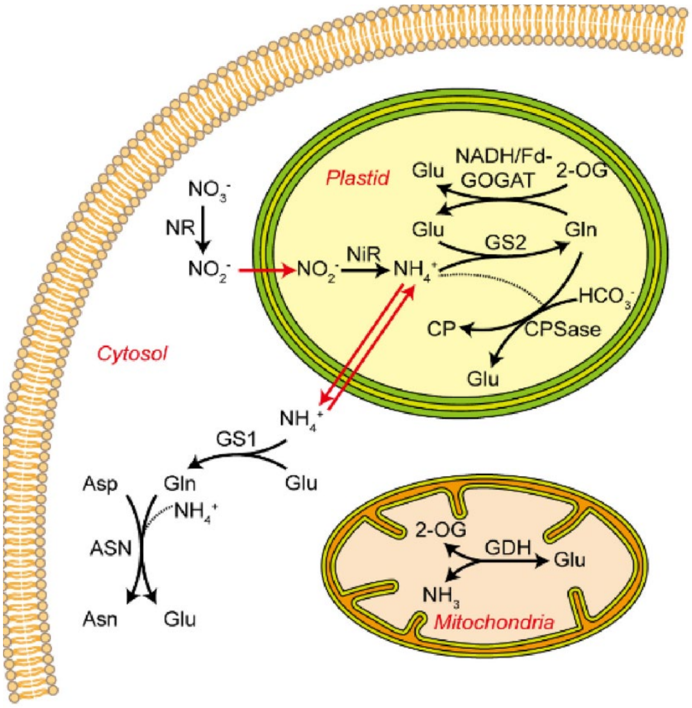

Figure 7. Diagram of nitrogen assimilation in wheat. 2-OG: 2-oxoglutarate; Asn: asparagine, ASN: asparagine synthetase, Asp: aspartate, CP: carbamoylphosphate, CPSase: carbamoylphosphate synthetase, GDH: glutamate dehydrogenase, Gln: glutamine, Glu: glutamate, GOGAT: glutamine-2-oxoglutarate aminotransferase, GS: glutamine synthetase, NiR: nitrite reductase, NR: nitrate reductase. Reprinted from Liu et al. (2022).

Urea uptake and metabolism

Urea uptake from the leaf apoplast is mediated by DUR3, which is a high-affinity transporter energetically driven by symport with protons. In wheat, DUR3 was rapidly (< 2 hours) downregulated after foliar treatments with urea, nitrate or ammonium (Kirika, 2021). A similar downregulation of DUR3 occurred in urea-supplied maize roots (Zanin et al., 2014). Expression of DUR3 in Arabidopsis roots was up-regulated in response to N deficiency (Liu et al., 2003). DUR3 has also been shown to play a role in urea retranslocation from senescing Arabidopsis leaves, where urea is produced in connection with mitochondrial degradation of the major nitrogen storage form, i.e., arginine (Bohner et al., 2015). Besides the energy-requiring urea transport by DUR3, passive urea transport is mediated by some members of the Major Intrinsic Proteins (MIP) family of aquaporins. Some of these are likely to mediate urea transport across the plasma membrane, while others mediate urea transport across the tonoplast or mitochondrial membrane (Witte, 2011). There is still very limited knowledge about how urea uptake is regulated and it cannot be excluded that it may be possible to boost urea uptake or urea partitioning in the plant by (inducible) overexpression of urea transporters.

Urea assimilation in plants involves an initial step of hydrolysis to carbamate and ammonia (Figure 8). This reaction is catalyzed by urease, a nickel (Ni) requiring metalloenzyme. Urease seems to be ubiquitously present in plants and urease activity does not, at least initially, seem rate limiting for urea assimilation (Witte et al., 2002). Plant urea metabolism including uptake, storage, internal transport, hydrolysis and assimilation of urea needs to be investigated to develop strategies for knowledge-based crop improvement (Witte, 2011). An interesting aspect is that supplying a small amount of nitrate together with urea boosts urea uptake and urea nitrogen assimilation (Garnica et al., 2009).

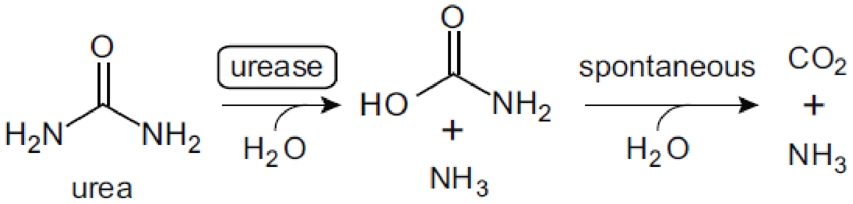

Figure 8. Urease activity in the urea hydrolyzing process. Reprinted from Witte (2011).

Phosphorus uptake and assimilation

Phosphorus (P) applied to plant leaves is primarily taken up via trichomes and fiber cells above leaf veins, cuticular cracks and stomata (Peirce et al., 2014; Arsic et al., 2022). Leaf uptake of P decreases if the plant is severely P deficient due to thicker cuticles and epidermal cell (Fernández et al., 2014).

Following plant uptake, the phosphate (P_i) can react with pyrophosphate in ADP to form energy-rich P bonds in ATP which upon subsequent hydrolysis delivers energy for biosynthesis and ion uptake. Pi may also form phosphate esters with sugars and alcohols that are intermediates in biosynthetic and catabolic processes. Finally, Pi is a building block in DNA, RNA and membrane lipids (Figure 9). During periods of rapid Pi uptake, part of the absorbed Pi may be stored in vacuoles (Maathuis, 2009; Hawkesford et al., 2023). Phosphorus deficiency reduces the concentration of P_i in the chloroplast stroma to levels that inhibit ATP synthesis. This causes accumulation of protons acidification of the chloroplast lumen, which inhibits linear electron flow and leads to repression of photosynthetic CO_2 fixation. The inhibition of the photosynthetic machinery influenced by P deficiency appears to be fully reversible and can be restored in less than 60 min after resupply of P_i to the leaf tissue (Carstensen et al., 2018).

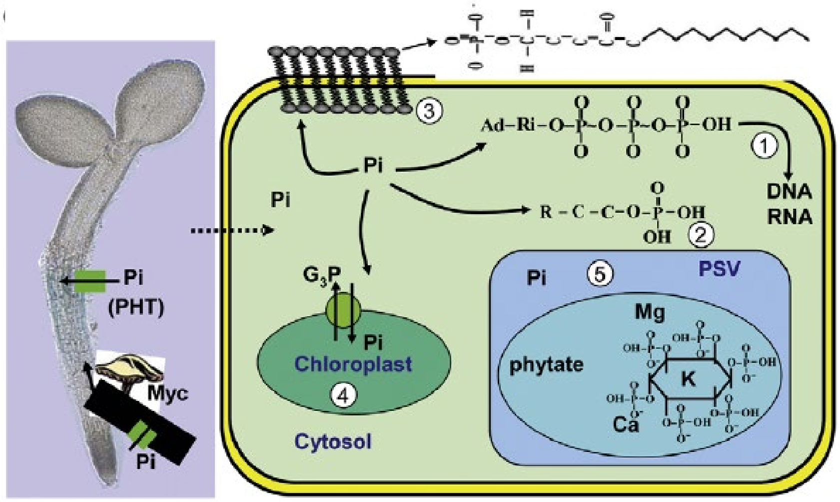

Figure 9. The functions of phosphorus (P) in plants. P is often growth limiting and many plants associate with mycorrhizal fungi (Myc) that improve P nutrition in return for reduced carbon. P is taken up directly as inorganic PO_4^{3-} (Pi) through H^+-coupled high-affinity transporters. Cellular Pi is essential in cellular energy homeostasis since it readily forms high-energy pyrophosphate (1) and ester (2) bonds. Phosphate groups form the lipophilic component of many membrane lipids (3) and are therefore essential for membrane composition and integrity. Chloroplast P, necessary for synthesis of high-energy bonds in photosynthesis, enters the chloroplast (4) in exchange for glyceraldehyde-3-phosphate (G_3P). In storage tissues (5), P is sequestered in the protein storage vacuole (PSV) as phytate together with minerals. Reprinted from Maathuis (2009).

The transport of Pi inside and between plant cells is mediated by phosphorus transporters belonging to the PHT1, PHT2, and SPX superfamilies (Figure 10) (Stigter and Plaxton, 2015; Shukla et al., 2016; Fabiańska et al., 2019). The PHT1 family embraces high-affinity transporters for Pi, mainly localized in root epidermal cells and in the outer cortex, but also contributing to Pi redistribution in shoots (Nussaume, 2011; López-Arredondo et al., 2014). The PHT2 family encodes low-affinity transporters localized in green tissues. In the chloroplasts, PHT2 transporters import Pi to maintain photosynthetic activity. They also act in Pi redistribution, e.g., loading and unloading of P in vascular tissues which influence P use efficiency (Versaw and Harrison, 2002; Guo et al., 2013). The SPX superfamily is represented by four classes that control Pi homeostasis, e.g., Pht5 or VPT which is commonly localized in young tissues mediating Pi transport between vacuole and cytoplasm (Wang et al., 2012).

The contribution of P transporters in the plasma membrane to the uptake of foliar-applied P is not known. No accumulation of foliar-applied P was observed in the apoplast of maize plant following foliar fertilization with 200 mM KH_2PO_4 (~0.6% P) and 0.1% (v/w) Silwet Gold as a wetting agent (Görlach et al., 2021b). The applied P was mostly taken up into the cytosol within the first 6 h and was associated with increased mRNA levels of PHT1 transporters (Görlach et al., 2021b). Further characterization of the expression and post-translational regulation of P-transporters in relation to acquisition of foliar P will be important for optimization of foliar-applied P. The same is the case for vacuolar P transporters, which may provide temporal P storage and mitigate leaf scorch if excessive amounts of P are absorbed. Leaf scorch may otherwise occur depending on the plant growth stage and the adjuvant added to the spray solution (Noack et al., 2010; Peirce et al., 2019).

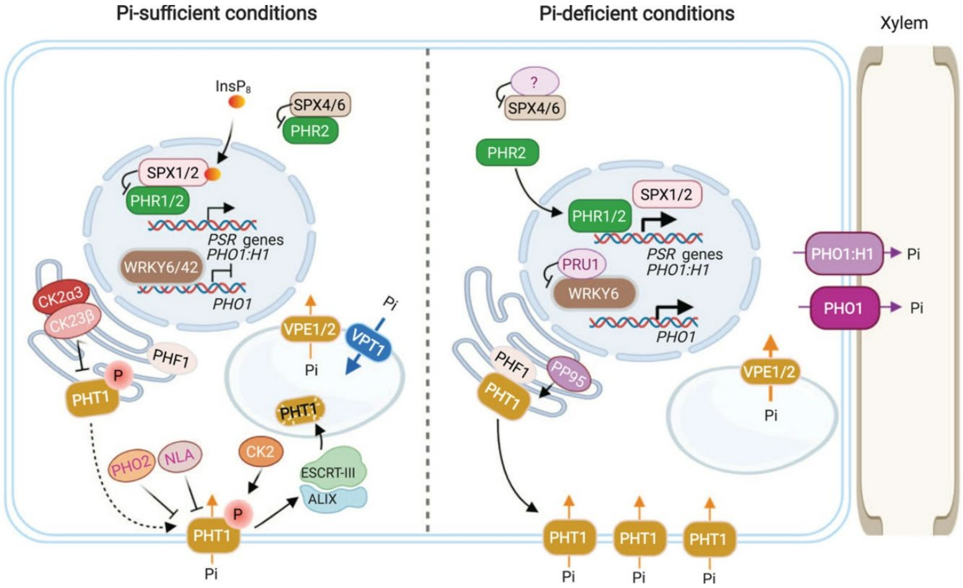

Figure 10. Phosphate transporters and signaling systems involved in regulating cellular Pi homeostasis in plants. Reprinted from Wang et al. (2021a).

3. Factors affecting the efficiency of foliar fertilization

Foliar fertilization constitutes a potentially cost-effective and environmental-friendly agricultural management technique. To achieve these benefits, it is important to optimize the conditions for nutrient uptake across the leaf barriers as affected by nutrient form, the concentration of salts in the applied solution, and the application time in relation to crop developmental stage and weather conditions. Optimization of these parameters is also a requirement for avoidance of undesirable effects, e.g., leaf scorch and run-off of nutrient solution to the soil surface (see section 3.6.).

3.1. Fertilizer source

3.1.1. Nitrogen

Nitrogen fertilizer sources used for foliar fertilization differ in their deliquescence and efflorescence points. These parameters characterize the physical state and the hygroscopicity of the applied nitrogen fertilizer source, i.e., the threshold of relative humidity at which the applied nitrogen salt will undergo phase transition from liquid to crystalline or vice-versa (Fernández et al., 2020). When water evaporates, the nitrogen solution on the leaf surface first turns into a supersaturated solution, whereupon the nitrogen salt eventually will crystallize. The relative humidity at which this transformation takes place is named the efflorescence point (POE). Oppositely, the phase transformation of a crystalline solid salt to a solution when the relative air humidity increases above a critical threshold is termed the deliquescence point (POD). Each nitrogen source has a specific POD and POE value (Table 1). The POE values are lower than the POD values, reflecting the formation of a supersaturated solution upon drying (Peng et al., 2022).

Table 1. The relative humidity at which deliquescence (POD = Point Of Deliquescence) and efflorescence (POE = Point Of Efflorescence) of different nitrogen sources used for foliar fertilization occur.

Substance	POD	POE
$Ca(NO_3)_2$	50[1]	?
$Ca(NO_3)_2 \times 4\ H_2O$	49-56	< 10[4]
$CO(NH_2)_2$ *	74[2]	50[5]
$Fe(NO_3)_2 \times 9\ H_2O$	54[3]	?
KNO_3	92-94	?
$Mg(NO_3)_2$	52-55	?
$Mg(NO_3)_2 \times 6\ H_2O$	49-54	?
$Mn(NO_3)_2 \times 4\ H_2O$[4]	42	?
NH_4Cl	76-79	45
NH_4NO_3	60-66	25-36
$(NH_4)_2SO_4$	78-82	30-48
UAN **	ǂ	ǂ
$Zn(NO_3)_2 \times 6\ H_2O$[4]	42	?

*Urea; **UAN, urea-ammonium nitrate; ?, no information about POD and POE was found in the scientific literature. ǂPOD and POE of UAN vary with the proportion of urea and ammonium nitrate used in the solution. From Peng et al. (2022) with modifications. [1]Guo et al. (2019); [2]Silva et al. (2020); [3]Fernández et al. (2013); [4]Fernández et al. (2020); [5]Casali et al. (2019).

Choosing a nitrogen salt with low point of efflorescence (POE) will, other things being equal, be important in foliar fertilization with nitrogen. Low POE implies that the applied nitrogen source will stay in solution on the leaves for a greater period once the relative humidity of the air varies along the day (i.e., higher value close to the sunrise, decreasing by noon and with a slight increase until the evening). It must be taken into account that the POE of nitrogen sources varies with temperature and interacts with other compounds (Corrêa et al., 2021; DeYoung and Shaw, 2021). Urea, for example, is a neutral molecule which, however, is polarized and forms hydrogen bonds. The resulting electrostatic interactions when co-formulating with inorganic nutrient salts, e.g., magnesium, may have some reducing effect on the hydrolysis of urea and provide a substantial decrease in the POE of the solution, but further studies are required. By co-formulating the urea solution with phosphoric acid or sulfuric acid, it is also possible to lower the pH of the solution, which will reduce ammonia loss.

The nitrogen uptake rate from different sources applied to leaves of crop species have only been investigated in few cases. Kyllingsbæk (1975) carried out a series of pot experiments for 2 years in which solutions of urea, ammonium nitrate, calcium nitrate, and ammonium sulphate in different concentrations (0.4-1.6 M) with surfactant (0.01% Tween or 0.01% Lissapol) were applied to barley leaves. The highest rates and amounts of nitrogen absorbed were obtained for urea and ammonium nitrate. The fastest nitrogen uptake rate occurred within the first four hours after application and after 8 hours 70-90% of the applied nitrogen in urea and ammonium nitrate was absorbed in the first experimental year and 40-60% in the second experimental year. Ammonium nitrate, calcium nitrate, and especially ammonium sulphate caused leaf scorch, while application of urea in corresponding concentrations did not scorch the leaves.

In a field experiment with winter wheat, Ferrari et al. (2021) found a greater yield response to foliar nitrogen application of urea compared to UAN. It has previously been reported that the uptake of urea is faster than ammonium nitrate because the cuticle has 10-20 times higher permeability for urea compared to ions (Fernández and Brown, 2013). In perennial ryegrass turf, the nitrogen uptake rate of urea, ammonium sulfate and potassium nitrate by leaves did not differ (Bowman and Paul, 1990).

Slow release nitrogen fertilizers such as urea-formaldehyde, methylene urea, and isobutylidene-diurea might be attractive as an alternative to urea in order to reduce leaf scorch and ammonia volatilization (Clapp and Parham, 1991; Shahena et al., 2021). These compounds can be absorbed by the leaves and may even be more mobile than urea (Widders, 1991; Heitholt, 1994). In a two-year field experiments with wheat in the USA, Dick et al. (2016) observed that foliar-applied UAN increased the grain protein content more than a controlled release fertilizer. Besides lack of yield responses, controlled release fertilizer has the disadvantage that they are more expensive than other nitrogen sources. In addition, urea-formaldehyde may emit formaldehyde to the air, a carcinogenic substance (Salthammer et al., 2010; Salthammer and Gunschera, 2021). A new nano urea liquid fertilizer is currently marketed in India (https://www.iffco.in/en/nano-urea-liquid-fertilizer), but proper scientific evidence for its claimed positive agronomic and environmental advantages are lacking (Frank and Husted, 2023).

3.1.2. Phosphorus

Two different phosphorus sources, viz. KH_2PO_4 and H_3PO_4 were compared in pot experiments, carried out over two years with maize plants in juvenile growth stages (Görlach et al., 2021a). The foliar P-fertilizers was applied three times with the final application given to plants in growth stage 16 (~5 leaf stage). A spraying technology with three double flat fan nozzles was used to apply the foliar P-fertilizers from above. Contamination of the soil was prevented by covering the pots with aluminum foil and wrapping the stems with paper. The P concentration of the fertilizer solutions was 200 mM (~0.6% P w/v) and 0.1% of the wetting agent Silwet Gold was added. The applied phosphorus concentration was equivalent to 1.24 kg P ha^{-1} in a total volume of 200 L ha^{-1}. The pH of the applied solution was 4.5, obtained by addition of NaOH to the H_3PO_4 solution in order to avoid leaf scorch. The foliar phosphorus was applied early in the morning (5:30 to 6 a.m.) to avoid leaf scorch by high irradiation and to take advantage of the higher air humidity. The foliar P-fertilization resulted in a significant increase in the phosphorus concentration in all plant parts ten days after the last application, regardless of phosphorus form, nutritional status, or year. The phosphorus concentration remained high only in those parts of the plant that were present during foliar application. Effects of foliar P-fertilization on biomass yields were sporadically visible until flowering, but not at maturity. In a hydroponics system, foliar H_2PO_4 application positively affected the growth of P-deficient maize plants, but the positive effect on CO_2 assimilation and phosphorus concentration was transient and disappeared some days after the foliar treatment (Henningsen et al., 2022). On this background it was concluded that foliar P-fertilization was not able to restore the functionality of phosphorus deficient maize plants during a prolonged experimental period (Henningsen et al., 2022).

3.2. Crop traits

A successful outcome of foliar fertilization depends on optimization taking into account the growth stage and nutrient requirement of the crop. Timing is essential, crops need an early supply of nitrogen and phosphorus to boost rapid development and growth. Properties such as leaf angle, leaf area index, trichome abundance and cuticle hydrophobicity vary among plant species and with the growth stage of the crop. These properties influence the droplet retention by the leaves and, thus, the proportion of the sprayed solution that will stay on the leaves rather than reach the soil.

3.2.1. Leaf and canopy properties

Overall, leaf surfaces can be classified as hydrophilic or hydrophobic based on the contact angle attained by a solution droplet (Figure 11). The degree of hydrophobicity is, together with the canopy structure (leaf area index and leaf erectness), important for selection of the type and amount of adjuvant that must be added to the nutrient solution to increase droplet retention (Holder, 2012; Ji et al., 2021). In addition, the right type of nozzle on the sprayer used for applying the nutrient solution must be selected (see section 3.3.2) to minimize runoff to the soil.

Trichomes constitute a potential nutrient uptake pathway by leaves (see section 2.1.). Some trichomes are hydrophilic and help in retaining droplets, while other more hydrophobic trichomes may hamper the adhesion of droplets onto the leaf surface (Brewer et al., 1991). Leaves within the same plant may vary in surface properties, and even within the same leaf, variation may occur between the adaxial and abaxial surfaces (Kerstiens, 1996).

The leaf cuticle is an important rate-determining step for foliar nutrient uptake due to its hydrophobic property affecting droplet adhesion and contact angle (Koch et al., 2006; Wang et al., 2015). Increasing wax content generally reduces droplet adhesion and increases the contact angle (Wagner et al., 2003). The quantity and composition of leaf wax vary between wheat genotypes and may influence the uptake of foliar-applied nutrients (Kirika, 2021).

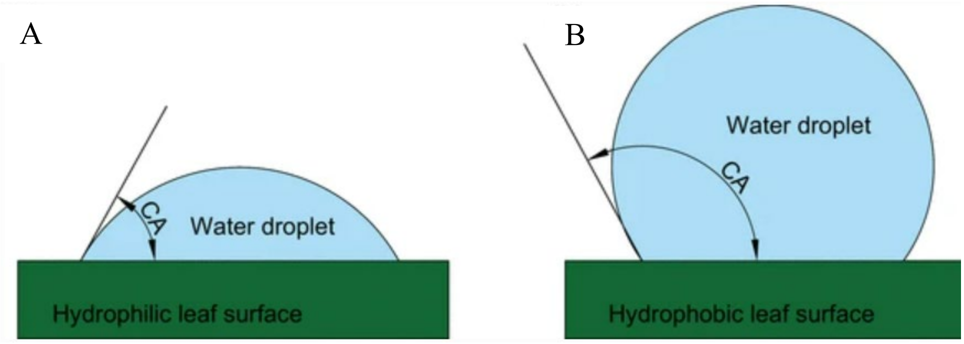

Figura 11. Shape of water droplet and contact angle (CA) for hydrophilic (A) and hydrophobic (B) leaf surface. Reprinted from Papierowska et al. (2018). Addition of adjuvants are important in order to decrease the contact angle and increase the spread of the solution on the leaf surface (see section 3.3.1).

The erectness of leaves (the leaf angle) influences droplet adhesion to the leaf surface (Figure 12). An erectophilic canopy structure may increase the efficiency of foliar fertilization as not just the top leaves of the canopy will receive the applied nutrient solution (Holder, 2012). Erectophilic genotypes are also anticipated to have higher photosynthetic efficiency because more light is penetrating into the deeper layers of the canopy (Mathan et al., 2016; Shaaf et al., 2019). The leaf erectness is influenced by environmental conditions, e.g., drought, that will decrease the leaf erectness.

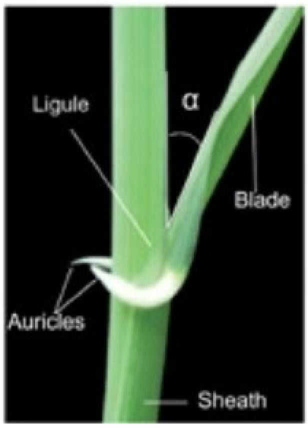

Figure 12. Structure of a barley leaf, comprised of the sheath and blade, the ligule and auricles; the leaf erectness is shown (α), i.e., the insertion angle at the lamina joint. Reprinted from Shaaf et al. (2019).

The deposition of spray liquid on the ground at different times during the growth period of a number of Danish crops was investigated in a comprehensive study carried out in 1999-2001 (Jensen and Spliid, 2003). The volume of liquid sprayed in these studies was 110-200 L ha^{-1}. In winter wheat, the results show that on average 50% of the sprayed liquid (34.5-61.5% as lower and upper limits in 95% confidence interval) was deposited on the leaves at growth stage (GS) 23-28, which typically occurs in early April. The crop cover was estimated to be around 40%. At GS 30-32 (mid-April), the crop cover was about 70% and 55-63% of the sprayed liquid was retained by the leaves. At GS 38-45 (around ear emergence), the crop covered 100% of the soil area, more than 90% of the sprayed solution was deposited on the leaves. In winter oilseed rape, the proportion of the sprayed solution that retained by the leaves was higher than 80% at GS 18-19, when more than 9 leaves had unfolded. No measurements were reported in winter barley.

In Australian studies with wheat around ear emergence (GS 50-53; 0.9 m tall plants, leaf area index 4.9±0.8), only 3% of urea applied at a rate of 50 kg N ha^{-1} in a 24% solution with adjuvant was deposited on the soil (Smith et al., 1991). When foliar N-fertilization was carried out on wheat with a low LAI, only 35% of solution was deposited onto the leaves (Readman et al., 2002).

3.2.2. Crop nutrient requirements

Foliar fertilization requires that the crop has attained a certain growth stage with sufficiently high leaf area for efficient retention of the sprayed solution. Foliar fertilization may then complement soil dressings of solid or liquid fertilizers broad-spread on the soil surface or placed close to the seeds in connection with sowing. Using foliar N-fertilization as a complement to soil N-fertilization provides possibility for reducing the rate of nitrogen applied to the soil and the subsequent losses to the environment (Readman et al., 2002; Saleem et al., 2013; Visioli et al., 2018). Significant yield response to foliar nitrogen in wheat can only be expected if the basal nitrogen dressings are suboptimal and when foliar nitrogen is applied prior to the grain filling period (GS 85). Wheat crops that have already received a high basal dressing of N-fertilizer applied to the soil will likely not show a significant yield response (Varga and Svečnjak, 2006; Rossmann et al., 2019; El-Sanatawy et al., 2021). On the other hand, it is important to note that an early supply of nitrogen which is sufficiently high to cover the requirements of the wheat crop up until ear emergence is important to realize the full potential of foliar nitrogen applied at ear emergence. This was shown by Penny et al. (1978, 1983) who tested the effect of foliar application of urea-ammonium-nitrate (UAN) with 50 kg N ha^{-1} to winter wheat plants that had previously been fertilized in early spring with solid calcium-ammonium-nitrate fertilizer applied to the soil at rates ranging from 0 to 150 kg N ha^{-1}. Foliar application of UAN as part of the total nitrogen dressing was up until a total application rate of 150 kg N ha^{-1}, consisting of 100 kg N ha^{-1} applied to the soil and 50 kg N ha^{-1} applied to the leaves, unable to make up for deficiencies in nitrogen applied earlier in the season (Figure 13). However, at application rate of

150 kg N ha^{-1}, yields were similar or higher where part of the nitrogen dressing was applied as foliar-N.

Uptake of nitrogen by roots can interact with foliar N-fertilization because root nitrogen uptake is highly regulated by feedback signals that come from shoots. Thus, amino acids and small peptides synthesized on the basis of foliar-applied nitrogen can produce signals moving to the roots and down-regulate the root transport system and reducing nitrogen uptake (Hawkesford et al., 2023). However, the application of an optimum level of basal nitrogen to the roots has been shown to result in a greater accumulation of grain nitrogen from foliar-applied ^{15}N due to higher grain numbers, resulting in a stronger sink for foliar-applied nitrogen (Kirika, 2021).

In order to reduce risks of leaf scorch and ammonia losses due to urea hydrolysis on the leaves, the maximum recommendable dose of foliar nitrogen to wheat crops is 20-30 kg N ha^{-1} per application event. This implies that usually 3-4 application events will be required to cover the full nitrogen requirement of the crop. These applications must be synchronized with the plant requirements for nitrogen in specific growth stages. Taking wheat as an example, the juvenile spike development period, and especially the rapid spike growth phase which has a duration of approximately 20 days, is critical in determining wheat yield potential (Ferrante et al., 2010). Application of foliar nitrogen to wheat crops after anthesis will predominantly affect the grain protein content (Xue et al., 2016a; Rossmann et al., 2019).

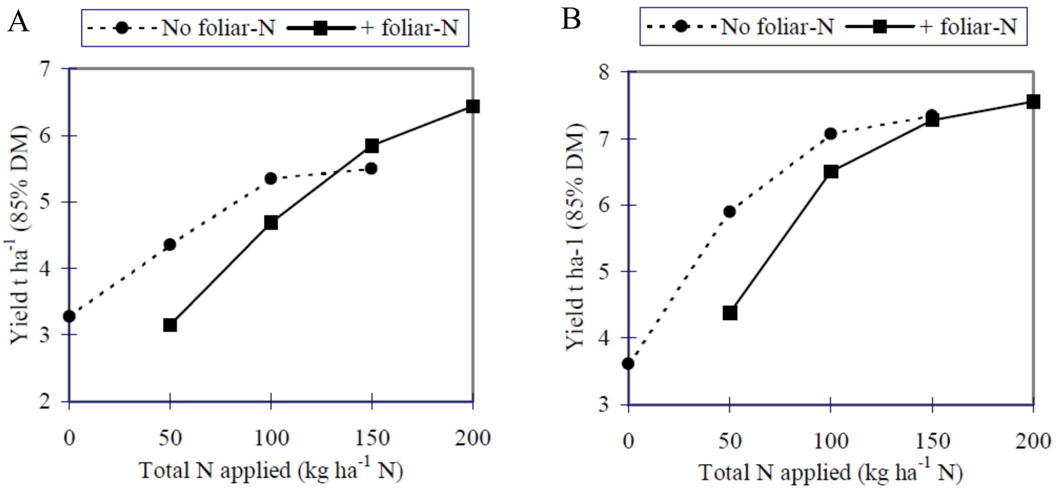

Figure 13. Effect of foliar application of 50 kg N ha^{-1} in urea-ammonium-nitrate (UAN) to winter wheat, half applied at ear emergence and half at anthesis. The plants had in early spring been fertilized with solid calcium-ammonium-nitrate fertilizer applied to the soil at rates ranging from 0 to 150 kg N ha^{-1}, providing a total soil + foliar nitrogen application of 0-200 kg N ha^{-1}. Grain yields in the foliar nitrogen treatments are compared with those obtained in treatments where the whole nitrogen dose was applied to the soil as solid calcium-ammonium-nitrate fertilizer. A) Mean data for 1974 and 1975; B) Mean data for 1978 and 1979. Reprinted from Turley et al. (2001), based on Penny et al. (1978, 1983).

3. Foliar fertilization technique

3.3.1. Adjuvants (surfactants)

The surfaces of plant leaves are covered by epicuticular wax and are accordingly commonly classified as hydrophobic with low droplet adherence. As the leaves get older, an increase in hydrophobicity is observed, which decreases droplet adherence and may decrease the efficiency of foliar fertilization (Fernández and Eichert, 2009; Puente and Baur, 2011). To increase droplet adherence and leaf wettability, i.e., decrease the contact angle between droplet and leaf surface, adjuvants must be added to the solution (Taylor, 2011; Peirce et al., 2019).

Adjuvants are products used to improve spray retention, increase spray coverage of the leaves and the penetration of nutrients into the leaves (Hazen, 2000). Adjuvants are classified into different types depending on their mode of action with respect to modification of the physical and/or application characteristics. The categories of main relevance for foliar fertilization are: penetrants, wetters, spreaders and stickers. Wetting agents lower the surface tension, thereby decreasing the contact angle (Figure 14). A sub-category of wetters consists of humectants, which are hygroscopic, water-absorbing substances that increase the drying time and prolong the time the solution maintains liquid form.

Addition of adjuvants has been shown to increase the uptake of nutrients by the leaves (Koontz and Biddulph, 1957; Rawluk et al., 2000; Fernández et al., 2006). In some cases, the decrease in the contact angle and the increase in the spread of the solution on the leaf surface may decrease the drying time and the leaf uptake because nutrients are only absorbed as long as they stay in solution (Ramsey et al., 2005; Gimenes et al., 2013; Fernández et al., 2020). In experiments with foliar P-fertilization of wheat, three commercially-available adjuvants with different effects on solution coverage and drying time on the leaves were compared (Peirce et al., 2016). The uptake of the phosphorus from the applied solution (1.85% P w/v as orthophosphoric acid) was very fast in all treatments and no differences were observed between the adjuvants. In experiments with foliar N-fertilization of grapefruit, the effect of two surfactants on the urea uptake by the leaves was evaluated (Orbović et al., 2001b). The addition of surfactant increased the uptake of urea within the first hour after application of droplets of a solution containing 1.65% urea (w/v). High concentrations of surfactant in solutions used for foliar fertilization may promote too rapid uptake of nutrients and increase risks of leaf scorch (Stein and Storey, 1986; Powlson et al., 1989; Peirce et al., 2019).

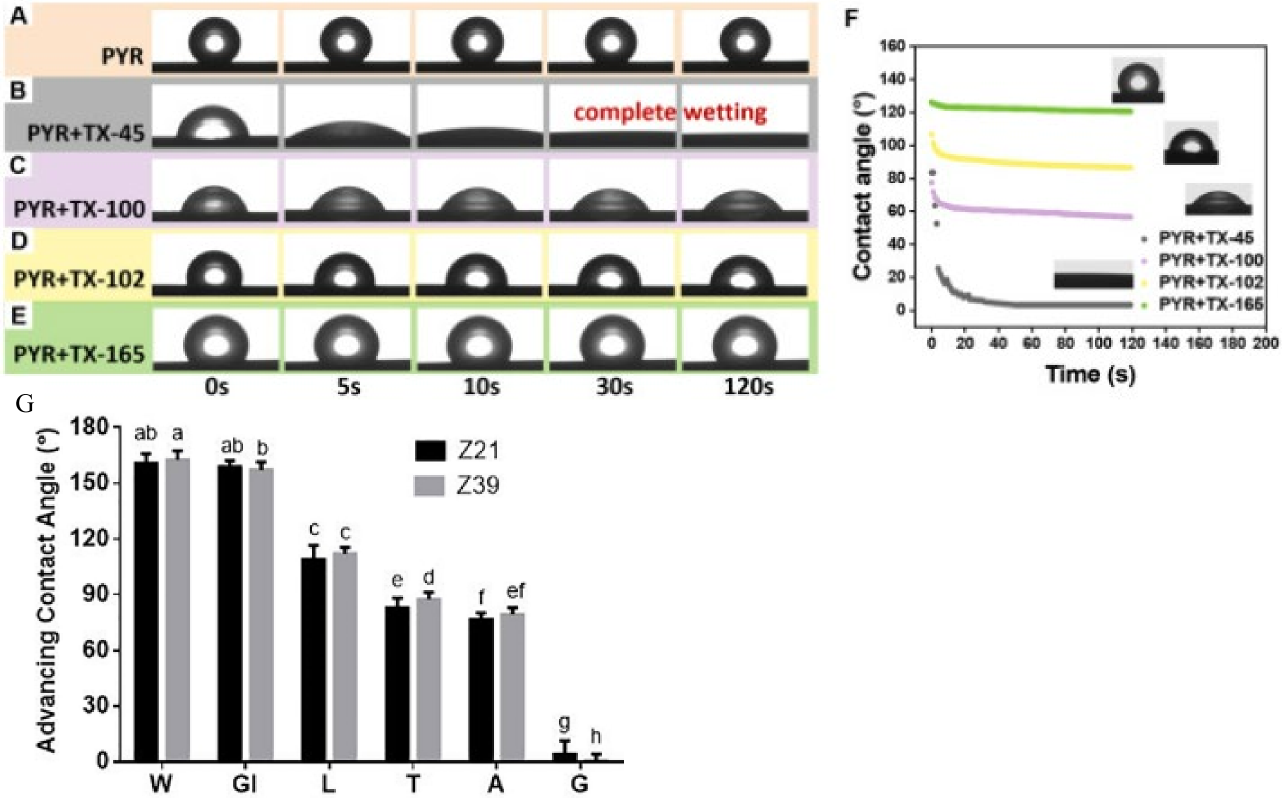

Figure 14. The contact angle development over time of aqueous droplets containing the pesticide pyraclostrobin (PYR) (A), PYR + the surfactant Triton-X (TX)-45 (B), PYR + TX-100 (C), PYR + TX-102 (D), and PYR + TX-165 (E) on the surface of scallion leaves. (F) The contact angle values of droplets on the surface of scallion leaves over time within 2 min; (G) Average advancing contact angle on adaxial side of fully expanded wheat leaves (tiller and main stem leaves) at 20 s for water and each of the adjuvants at both foliar timings (± standard deviation), Treatments: W-water, Gl-Glycerol, L-LI 700®, T-Triton™ X-100, A-Agral® and G- Genapol® X-080. Statistical differences between advancing contact angles indicated on graph with different letters ($p \leq 0.05$, l.s.d. 3.95). Reprinted from Bao et al. (2022) and Peirce et al. (2019).

3.3.2. Nozzles

To maximize the efficiency of foliar fertilizers, the nutrient solution has to be deposited and retained on the leaves. Nozzles are used to convert the nutrient solution into droplets and to achieve this desired leaf coverage pattern.

Different types of nozzles providing different spray patterns are available. The main types of nozzles are flat fan, hollow cone, and full cone (Figure 15A). Flat fan nozzles are widely used for broadcast applications, fitting better for the purpose of foliar fertilization as small (fine) droplets can be generated. However, the distance between the nozzles must be adjusted to obtain an overlap of the fans required in order to apply the same volume across the spray boom. Nozzles also differ in the spray angle (Figure 15B) and in the application characteristics. Spray angle influences the penetration of the solution in the plant canopy, i.e., smaller and greater angles, respectively, increase and decrease the penetration of the solution in the plant canopy. Nozzles application characteristics are described in the manufacturer's catalogs of each nozzle. Depending on the nozzle operating pressure and flow rate, different droplet sizes can be generated. Increasing nozzle pressure decreases the median diameter of droplets, whereas greater nozzle flow rate promotes bigger droplets (Hanks, 1995; Nuyttens et al., 2007).

Droplet size is an important parameter affecting the efficiency of foliar fertilizers. Very fine droplets can increase the solution drift decreasing the spray accuracy, while coarse and very coarse droplets may lead to lower leaf coverage and increase the droplet runoff. Generally, small droplets (i.e., extremely fine, very-fine and fine, respectively, <60 μm, 61 to 105 μm, and 106 to 235 μm volume median diameter) optimize spray retention by cereals (Lan et al., 2008). However, small droplet sizes <100 μm imply risks of increasing losses due to wind drift (Turley et al., 2001; Hilz and Vermeer, 2013). The addition of a adjuvant can attenuate solution drift by increasing droplet density, but the use of adjuvants in the solution might change the nozzle spray pattern and the size of the droplets, needing specific studies (Butler Ellis and Tuck, 1999; Miller and Butler Ellis, 2000; Sijs and Bonn, 2020).

The volume (flow) of the spray solution seems to influence the leaf coverage more than the droplet size, i.e., leaf coverage seems up to a certain level to increase with the volume of solution applied (Ferguson et al., 2016; Ji et al., 2021). The maximum volume that can be applied to achieve ample foliar retention and avoid solution runoff depends on the leaf area index (LAI) and leaf properties (de Oliveira et al., 2019; Musiu et al., 2019; Zhang and Branham, 2019).

To maximize leaf retention of foliar fertilizers carried out in crops with relatively low LAI, the type and position of the nozzles in the boom sprayer must be adjusted so that they spray small droplets and focus on the crop rows. At high LAI, the applied volume of solution and/or the pressure in the nozzles must be increased to obtain as uniform a distribution of the applied nutrients in the canopy as possible.

Turley et al. (2001) reported results from experiments examining spray volumes ranging from 100 to 300 L ha^{-1}, at three spray qualities (fine, medium and coarse). The reported results showed that the growth stage of the crop had the greatest effect on spray deposition, while spray quality and spray volume had very little consistent effect on deposition rates or penetration into the crop canopy. At full ear emergence of wheat crops, 12% of an applied spray was intercepted by the ear, 65% by the flag leaf and 22.5% by the leaf below the flag leaf (Turley et al., 2001).

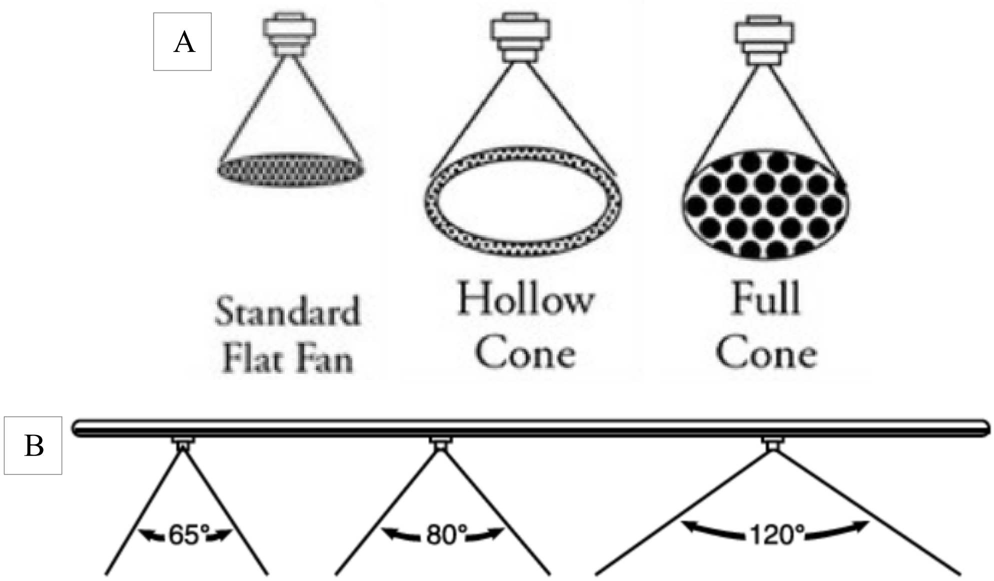

Figure 15. A. Pattern of the spray of common nozzle types used in agriculture; B. Examples of nozzle spray angles. Reprinted from Hofman (2018).

3.4. Weather parameters

Several weather parameters, including air humidity, air temperature, wind speed, rainfall and solar radiation, interfere with crop responses to foliar fertilization.

Air humidity affects the drying time of the sprayed solution intercepted by the canopy (section 3.1.). Air humidity also interferes with nutrient uptake by the leaves, acting on cuticle hydration (Figure 2) and stomatal activation (Figure 3 and Burkhardt, 2010; Fernández et al., 2017). Foliar fertilization carried out during periods with high air humidity has been shown to improve the foliar uptake of N-fertilizer in plant species like citrus (Bondada et al., 2001), cotton (Clor et al., 1963), grapefruit (Orbović et al., 2001a) and oaks (Clor et al., 1964). A similar relationship was observed when iron and calcium uptake by the leaves was investigated (Fernández and Ebert, 2005; Schönherr et al., 2005).

Air temperature influences the physico-chemical properties of the sprayed solution (Fernández et al., 2013). The solubility of nutrient salts increases with temperature, whereas surface tension and point of deliquescence (POD) decrease. Under field conditions, the effects of air temperature and humidity cannot be separated. Drying of the nutrient solution droplets is accelerated at high temperatures due to an increase in water evaporation, which will decrease nutrient uptake by the leaves. Under controlled conditions, urea uptake by the cuticle isolated from grapefruit leaves increased with air temperature from 19 to 28 ºC (Orbović et al., 2001a). Urease activity and stomatal conductance also increase with temperature under conditions with adequate air humidity (Krajewska et al., 2012; Urban et al., 2017; Feder et al., 2021). Too rapid uptake and hydrolysis of urea applied to the leaves at high temperatures will increase the risks of leaf scorch. In addition, hydrolysis of urea on the leaf surface increases with temperature and may lead to ammonia volatilization (see section 3.6.). Foliar fertilization should therefore not be carried out during conditions with relatively high temperatures. Direct solar radiation will have the same effects as high temperatures and must also be avoided.

Wind speed influences the deposition accuracy of sprayed solution on plant leaves by affecting the potential drift of solution, particularly the fine droplets (Al Heidary et al., 2014; Perkins et al., 2022). Rainfall may wash off the solution from the leaves; occurrence between 0.5 to 7 hours after foliar nitrogen fertilization decreased 50% of the urea-N uptake by sugarcane plant leaves (Trivelin et al., 1985). Thus, if it rains within the first few days after foliar fertilization, so that urea is washed down from the leaves to the soil, this can result in increased ammonia volatilization. It will depend on the volume of rainfall, which, if it is sufficiently large for the urea to be incorporated into the top cm of soil, ammonia volatilization will not be significant (Sommer et al., 2004).

Foliar fertilization should be carried out when there is no forecast of rain in the next few days to prevent urea washing down to the soil. Within the day of application, foliar fertilization should not be carried out in the middle of the day, when the sun is shining and the air temperature is relatively high, as this increases the risk of the sprayed solution drying out on the leaves and of leaf scorch. However, it is not sufficiently elucidated whether application early in the morning or in cooler conditions early in the evening is the most optimal (Gooding and Davies, 1992).

Before foliar fertilization is carried out, efforts must be taken to ensure optimal weather conditions by careful inspection of the weather forecast for the first days after foliar fertilization. However, it may not in all cases be practically feasible to carry out foliar fertilization under ideal weather conditions (Dick et al., 2016). Some technologies have been developed, which allow some degree of compensation for sub-optimal weather conditions. For example, by adjusting the application technique, i.e., choosing the right nozzles and adding an adjuvant, solution wind drift may be attenuated. By adding an adjuvant (i.e., humectant) to the solution, the drying time of droplet on plant leaves will increase, mitigating the influence of low air humidity (see sections 3.2.1 and 3.2.2.).

3.5. Potential positive side effects

By bypassing the soil, foliar N-fertilization holds potential for reducing NH_3 volatilization, N_2O emission, and NO_3^- leaching. Besides these positive effects, foliar fertilization may reduce soil acidification resulting from nitrification of ammonium in the soil and from uptake of ammonium by the roots (Zeng et al., 2017; Kuzyakov and Razavi, 2019). Soil acidification has a range of negative effects on the activity and diversity of soil microorganisms (Bai et al., 2020) and may in addition increase N_2O emission (Wang et al., 2021b; Žurovec et al., 2021; Zheng et al., 2022). Soil acidification can be reduced by lime application. However, liming leads to CO_2 emission and it is therefore desirable to reduce acidification (West and McBride, 2005; Tian and Niu, 2015; Cho et al., 2019). Foliar N-fertilization may also reduce abiotic stress of crops due to the activation of physiological process (e.g., antioxidant defense system) (Gou et al., 2017; Rodrigues et al., 2021) which might lead, when no stress condition happens, to an increase in grain yield (Moreira et al., 2017; Kirika, 2021).

The main potential advantage of foliar P-fertilization will be that immobilization in the soil is circumvented. Besides reducing the plant availability, phosphorus accumulation in soil may inhibit mycorrhizal colonization and functioning (Kobae, 2019). Foliar P-fertilization may thus stimulate the nutritional benefits of mycorrhizal associations and their antagonistic effects on root fungal pathogens (Elmer and Datnoff, 2014). Foliar application of phosphorus may also inhibit fungal pathogens causing diseases such as powdery mildew and rust (Reuveni and Reuveni, 1998).

3.6. Unintended effects

3.6.1. Leaf scorch

Leaf scorch is characterized by chlorosis and necrosis of the leaf tip (Figure 16). This damage has been observed with different nitrogen sources, e.g., urea, urea-ammonium nitrate (UAN), and ammonium nitrate. The leaf scorch may be due to osmotic damage caused by soluble salts or may reflect toxic intra-cellular metabolic effects of the nutrient elements or associated counter-ions (Fernández and Brown, 2013). The main reason for leaf scorch after foliar N-fertilization seems to be an increase in the ammonium concentration due to lack of plant nitrogen assimilation capacity (Castro et al., 2022). Recently, it was demonstrated that ammonium toxicity is reinforced by acidic stress caused by protons liberated during ammonium assimilation by chloroplastic glutamine synthetase (Hachiya et al., 2021).

The nitrogen concentration in the solution which promotes leaf scorch was evaluated in controlled conditions comparing two nitrogen sources, viz. urea and urea-ammonium nitrate (UAN), applied to wheat leaves. Nitrogen concentrations in solutions of urea and urea-ammonium nitrate higher than 4 and 10% N, respectively, caused leaf scorch (Castro et al., 2022). Similar observation was obtained when urea (10% of N, 30 kg N ha^{-1}) was applied to wheat leaves of plants growing in soil fertilized with low or high nitrogen amount (Varga and Svečnjak, 2006). Application of solutions containing 12.5% of urea-N and 28.8% UAN-N to wheat plants caused mild scorch and plants recovered without compromising the grain yield (Abad et al., 2004; Dick et al., 2016). In other crops, leaf scorch has been observed following foliar fertilization with much lower nitrogen concentrations in urea solution. This was, e.g., the case for soybean, where leaf scorch was observed following the application of a solution with 1.15% N, while scorch in escarole (*Cichorium endivia*) occurred already at 0.23% of urea-N (Krogmeier et al., 1989; Otálora et al., 2018).

Figure 16. Leaf scorch of the leaf tip 5 days after the application of urea solution (3 droplets of 3 µL each with a concentration of 12% N) with surfactant onto the youngest fully expanded leaves.

A comparison of nitrogen sources, i.e., UAN (34% N) and ammonium sulfate (11.4% N), applied to the leaves of field-grown wheat plants showed more severe leaf scorch in the ammonium sulfate treatment. Furthermore, leaf scorch increased with the volume of UAN-solution applied to the leaves even though the nitrogen concentration in the solution was the same (Woolfolk et al., 2002). In the first year of a two-year field experiment with wheat, it was observed very only mild leaf scorch after foliar application of urea or urea-ammonium nitrate solutions containing 2 to 8% N (Ferrari et al., 2021). However, in the second year, severe leaf scorch occurred following application of an 8% solution of urea-N at the highest nitrogen application rate of 32 kg N ha^{-1}. The more severe leaf scorch was likely due to 3 ºC higher air temperature in the second experimental year compared to the first.

Where leaf scorch does occur, damage can typically affect up to 10% of the sprayed leaves at application rates of 40-60 kg N ha^{-1} (Turley et al., 2001). In most cases, wheat seems to be able to tolerate scorch of the leaf tips on the flag leaf after the application of up to 40 kg N ha^{-1} without causing measurable yield losses, regardless of whether the leaves are fertilized with urea or ammonium nitrate between GS 39 (flag leaf visible) and 73 (kernels in early milk stage) (Readman et al., 2002; Ferrari et al., 2021). Adjuvants can increase the uptake of foliar-applied nitrogen, but implies risk of increasing leaf scorch.

Leaf scorch associated with foliar phosphorus nutrition may also be a significant problem. Only a limited amount of a given phosphorus compound can be applied without damaging the leaf. The damage seems predominantly to be a result of nutrient imbalance under the fertilizer droplets rather than osmotic effects (Fernández and Brown, 2013).

3.6.2. Ammonia volatilization

There are only very few results from direct measurements of the time course of the transformation of urea on living leaves and the resulting ammonia loss after foliar fertilization with urea. The most comprehensive study was conducted in an Australian field trial with winter wheat, where 50 kg N ha^{-1} in urea was applied as foliar fertilizer (Smith et al., 1991). The urea solution contained 24% N with a surfactant (Nufarm) and was applied during ear emergence (GS 50-53; 0.9 m tall plants, leaf area index 4.9±0.8). After the foliar N-fertilization, ammonia volatilization was continuously measured with a state-of-the-art micrometeorological method, and plant samples were taken daily in order to investigate the amount of urea that remained on the leaf surface and could be washed off with distilled water. The field trial was supplemented with investigations in smaller plots, where ^{15}N-labelled urea was applied. The obtained results showed that 97% of the applied amount of urea was deposited on the leaves, and only 3% was recovered in the top 0.15 m of soil immediately after foliar fertilization. Urea was quickly taken up by the plants and 4 hours after the foliar fertilization, only 18% of the applied nitrogen remained on the leaf surface. The amount of ammonium on the leaf surface, originating from urea hydrolysis, was consistently low. The highest concentration of ammonium on the leaf surface was measured 4 days after foliar fertilization and corresponded to 0.32% of the applied nitrogen. Ammonia volatilization was very small for the first

5 days after foliar fertilization, but increased after 5 mm of rain on day 6 to 0.022 kg N ha^{-1} h^{-1}, due to hydrolysis of urea washed off to the soil. Thereafter, ammonia volatilization decreased again to a negligible low level 12 days after foliar fertilization. The total amount of ammonia volatilized was 2.1 kg N ha^{-1}, corresponding to 4.3% of the nitrogen applied. Analysis of ^{15}N-recoveries confirmed the results from the micrometeorological measurements, i.e., very small loss of ammonia until the precipitation event (Smith et al., 1991). At maturity, 69% of the supplied amount of nitrogen was recovered in the plants, and 12% in the soil. The loss of 19% was estimated to be partly due to ammonia volatilization (measured to be 4.3% of the supplied amount of nitrogen) and partly due to denitrification (15%; not measured directly, but determined by mass balance considerations).

The transformation of urea in leaves of a meadow of ryegrass that had been mowed to a height of 0.04 m 3 days prior to foliar N-fertilization (approx. 12.5 kg N ha^{-1}, dissolved in 0.5 or 2 liter of water with 0.1% surfactant [Tween 80]) was investigated (Bowman and Paul, 1990). At the low volume of N-solution sprayed, 90% of the added urea was recovered on the plants 30 minutes after foliar fertilization. At the high volume of N-solution, half of the urea was deposited on the soil. By measuring the amount of ammonium on leaf samples taken, it was demonstrated that only a very small amount of urea was hydrolyzed on the leaf surface within the first 48 hours after foliar fertilization. The ammonia evaporation was measured using a chamber and amounted to 5.3 and 11.6% of the urea-N applied to the leaves with the low and high volume of N-solution, respectively.

It is well known that the addition of a urease inhibitor to urea-containing fertilizers applied to soil can reduce the hydrolysis of urea and the consequent emission of ammonia (Cantarella et al., 2018). The addition of the urease inhibitor N-(n-Butyl) thiophosphoric triamide (NBPT) did not increase nitrogen recovery after foliar N-fertilization of wheat with urea (Rawluk et al., 2000). The addition of urease inhibitor has the disadvantage that it can increase leaf scorch as observed following the addition of phenylphosphorodiamidate to the urea solution applied to soybean and wheat leaves (Krogmeier et al., 1989; Powlson et al., 1989). Leaf scorch was also observed in wheat, pea, and maize leaves following soil application of urea + NBPT (Artola et al., 2011; Cruchaga et al., 2011; Zanin et al., 2016). The leaf scorch may be due to a toxic effect of urea that accumulates in the leaves (Zanin et al., 2016).

Taken together, there is no significant ammonia volatilization from urea on the leaf surface. Urea is taken up at a high rate in the first 12 hours after application, after which the uptake rate levels off. Depending on the amount applied, typically at least 80% will be absorbed within 24 hours. A very small proportion (<1%) of urea may hydrolyze while still being on the leaf surface. Foliar fertilization with urea should only be carried out with a relatively small amount of nitrogen per application event, e.g., 10-20 kg N ha^{-1}, so that the risk of ammonia loss is minimized. At the same time, it will reduce the risk of leaf scorch. If larger quantities of nitrogen are to be applied, the foliar fertilizer should be split at intervals of a few days. An adjuvant should be added to the solution in order to reduce surface tension and ensure optimal leaf contact and uptake of nutrients in the leaves. Furthermore, co-formulation with other nutrients and lowering the pH of the sprayed solution may prevent ammonia loss.

Foliar fertilization of winter wheat in early growth stages when the leaf cover is still relatively limited, will imply that 30-60% of the sprayed solution hits the soil surface. This can result in a loss of ammonia, which, even without the addition of a urease inhibitor, can be expected to amount to a maximum of 5% of the nitrogen applied. This loss rate is lower than those often recorded following application of solid, granular urea fertilizer (Sommer et al., 2004). The difference is due to the fact that the sprayed urea solution will be distributed over a larger soil surface area that can absorb the liberated ammonium and counteract the pH increase, which is triggered by the concentrated chemical processes around a dissolving urea grain. For winter barley and winter oilseed rape crops, which will have a slightly larger leaf cover than winter wheat, it must be expected that a greater proportion of the sprayed solution will be retained on the leaves, reducing the risk of ammonia volatilization. In the case of foliar fertilization with 10-20 kg urea-N ha^{-1} after May 1st, when the crop fully covers the soil surface area, the loss of ammonia can be assumed to be very low. Overall, it must be assessed that the use of urease inhibitor in connection with foliar fertilization results at best in a marginally lower risk of ammonia volatilization. The addition of urease inhibitor also seems to increase the risk of leaf scorch.

4. Crop responses to foliar fertilization

4.1. International results

4.1.1. Winter wheat

The response of winter wheat crops to N-fertilization depends on an array of plant parameters and environmental conditions controlling plant growth and nitrogen use efficiency. Consequently, yield responses to foliar N-fertilization are variable, with contrasting effects recorded between seasons and between sites (Gooding and Davies, 1992; Turley et al., 2001). The overall nitrogen demand of the crop is an important parameter. Thus, the amount of plant-available soil-borne inorganic nitrogen and the quantity of N-fertilizer applied to the soil before foliar N-fertilization must be taken into account.

Other things being equal, the largest response to foliar N-fertilization can be anticipated under conditions where the amount of nitrogen taken up from the soil by the roots is limited. This may typically be the case in dry years or in situations where root efficiency is limited by, e.g., physical soil restrictions or reduced supply of photosynthates from the leaves during reproductive growth stages. A considerable part of the nitrogen demand of wheat crops, up to 30-40%, corresponding to 60-80 kg N ha^{-1}, is accumulated after the flag leaf has emerged (Pask et al., 2012). Thus, if soil conditions limit N uptake, foliar N-fertilization must be anticipated to be more effective than soil-applied nitrogen.

The developmental stage of the crop is important. Foliar N-fertilization at flag leaf stage or ear emergence primarily boosts grain yields. This reflects a positive effect of nitrogen on the duration of canopy green area and photosynthesis per unit leaf area. Following foliar applications of urea, a significant increase in several yield components, e.g., the number of effective tillers per unit soil surface area, the number of spikelets per spike and grain per spike, have been observed (Rahman et al., 2014; Wagan et al., 2017). Overall, grain yield responses to foliar-applied urea decline when the application is delayed much beyond flag leaf emergence, implying that the later after flag leaf emergence that foliar N-fertilization is carried out, the smaller the grain yield response. Shah et al. (2003) reported that applications before full ear emergence had greater effects on yield than applications between end of anthesis (GS 69) and early dough development (GS 83), while applications after soft dough (GS 85) had no effect on yield.

In experiments with wheat crops grown at 4 different locations in England, Powlson et al. (1987, 1989) applied 30 kg urea-N ha^{-1} to the leaves split in 2 times, i.e., half was applied 3 weeks before anthesis (GS 32-51) and half 5 weeks later (GS 69-73), when the LAI and leaf retention of the sprayed urea solution (233 L ha^{-1}; 14% urea-N) were considered optimal. Prior to foliar urea-N fertilization, the wheat crop had been fertilized with a high amount of nitrogen via the soil (210 kg N ha^{-1}). Grain yields were around 9.5 Mg ha^{-1} and foliar N-fertilization did not significantly increase yield of either grain or straw + chaff. The average recovery of ^{15}N-urea applied to the leaves amounted at harvest to 62% (45-77%) of which 1 and 11% of ^{15}N-urea was present in the soil. The recovery of ^{15}N-urea applied to the leaves was slightly less after application at GS 39 than at GS 73, respectively 58 and 64%, which was probably due to a larger part being deposited on the soil and hydrolyzed here at the early application. It should be noted that the relatively high amount of nitrogen applied to the wheat crop via the soil (210 kg N ha^{-1}) before foliar N-fertilization may have limited the absorption of nitrogen from urea supplied to the leaves. Another factor that may have contributed to relatively low recoveries may be that the foliar N-fertilization was in some cases carried out in the middle of the day, regardless of whether the air temperature and solar radiation were high. Furthermore, in these experiments, a time series of measurements was not made immediately after the supply, but only at crop maturity. Loss of ^{15}N from the above-ground plant parts in these cases cannot only be attributed to ammonia volatilization, but can be influenced by other loss items such as loss of leaf material, leaching from the leaves to the soil surface with subsequent denitrification and leaching to deeper soil layers (Wetselaar and Farquhar, 1980).

Post-anthesis foliar N-fertilization (GS 65-79) primarily improves the grain protein content and may be more effective in doing so than soil applications (Fageria et al., 2009), because it provides a rapid and efficient transport of nitrogen to the grain. A positive effect on foliar N-fertilization improved grain protein even under conditions where the crop was well-supplied with nitrogen from the soil (Powlson et al., 1989; Rawluk et al., 2000). Late foliar application of urea (40 kg N ha^{-1}) at anthesis (GS 69) improved baking quality of wheat only when the total nitrogen uptake was low due to low fertilization or unfavorable weather conditions (Visioli et al., 2018; Rossmann et al., 2019).

The effect of increasing foliar N-fertilization of wheat, respectively 64, 72 and 88 kg N ha^{-1}, supplied as urea was investigated in a 2-year field trial by Ferrari et al. (2021). In connection with sowing, 32 kg N ha^{-1} in granular ammonium nitrate had been added to the soil (Table 2). The results obtained in the foliar nitrogen treatments were compared with controls receiving only 32 kg N ha^{-1} applied to the soil at sowing or 148 kg N ha^{-1} split on two soil applications of granular ammonium nitrate, followed by foliar urea-N application of 12 kg N ha^{-1} at flowering. The total amount of nitrogen applied in the foliar nitrogen treatments was thus 25-40% less than that in the fully-fertilized control plots. Nevertheless, the three foliar treatments resulted in a small, but significant ($p > 0.05$), yield improvement. Grain protein levels were not significantly different from those measured in the control plots. Foliar N-fertilization significantly improved the nitrogen use efficiency (Table 2). The improvement was quite considerable, amounting to > 30%.

In one trial year, a very high effect of urea-N (> 75-100%), significantly higher than that of UAN-N, was measured (Ferrari et al., 2021). It has previously been reported that urea is taken up faster in leaves than ammonium nitrate, as the leaf surface (the cuticle) has a higher permeability (10-20 times) for urea compared to the inorganic ions (Fernández and Brown, 2013). In the first experimental year (2019) there were no problems with leaf scorch, while this was the case in the second experimental year (2020), especially at the highest nitrogen dose of 32 kg N ha^{-1}, probably due to a 3 °C higher air temperature in May 2020 in compared to 2019. This illustrates the importance of weather conditions for the risk of leaf scorch (Gooding and Davies, 1992). In most cases, wheat seems to be able to tolerate leaf tip scorch on the flag leaf after the application of up to 40 kg N ha^{-1} without causing measurable yield losses, regardless of whether the leaves are fertilized with urea or ammonium nitrate between GS 39 (flag leaf visible) and GS 73 (kernels in early milk stage) (Readman et al., 2002; Ferrari et al., 2021).

Foliar N-fertilization inevitably implies risks of leaf scorch which may reduce yield gains or even lead to yield reductions. Leaf scorch is mainly a problem following spraying of solutions with a high concentration of urea, e.g., 20%, used to provide relatively high nitrogen amounts (> 40 kg N ha^{-1}). Lower foliar N-fertilization rates around 30 kg N ha^{-1} may also cause scorch, but typically only 10% or less of the flag leaf area is affected, which may not lead to yield reductions (Dick et al., 2016). Multiple applications of nitrogen to the leaves may cause scorch of 30-40% of the flag leaf area and cause yield depressions of up to 0.5 Mg ha^{-1} (Turley et al., 2001). The risk of leaf scorch can be reduced by reducing the urea concentration and by splitting high application rates over some days. Applying urea in a mixture with fungicides may increase scorch risks and should be avoided when more than 30 kg N ha^{-1} is applied. Foliar fertilization should only be carried out under cool, cloudy conditions with low air humidity and dry leaves in order to minimize risks for leaf scorch.

Table 2. Effect of increasing foliar N-fertilization on the yield and nitrogen use efficiency of winter wheat (compiled based on Ferrari et al., 2021).

Year	Nitrogen treatment (kg N ha^{-1}) Soil*	Foliar**	Total N (kg ha^{-1})	Grain yield (Mg ha^{-1})	Nitrogen use efficiency (kg grain / kg N applied)
2019	32	0	32	5.57 ± 0.01	-
	148	12	160	6.39 ± 0.04	39.9 ± 0.3
	32	64	96	6.53 ± 0.10	68.0 ± 1.0
	32	72	104	6.19 ± 0.10	59.6 ± 0.9
	32	88	120	6.52 ± 0.07	54.4 ± 0.6
2020	32	0	32	5.91 ± 0.76	-
	148	12	160	6.12 ± 0.44	38.3 ± 4.7
	32	64	96	6.82 ± 0.29	71.1 ± 5.2
	32	72	104	6.21 ± 0.64	59.8 ± 10.7
	32	88	120	6.26 ± 0.29	52.2 ± 4.2

*The control treatment consisting of 160 kg N ha^{-1} was applied as 32, 58 and 58 kg N ha^{-1} in granular ammonium nitrate applied at owing, tillering (GS 26) and stem elongation (GS 37), respectively, plus 12 kg N ha^{-1} in urea as foliar supply at flowering (GS 62).

4.1.2. Winter oilseed rape

Foliar fertilization of winter oilseed rape has only been investigated in very few cases. In a 2-year field experiment embracing 10 different treatments, split nitrogen application (recommended basal dose + foliar spray) significantly increased growth and yield of oilseed rape (Pegu et al., 2020). The best results were obtained in a treatment consisting of a recommended basal dose of NPK + foliar spray of 2% urea at 20 and 40 days after sowing.

4.1.3. Grassland

A series of trials investigating the effect of foliar N-fertilization on yield responses and nitrogen use efficiency in grassland was carried out in 2019-2021 by the Agricultural Development and Advisory Service in Wales (Howells and Little, 2022). The trials were carried out at four different sites. At each site, one field of approximately 6 ha was divided into three plots of equal size and the following fertilizer treatments were implemented: (1) Conventional prilled-N (compound not specified) applied every 21 days; (2) Foliar feed (a mixture of urea and humic acid) applied at intervals of 21 days during the grazing season; (3) Control (no nitrogen). Plots were mostly grazed, but in 2020 and 2021, additional plots were set up on one of the sites to look at foliar N-fertilization in the context of silage systems. The grazed plots received between 205 and 275 kg N ha^{-1}, while foliar fertilized plots received between 46 and 110 kg N ha^{-1}. Treatments in which low rates of foliar nitrogen was applied in 2019 and 2020 consisted of 20 kg urea and 1.5 L humic acid diluted in 20 L water and applied at 200 L ha^{-1}. For obtaining high rates of foliar nitrogen application in 2021, 40 kg urea was used with other conditions being equal to the low N-rate treatments. The plots for silage received 425-460 kg prilled-N ha^{-1} or 182-204 kg N ha^{-1} as foliar fertilizer. The key findings were:

- It was possible to achieve comparable yields (15-20 Mg DM ha^{-1}) to the conventional plots using foliar fertilization systems;
- The nitrogen use efficiency (NUE) defined as the increase in DM yield per additional kg of N applied was much greater (between 2 and 3 times higher) in foliar fed systems. On all sites with exception of one, NUE continued to be significantly higher in foliar fed plots, achieving similar DM yields to conventional plots by applying only 40-50% of the nitrogen, depending on the specific site;
- Foliar fed systems achieved higher yields in adverse conditions, for example cool and/or dry conditions. This could be because the uptake of nitrogen through the leaves was less affected by adverse soil conditions compared to uptake through the roots; and

- On average the cost of nitrogen per liter of additional milk produced was 39% lower in the foliar fed systems.

Howells and Little (2022) finally concluded that, due to the higher NUE, foliar feed systems might potentially deliver significant benefits relative to conventional systems receiving solid fertilizers.

4.1.4. Sugarcane

Foliar N-fertilization is an important management tool for sugarcane as it is a semi-perennial crop. Sugarcane is harvested throughout the year and the plant regrowth occurs in different weather conditions, some of which, e.g. drought, limit the nitrogen uptake by roots (de Castro et al., 2022). Under these conditions, foliar N-fertilization is essential in order to synchronize plant nitrogen requirement with the application time, improving nitrogen use efficiency. Experiments carried out in greenhouse and bed conditions have demonstrated N-fertilizer recoveries of ~73% by sugarcane plants following foliar N-fertilization against only ~29% following soil N-fertilization (Trivelin et al., 1988; Otto et al., 2016; Quassi de Castro et al., 2021; Quassi de Castro, 2022). Based on these data, Quassi de Castro (2022) calculated that the N-fertilizer rate could be reduced by 37% without negative effects on sugarcane yield.

To validate the estimated potential of foliar N-fertilization to reduce the total nitrogen application to sugarcane crops, Quassi de Castro (2022) carried out field experiments over three years. At two field sites, fifteen treatments were set up to investigate the adoption of foliar N-fertilization, complementing soil N-fertilization (Table 3). The N-fertilizer sources used were ammonium nitrate and urea for soil and foliar N-fertilization, respectively. The urea solution was prepared on the same day as the foliar N-fertilization was carried out by diluting urea (45% N) in water (solution with 20% N). The urea-N rate sprayed to the leaves was 12 kg N ha^{-1}. Urea-N rates greater than 12 kg N ha^{-1} were split into two (24 kg N ha^{-1}) or three (36 kg N ha^{-1}) application times, spaced approximately 1 month apart. The volume of urea-N solution sprayed was 60 L ha^{-1}.

Measurements of the accumulated sugarcane stalk yield (sum of the three years) showed that by adopting foliar N-fertilization (applied three times during the growing season) to complement soil N-fertilization ($40_{\text{soil}} + 12_{\text{foliar}}$ kg N ha^{-1} at site 1 and $60_{\text{soil}} + 36_{\text{foliar}}$ kg N ha^{-1} at site 2) the total N-fertilizer amount applied could be reduced by 57% at site 1 and 20% at site 2 without causing significant negative effects on yield (Table 3). These N-fertilizer savings were calculated relative to the $120_{soil} + 0_{foliar}$ kg N ha^{-1} treatment which is the usual N-fertilizer rate applied in sugarcane fields cropped with the variety used in the experiment.

Table 3. Accumulated sugarcane stalk yield (Mg ha^{-1}), agronomic efficiency (Mg stalk kg^{-1} N applied), and partial factor productivity of applied N (Mg stalk kg^{-1} N applied) over three years at two experimental sites (compiled based on Quassi de Castro, 2022).

Soil N-fertilization	Foliar N-fertilization	Site 1				Site 2			
kg N ha^{-1}		Yield‡		A.E.*	PFP**	Yield‡		A.E.	PFP
0	0	319.7	def	-	-	326.9	g	-	-
40	0	357.5	bcdef	0.3	3.0	372.5	defg	0.4	3.1
60	0	382.8	ab	0.4	2.1	426.9	bc	0.6	2.4
80	0	423.8	a	0.4	1.8	415.1	bcde	0.4	1.7
120	0	417.1	a	0.3	1.2	483.6	a	0.4	1.3
160	0	417.7	a	0.2	0.9	410.5	bcde	0.2	0.9
0	12	321.7	cdef	0.1	8.9	325.3	g	0.0	9.0
0	24	298.8	f	-0.3	4.2	337.8	fg	0.2	4.7
0	36	311.2	ef	-0.1	2.9	340.3	fg	0.1	3.2
40	12	380.7	abc	0.4	2.4	366.8	efg	0.3	2.4
40	24	370.2	abcde	0.3	1.9	399.5	bcde	0.4	2.1
40	36	419.6	a	0.4	1.8	419.0	bcde	0.4	1.8
60	12	396.6	ab	0.4	1.8	377.9	bcd	0.2	1.7
60	24	377.6	abcd	0.2	1.5	380.9	cdef	0.2	1.5
60	36	394.9	ab	0.3	1.4	447.7	ab	0.4	1.6

‡ Small letters indicate differences between treatments according to Fisher's LSD post-hoc test ($p < 0.05$).
* Agronomic Efficiency (A.E.) → A.E. (Mg stalk kg^{-1} N applied) = $(SY_N - SY_{WN})$/N-rate
** Partial Factor Productivity of applied N (PFP) → PFP (Mg stalk kg^{-1} N applied) = SY_N/N-rate
SY_N is the sugarcane stalk yield (Mg ha^{-1}) with applied N; SY_{WN} is the sugarcane stalk yield in the control treatment without soil and foliar N-fertilization, i.e., 0+0; N-rate is the total N-fertilizer rate applied (kg N ha^{-1}), i.e., sum of soil N-fertilization and foliar N-fertilization.

4.1.5. Foliar phosphorus fertilization

Field experiments with winter wheat were carried out over three years in the USA to determine the effect of foliar applications of phosphorus on winter wheat grain yields, phosphorus uptake, and use efficiency (Mosali et al., 2006). The applied foliar phosphorus rates in the two first experimental years were 0, 1, 2, and 4 kg P ha^{-1} (KH_2PO_4) and in the last year additionally 8, 12, 16, and 20 kg P ha^{-1} with and without pre-sowing rates of 30 kg P ha^{-1}. Foliar P-fertilization at growth stage 32-37 (second knee visible) generally increased grain yields and phosphorus uptake versus no foliar phosphorus. Early application of foliar phosphorus was generally better than later applications around ear emergence in terms of grain yield and phosphorus uptake. Addition of foliar phosphorus in excess of 8 kg P ha^{-1} did not improve grain yields. It was concluded that low rates of foliar applied phosphorus might correct mid-season phosphorus deficiency in winter wheat, and might result in higher phosphorus use efficiency. Combining seed dressing and foliar phosphorus to spring wheat have under greenhouse conditions shown promising results (Talboys et al., 2020).

Foliar P-fertilization of potato was investigated by Ekelöf et al. (2012), who determined the impact of soil moisture and soil P-supply on the responsiveness to foliar P-application under controlled environmental conditions. Plant dry matter yields, P-accumulation and P use efficiency with or without foliar application were determined at five soil P-levels in combination with two soil moisture levels. A positive response to foliar phosphorus was observed only in irrigated plants. Further field experiments are required to document the effect of foliar P-fertilization on tuber establishment, growth and starch biosynthesis in potato crops.

4.2. Danish results

4.2.1. Current strategy for nitrogen fertilization of winter wheat

Nitrogen applied to wheat crops grown for feed purposes can according to SEGES, the Danish knowledge and innovation centre for agriculture, advantageously be split on 2-3 dressings. The first dressing should consist of 40-80 kg N ha^{-1}, which must be applied as early in spring as possible and with the highest amount where the crop is weakly developed. The second dressing must be applied mid-April and the third at GS 33-39. In bread wheat, a fourth supply can be applied at GS 55-59 with an amount of 30-40 kg N ha^{-1} to ensure a sufficient content and a better quality of protein. The first and second supply of nitrogen can be supplied in the form of slurry. If liquid commercial or livestock manure is used, the second application must take place around April 1st.

A comprehensive number of field trials dealing with application of liquid nitrogen fertilizers to winter wheat have been conducted by SEGES Innovation. The major part of these experiments has not specifically focused on foliar fertilization, but more widely on the use of liquid fertilizers as a substitute for solid fertilizers. Up until GS 30 in wheat, attained by approximately May 1st, the application of liquid fertilizers has been assumed to represent soil fertilization. The extent to which the sprayed solution was retained by the crop canopy or deposited on the soil surface has not been assessed.

Since many of the experiments reported by SEGES Innovation have not specifically focused on foliar N-fertilization, important conditions affecting the potential efficiency of the nitrogen solution sprayed on the above-ground parts of the crop have not in all cases been optimized. This includes parameters such as the nitrogen concentration in the applied solution, the volume of solution applied, addition of adjuvants to maximize the foliar coverage of the sprayed solution, the type of nozzles used and the weather conditions around the time of application. These circumstances imply some uncertainties in implementing the results reported by SEGES Innovation for assessment of the potential efficiency of foliar N-fertilizers.

4.2.2. Foliar nitrogen fertilization of winter wheat

In 12 winter wheat trials conducted in the period from 2008 until 2010, SEGES Innovation compared two different liquid fertilizers, viz. NS 27-4 and N-32 with solid NS 27-4 fertilizer (SEGES 2010, p. 215). The two liquid N-fertilizers roughly contained 25% nitrate, 25% ammonium and 50% urea. They were applied in a dose of 150 kg N ha^{-1} split on 50 kg N ha^{-1} late March and the rest between April 20th and May 6th. The liquid fertilizers had a significantly poorer effect on the grain yield compared to the solid fertilizer. Assessed in terms of NUE, liquid NS 27-4 and N-32 had about 6% lower NUE relative to solid NS27-4, implying that only 94 kg N in the solid NS fertilizer were required to replace 100 kg N in the liquid fertilizer. Addition of the urease inhibitor Agrotain to N-32 improved the NUE to the level of the solid fertilizer.

Over the period from 2019 to 2021, 13 field trials were carried out by SEGES Innovation to explore if additional nitrogen applied to winter wheat late in the growing season, i.e., after anthesis, could increase the grain protein level (SEGES 2021, p. 234). Before the experimental treatments were initiated, the winter wheat crops had received a basic amount of nitrogen corresponding to the normal for winter wheat grown for feed purposes. In the experiments, the urea-based liquid fertilizer N18 with the urease inhibitor Agrotain was applied with a flat fan nozzle (fladspredедyse). The amount applied was 15 kg N ha^{-1} at anthesis (GS 55), followed by 40 kg N ha^{-1} applied either at GS 65 (mid-flowering) or GS 73-75 (grain content milky, grains reached final size). The effects of the liquid N-fertilizer on grain yield and grain protein content were compared to those obtained after application of the solid fertilizers calcium nitrate or NS 27-4 applied at GS 55 (half of ear emerged above flag leaf ligule). The results showed that liquid N-fertilization did not result in higher grain yields or higher protein levels than solid NS 27-4 or calcium nitrate. The lack of response to foliar N-fertilization was not due to leaf scorch as no significant damages were observed following application of 40 kg N ha^{-1}.

In 2021, SEGES Innovation also carried out an experiment in which different strategies embracing larger quantities of nitrogen applied as foliar fertilization to winter wheat were compared with the traditional use of solid fertilizers applied to the soil surface (SEGES, 2021 p. 231). The foliar N-fertilization was carried out using a flat fan nozzle (fladsprededyse) in the period between April 28th and June 9th, where the crop attained between GS 29 (main shoot and tillers) and GS 69 (flowering complete). The foliar fertilizer consisted of Flex foliar N22 applied in amounts between 63 and 147 kg N ha^{-1}, distributed over two to seven application occasions, each consisting of 9 to 50 kg N ha^{-1}. Before foliar N-fertilization, the experimental plots had received 50 kg N ha^{-1} (fertilizer NS 27-4) at the start of growing season (i.e., March 10th), followed by between 0 to 90 kg N ha^{-1} at April 15th. The results showed no significant yield differences between the use of solid fertilizer only or foliar N-fertilization strategies embracing application of a total amount of 200 kg N ha^{-1}. This was the case regardless of whether the foliar fertilization was carried out two times with 50 kg N ha^{-1} each or four to seven times with a lower amount (9 to 30 kg N ha^{-1}) per application. Due to heavy rain during the period, a large proportion of the fertilizer applied to the leaves was presumably washed off from the above-ground crop parts to the soil.

The winter wheat trials with foliar N-fertilization were continued by SEGES Innovation in 2022. In this year, four applications of nitrogen to the leaves were compared to either three or four applications of solid NS fertilizer at nine different locations in Denmark. Prior to foliar N-fertilization, the plots received 50 kg N ha^{-1} in solid NS fertilizer mid-March and mid-April. The foliar nitrogen treatments consisted of Flex foliar NS 18-2 (94% urea and 6% nitrate with surfactant Agropol) split on 30 kg N ha^{-1} around May 1st (GS 30), 30 kg N ha^{-1} around May 15th (GS 37-45), 25 kg N ha^{-1} by the end of May (GS 55), and finally 15 kg N ha^{-1} around June 11th. On average of the nine trials, the foliar N-fertilization resulted in a grain yield of 10.5 Mg ha^{-1}, which was not significantly lower than the 10.7 Mg ha^{-1} recorded in the control plots, which had been applied 200 kg N ha^{-1} in solid NS fertilizer. However, distributed across the nine locations, the foliar N-fertilization resulted in a significantly lower grain yield in four out of nine cases. The average nitrogen content in the harvested grain was 152 kg N ha^{-1} in the foliar nitrogen plots versus 154 kg N ha^{-1} in the control plots.

4.2.3. Foliar nitrogen fertilization of winter oilseed rape

Winter oilseed rape crops growing in Denmark typically receive a final dressing of nitrogen consisting of solid N-fertilizer applied the soil surface in the beginning of April. This early nitrogen fertilization may promote excessive vegetative growth and latent nitrogen deficiency may develop during the seed-filling stage. It may accordingly be advantageous to postpone part of the N-fertilizer application to the flowering phase, making foliar fertilization over a relatively long period from the middle of flowering until approximately 2 weeks after flowering potentially interesting. With the aim of investigating risks of leaf scorch following foliar N-fertilization of winter oilseed rape around flowering, SEGES Innovation carried out 9 experiments in the period 2016-2018 (SEGES 2018, p. 218). The obtained results showed that the amount of nitrogen applied was very important for scorching risks. Following application of 20 or 40 kg N ha^{-1} as urea without fungicide, no significant scorch injuries were observed, while application of 40 kg N ha^{-1} with fungicide or 80 kg N ha^{-1} without fungicide caused severe leaf scorch. There was no difference in the leaf scorch whether a low-drift nozzle (lavdriftsdyse) or a fertilizer nozzle (gødningsdyse) was used. Addition of the urease inhibitor Agrotain did not appear to increase the leaf scorch. Foliar N-fertilization carried out in the morning (i.e., on wet plants) caused more severe leaf scorch than when done in the afternoon (i.e., on dry plants in cloudless weather).

4.2.4. Foliar nitrogen fertilization of starch potatoes

In order to investigate if foliar N-fertilization of starch potatoes was able to prevent premature senescence and prolong growth, SEGES Innovation carried out 3 experiments in the period from 2018-2020 (SEGES 2020, p. 291). No significant positive yield responses to repeated sprayings with liquid nitrogen (3 × 5 kg or 5 × 3 kg N ha^{-1}) after mid-July were recorded. Evaluated across all experiments, SEGES Innovation did not exclude that foliar N-fertilization of starch potatoes in August might have a beneficial effect on yields, but more experimental evidence is required before a final recommendation can be made.

5. The potential of foliar fertilization in precision agriculture

5.1. Remote sensing

Digital technologies are increasingly used to monitor, collect and analyze data about conditions in the field. These technologies make it possible to more precisely take into account the actual nutrient status of crops so that the application of fertilizers in the field can be graduated according to spatial differences in crop nutrient requirements. Thus, precision agriculture is an important tool to optimize the nutrient use efficiency by crops and potentially reduce the amount of fertilizer applied. By providing a direct and immediate supply of nutrients, foliar fertilization is ideally suited for precision agriculture because fertilizer applications can be closely synchronized with the crop demand.

The basic information required for precision fertilization is data on plant nutrition status and plant biomass (Cilia et al., 2014). Once maps of spatial differences in plant nutrient requirements have been created, fertilizer can be applied in graduated rate (improving the NUE) (Hedley, 2015). The combination of these data with soil fertility maps may further improve the prediction accuracy of crop nutrient requirements to optimize yields (Nawar et al., 2017; Guerrero et al., 2021; Pedersen et al., 2021).

Remote sensing provides a nondestructive method to assess crop nitrogen status. Optical sensors, typically hyperspectral, are used to measure the spectral reflectance of crops, which are used to derive vegetation indexes (VIs) (Sharifi, 2020). Commonly used VIs are red and green VIs, Normalized Difference Vegetation Index (NDVI) and, more recently, Normalized Difference Red Edge (NDRE) (Li et al., 2008; Aranguren et al., 2020). Models and algorithms have been derived to translate reflectance indices obtained by sensors into N-fertilizer requirements (Ali, 2020; Kapp-Junior et al., 2020).

Vegetation indices may be obtained using satellites in which the spatial resolution (more bands) of the sensors has been improved to obtain a more accurate prediction of crop nitrogen status. However, the relatively poor temporal resolution of satellites (i.e., infrequency of overpasses) complicates their use on-farm. Unmanned aerial vehicles (UAVs) mounted with sensors are a tool to evaluate the crop nitrogen status more frequently (Liu et al., 2017; Lu et al., 2019; Argento et al., 2021). Domestic digital cameras, which measure the intensity of reflectance in the red, green, and blue bands, can also be used in UAVs to diagnose plant nitrogen status after image processing (Figure 17) (Li et al., 2010; Lu et al., 2021).

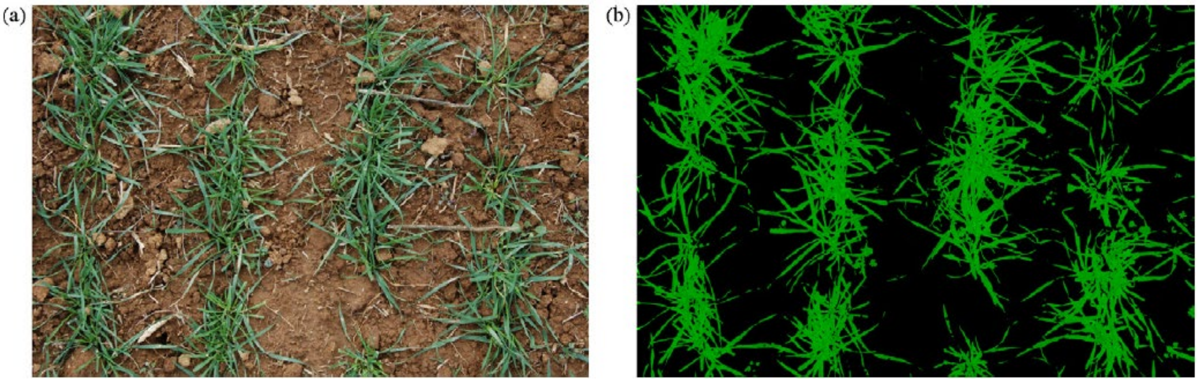

Figure 17. Image of 0.43 m^2 of a wheat crop captured by a digital camera (a) and the same image processed to highlight pixels with Soil Adjustment Vegetation Index$_{Green}$ > 0 (b). Reprinted from Li et al. (2010).

To be more accurate in the variable fertilizer rate, proximal sensors (e.g., Crop Circle®, GreenSeeker® and Yara N-Sensor®) can be used providing on-the-go signal to a variable-rate controller to adjust the N-fertilizer rate. GreenSeeker (NTech Industries) and Yara N-Sensor estimate the crop nitrogen status based on measurements of the reflectance in the red and near-infrared regions. The Yara N-Sensor furthermore estimates a biomass index by comparison with reference values obtained in plots with low and high nitrogen application rates in the field. Based on these data, the NDVI and the nitrogen uptake (kg N ha^{-1}) are calculated at the time of measurement. Crop Circle (Holland-Scientific) also has these wavebands and a specific model (ACS-470 sensor) works with six wave bands covering blue, green, red, red-edge, and near-infrared, offering NDVI and NDRE (Cao et al., 2013). NDRE seems to be more powerful than NDVI as NDVI can become saturated at medium to high biomass and high leaf area index (Li et al., 2010; Erdle et al., 2011; Cao et al., 2015).

So far, algorithms and models for N-fertilization have only been adopted for soil N-fertilization (Söderström et al., 2017). Adjustments to foliar N-fertilization strategies will be required before the potential economic and environmental benefits can be harvested. With further technological hardware development, e.g., using canopy sensors in the spray nozzles, foliar N-fertilization may become even more accurate, since spraying will only be triggered where there are plants. This technology already exists for the application of herbicides (Tian, 2002; Xu et al., 2018).

5.2. Drone systems

Limitations in sprayer capacity may prevent farmers to apply foliar fertilization under optimum weather conditions. In such cases, unmanned aerial vehicles (UAVs), mainly drones, may offer a solution. The use of drones in agriculture is relatively new (van der Merwe et al., 2020; Klauser and Pauschinger, 2021; Drones | AgTech, 2023). There are still only few published reports on the effect of foliar fertilization by drones on plant yield and nutritional status (Xu et al., 2021; Crause et al., 2023), but an increase of knowledge is expected for the coming years (Rejeb et al., 2022; Hafeez et al., 2023). So far, the influence of flight parameters for UAVs (e.g., speed and altitude) and weather parameters (e.g., air temperature, air humidity and wind speed) on droplet size and deposition onto the plant canopy have been investigated only for pesticides (Hu et al., 2022; Mogili et al., 2022).

The tank volume of a drone is small (8 to 40 L) and the flow rate of solution during the spraying is low, ranging from 10 to 30 L h^{-1}. In order to obtain a good plant coverage by the solution, small droplets should be applied, which may increase the drift of solution (Yu et al., 2021; Wang et al., 2023). To solve this problem, air-assisted nozzles or electrostatic spray system must be used (Price and Harrell; Bayat and Bozdogan, 2005; Chen et al., 2021). New nozzle types have also been developed to attenuate solution losses through drift (Kim et al., 2021). Droplet deposition on the canopy seems to depend on the time during the day when the spraying is carried out. A higher proportion of the droplets was retained by the canopy when applied at night than during the day (Tian et al., 2020). Combined with maps of soil fertility and biomass indexes (section 5.1), the flight route of drones can be programmed so that the amount of nutrients applied are graduated according to predicted requirement of the crop in the targeted spray area (Xue et al., 2016b). By adopting delivery route planning, one person can control a fleet of drones, enabling foliar fertilization to be carried out on large areas under optimal conditions.

6. Environmental and climate mitigation effects

Foliar fertilization constitutes a tool that may potentially help to better match the supply of fertilizer with the actual nitrogen demand of crops. This is the case because, nutrients sprayed on the leaves will be more directly available to the plants than nutrients in solid fertilizers applied to the soil below a well-established crop canopy. Foliar fertilization will thus imply better possibilities for delaying part of the fertilizer application in order to take the predicted yield potential and nutrient requirement in the specific growing season into account. Supplying a proportion of the nitrogen via the foliage will potentially also reduce nitrogen losses by leaching or denitrification. Taken together, this implies a potentially better nitrogen use efficiency by foliar fertilizers compared to soil fertilizers. As already described, the potentially higher nitrogen use efficiency cannot be obtained by just applying nitrogen to the plant canopy, but will only be achieved when care is taken to optimize the conditions for foliar fertilization, i.e., choosing the right weather and plant conditions as well as using the right application technique.

A quantitative estimate of the potential improvement of the nitrogen use efficiency by foliar fertilization can be obtained based on published values for the recoveries of nitrogen in solid fertilizers versus foliar fertilizers. The proportion of soil-applied N-fertilizer taken up by the crop has in a number of reviews been reported to range between 33 to 47% (Lassaletta et al., 2014; Zörb et al., 2018; Mosleth et al., 2020), implying that 67 to 53% of N-fertilizer remains in the soil and can be lost to the environment. A large number of measurements of the uptake of nitrogen applied to plant leaves show higher recoveries, on average 61% (Table 4). This average recovery includes values ranging from 21 to 99% (Table 4), reflecting the use of different application methods (e.g., solution with or without adjuvants, the concentration of nitrogen in the solution, application technique) and different experimental conditions (e.g., soil previously fertilized or not with nitrogen, greenhouse, growth chamber or field conditions), conditions that influence the effectiveness of foliar N-fertilization.

Table 4. Nitrogen recovery expressed as percentage of applied nitrogen recovered in shoots (NRP, %) following foliar fertilization of different crop species with urea.

Crop	Experimental condition	N-rate (kg N ha^{-1})	Adjuvant	Application method	NRP (%)	Articles
Bentgrass	Growth chamber	50	Triton X-100	Spray	56.5	Bowman & Paul (1990)
Bentgrass	Growth chamber	25	Tween 80	Spray	44.4⸙	Wesely et al. (1985)
Bluegrass	Field	50	Tween 80	Spray	62.0⸙	Bowman & Paul (1990)
Bluegrass	Field	50	Tween 80	Spray	70.0⸙	Bowman & Paul (1990)
Bluegrass	Growth chamber	50	Triton X-100	Spray	42.8	Bowman & Paul (1990)
Bluegrass	Field	50	-	Spray	21.0⸙	Bowman et al. (1987)
Bluegrass	Field	50	-	Spray	75.0⸙	Bowman et al. (1987)
Bluegrass	Growth chamber	25	Tween 80	Spray	40.4⸙	Wesely et al. (1985)
Bluegrass	Growth chamber	25	Tween 80	Spray	63.6⸙	Wesely et al. (1985)
Coffee	Field	56 mg	Not added	Brush	95.2	Malavolta et al. (1959)
Coffee	Field	56 mg	Not added	Brush	94.0	Malavolta et al. (1959)
Fescue	Growth chamber	25	Tween 80	Spray	67.6⸙	Wesely et al. (1985)
Maize	Field	22.3	Tween 80	Spray	32.3	Below et al. (1985)
Olive	Field	670 µg $leaf^{-1}$	L-77	Pipette	86.7	Klein et al. (1984)
Olive	Field	670 µg $leaf^{-1}$	L-77	Pipette	95.2	Klein et al. (1984)
Red fescue	Growth chamber	25	Tween 80	Spray	50.0⸙	Wesely et al. (1985)
Ryegrass	Growth chamber	50	Triton X-100	Spray	34.9	Bowman & Paul (1992)
Ryegrass	Growth chamber	25	Tween 80	Spray	51.6⸙	Wesely et al. (1985)
Ryegrass	Growth chamber	25	Tween 80	Spray	50.0⸙	Wesely et al. (1985)
Soybean	Field	20-25 droplets $leaf^{-1}$	Tween 80	Pipette	67.0	Morris & Weaver (1983)
Soybean	Field	20-25 droplets $leaf^{-1}$	Tween 80	Pipette	81.0	Morris & Weaver (1983)
Soybean	Field	21	Tween 80	Spray	68.8	Vasilas et al. (1980)

Soybean	Field	21	Tween 80	Spray	67.0	Vasilas et al. (1980)
Strawberry	Field	-	Not added	-	99.0	Nestby & Tagliavini (2005)
Sugarcane	Field	43.5*	Sucrose	Brush	74.5	Trivelin et al. (1984)
Sugarcane	Field	43.5*	Sucrose	Brush	49.9 Δ	Trivelin et al. (1984)
Sugarcane	Greenhouse	5.5**	Sucrose	Brush	69.1	Trivelin et al. (1988)
Sugarcane	Field	12	Sucrose	Spray	95.0	Trivelin et al. (1985)
Sugarcane	Field	12	Sucrose	Spray	48.0Δ	Trivelin et al. (1985)
Sugarcane	Greenhouse	-	Not added	Spray	76.5	Takahashi (1959)
Sugarcane	Field	12	Not added	Spray	46.8	Quassi de Castro (2022)
Sugarcane	Field	24	Not added	Spray	65.3	Quassi de Castro (2022)
Sugarcane	Field	36	Not added	Spray	70.8	Quassi de Castro (2022)
Sugarcane	Field	12	Not added	Spray	36.6	Quassi de Castro (2022)
Sugarcane	Field	24	Not added	Spray	41.2	Quassi de Castro (2022)
Sugarcane	Field	36	Not added	Spray	53.7	Quassi de Castro (2022)
Sugarcane	Greenhouse	5	Sucrose	Pipette	74.5	Quassi de Castro (2022)
Sugarcane	Greenhouse	10	Sucrose	Pipette	61.8	Quassi de Castro (2022)
Sugarcane	Greenhouse	15	Sucrose	Pipette	58.7	Quassi de Castro (2022)
Sugarcane	Greenhouse	20	Sucrose	Pipette	54.3	Quassi de Castro (2022)
Sugarcane	Greenhouse	6.7	Triton X-100	Brush	51.3	Leite et al. (2020)
Sugarcane	Greenhouse	6.7	Triton X-100	Spray	21.8	Leite et al. (2020)
Tall fescue	Growth chamber	50	Triton X-100	Spray	53.3	Bowman & Paul (1990)
Tall fescue	Growth chamber	25	Tween 80	Spray	48.4⸙	Wesely et al. (1985)
Tomato	Greenhouse	2.182 mg plant^{-1}	Tween 20	Brush	64.2	Tan et al. (1999)
Wheat	Field	50	Nufarm	Spray	69.0	Smith et al. (1991)
Wheat	Field	40	-	Spray	64.9	Powlson et al. (1989)
Wheat	Field	20	-	Spray	71.4	Powlson et al. (1989)
Wheat	Field	60	-	Spray	63.7	Powlson et al. (1989)
Wheat	Field	29.3	-	Spray	62.0	Powlson et al. (1987)

⸙ NRP was calculated by indirect measurements (i.e. without use of ^{15}N-urea), while all other data derive from experiments in which ^{15}N-labelled urea [$CO(^{15}NH_2)_2$] was used;

*N-rate in kg ha^{-1} was calculated based on a reported application of 652 mg N plant^{-1}, assuming 10 plants m^{-1} and 1.5 m space between sugarcane rows;

** N-rate in kg ha^{-1} was calculated based on a reported application of 82 mg N plant^{-1}, assuming 10 plants m^{-1} and 1.5 m space between sugarcane rows;

*** N-rate in kg ha^{-1} was calculated based on a reported application of 100 mg N plant^{-1}, assuming 10 plants m^{-1} and 1.5 m space between sugarcane rows.

Δ Rainfall was simulated after foliar N-fertilization.

Under optimum conditions, as occurred in 2022 in Denmark, the proportion of N-fertilizer harvested within the grain of wheat plants reached 50% and was 48%, on average, for the period 2017-2021 (SEGES 2022, p. 181). Assuming that foliar N-fertilizer uptake by the leaves provides better N-fertilizer recovery than soil N-fertilization (average of 61% for different crops, and 66% for wheat; Table 4), this means that 100 kg N ha^{-1} applied to the soil can be substituted by 73 kg N ha^{-1} applied to the leaves, thus reducing the N-fertilizer consumption with 27% without negatively affecting the amount of nitrogen taken up by the crop (equation below). In practice, foliar N-fertilization will be combined with soil N-fertilization. If 50% of the nitrogen is applied by foliar-fertilization, the potential N-fertilizer saving will be reduced to 14%. The general equation for calculation of the amount of N-fertilizer that can potentially be saved if part of it is applied via foliar fertilization instead of soil fertilization is:

$$Nitrogen\ fertilizer\ saving\ (\%) = 100 - \left\{ \left[\frac{\frac{X}{R_F} + \frac{(Y - X)}{R_S}}{\frac{Y}{R_S}} \right] \times 100 \right\}$$

in which X is the amount of nitrogen (kg N ha^{-1}) applied via foliar N-fertilization, Y is the total amount of nitrogen (kg N ha^{-1}) to be applied via foliar- plus soil-fertilization, R_F is the proportion of N-fertilizer recovered following foliar N-fertilization (e.g., 0.66 by wheat; Table 4) and R_S is the proportion of N-fertilizer recovered following soil N-fertilization (e.g., 0.48 for wheat).

It must be noted that the assumed soil N-fertilizer use efficiency of 48-50% for wheat grain production represents the marginal recovery within the grain of fertilizer-N within the first season after application. If nitrogen use efficiency is calculated relative to the total amount of nitrogen removed from the field in grain plus straw, then the nitrogen use efficiency would rather amount to approx. 80%. The difference reflects the contribution of soil-N derived from mineralization of organic matter. Seen over a time horizon of 2-5 years, increased use of foliar N-fertilization might promote a decrease in the soil nitrogen stock and in the background nitrogen mineralization, because less fertilizer-N becomes immobilized in the soil. However, the residual effect of fertilizer-N is generally assumed to be relatively small (Riley, 2016; Quemada et al., 2019) and since the amount of plant residues in the form of roots and stubble will only be marginally affected, background mineralization would not be expected to change significantly.

Applying nitrogen via foliar fertilization implies that less nitrogen comes in contact with the soil, where the microbial processes leading to denitrification occur. This will reduce emissions of the potent greenhouse gas nitrous oxide (N_2O) and thereby the impact of agriculture on climate change. The reduction in N_2O emission will not be fully proportional to the amount of nitrogen supplied via foliar fertilization because some of the applied nitrogen may not land on the leaves but rather on the soil surface (see section 3.2.1). In addition, plants are continuously depositing organic matter in the soil through rhizodeposition, which may stimulate N_2O production in the rhizosphere, from where the transport out of the soil could be mediated by the plants (Chang et al., 1998).

7. Further research requirements

There is an urgent need for further studies of nutrient uptake efficiencies and crop yield responses in well-designed and well-executed field experiments. This is required in order to provide more detailed and better information on the optimization of the timing of foliar fertilization in relation to crop nutritional requirements, the composition of the sprayed solution and the use of high-technology sprayers and sensors.

Some examples of further research need that are required to explore the full potential of foliar fertilization are:

- Nitrogen uptake rates and recoveries using frequent applications of a relatively small amount of nitrogen, e.g., max. 10-20 kg N ha^{-1}, to ensure high uptake, minimize scorch risks and to match the nitrogen demand at specific growth stages, that are critical with respect to determining the yield potential of crops.
- Crop responses to foliar P-fertilization. In particular the uptake of foliar applied phosphorus in potato crops for starch production with the aim of optimizing the establishment, growth and starch content of the tubers.
- Relationship between leaf surface properties, nutrient uptake and assimilation among high-yielding genotypes. Do genotypes differ in response to foliar fertilization and in susceptibility to leaf scorch?
- What is the ideal composition of the nitrogen form used? Urea should be the main component, but addition of a small amount of nitrate may be beneficial. It is well known that there are synergies between nitrate and ammonium assimilation, because nitrate reduction consumes two protons, which may neutralize some of the acidity generated by ammonium assimilation. In addition, nitrate has key functions in signaling networks regulating plant growth.

- Adjuvants are required for reducing the surface tension of the liquid fertilizer droplets, which is important in order to obtain better coverage and adhesion of the sprayed solution on the leaf surfaces. Choosing the right adjuvant may have a large impact on the response to foliar fertilization (Peirce et al., 2019; Fernández et al., 2021). There are many different possibilities for selecting an adjuvant, but further studies are required to optimize them and to develop new adjuvants.
- The effect of adding organic nitrogen to urea solutions used for foliar N-fertilization should be further investigated. There seems to be a positive effect of adding humic acid in the foliar nutrient solution (Leite et al., 2020; Howells and Little, 2022). Alternatively, protein hydrolysates, extracts of plant materials or composts may be used. These organic compounds may provide a source of nitrogen but little is known about how fast they are absorbed and metabolized. Addition of a carbon source such as sucrose or molasses may help to provide carbon skeletons for ammonium assimilation, thus increasing the use efficiency and counteracting leaf scorch. Addition of amino acids to foliar sprays may also provide a protection against oxidative stress (Teixeira et al., 2017).
- Other synergists: The solubility of the sprayed solution at low air humidity may be increased by addition of, e.g., magnesium salts and humectants, but further research is required to establish the optimum concentrations and formulations. There is a further need to develop and explore the use of nanoparticle fertilizers to improve uptake rate by plant leaves (Husted et al., 2022).
- Establish sprayer nozzles types for optimal distribution of the sprayed solution in the canopy depending on the leaf area index and the properties of the leaf surface in the crop under consideration.
- The prospects of using high-resolution maps of in-field variations of plant biomass based on drone-based NDVI cameras or satellite measurements, e.g., Cropsat, for precision fertilization should be further explored. As a more long-term perspective, high-tech sprayers and sensors for precision fertilization based on tractor mounted sensors with sufficiently high resolution and fast response time should be explored in combination with algorithms that can translate sensor responses into regulation of the volume of nutrient solution delivered by the sprayer.
- The impact of foliar nitrogen fertilization with respect to reducing nitrous oxide emissions and nitrate leaching must be further quantified in field experiments.

8. Conclusions

Provided foliar fertilization is carried out in the correct way under carefully optimized conditions, it is possible to obtain higher nutrient efficiencies than is the case for conventional soil-based fertilizer applications. However, successful implementation of foliar fertilization requires careful optimization of the conditions for nutrient uptake across the leaf barriers as affected by the form of nutrient applied, the concentration of salts in the applied solution, the addition of adjuvant and the application time in relation to crop developmental stage and weather conditions. Thus, foliar fertilization is more demanding with respect to technical knowledge and management skills than the conventional use of solid fertilizers. If not carried out appropriately, foliar fertilization with nitrogen or phosphorus will imply a considerable risk of causing negative yield responses.

The potential improvement of nutrient use efficiency by foliar fertilization provides possibility for reducing fertilizer rates without compromising crop yields or lowering the quality of the harvested products in terms of protein content and quality. Taking winter wheat as an example, the N-fertilizer consumption may be reduced with up to 14% if half of the N-fertilizer is supplied via foliar fertilization with urea. Foliar N-fertilizers should only be applied with a relatively small amount of urea-N per application event, up to 20 kg N ha^{-1}, so that the risk of ammonia loss is minimized. At the same time, this will reduce the risk of leaf scorch.

Adjuvants (spreading adhesives and humectants) must be added to the solution in order to reduce surface tension and ensure optimal leaf contact and absorption of nutrients in the leaves.

Improvement of the nutrient use efficiency by foliar fertilization will have attractive economic and environmental benefits via reducing fertilizers costs, nitrous oxide emissions and nitrate leaching. This will be important for the future sustainability of agriculture under conditions with carbon dioxide taxation and more strict environmental regulations. However, there is an urgent need for further studies of nutrient uptake efficiencies and crop yield responses in well-designed and well-executed field experiments. This is required in order to provide more detailed and better information on the optimization of the timing of foliar fertilization in relation to the complex interactions between crop parameters, application techniques and weather conditions.

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