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Managing Nitrogen Toxicity in the Soilless Culture System: A Review

Puteri Edaroyati Megat Wahab[1]*, M. Hafiz Che-Othman[2] and Abdel Razzaq Mohammad Al-Tawaha[3]

[1]Department of Crop Science, Faculty of Agriculture, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia
[2]Department of Biological Sciences and Biotechnology, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, 43650 UKM Bangi, Selangor, Malaysia
[3]Horticulture Research Directorate, National Agricultural Research Center (NARC), Baq'a 19381, Jordan
**Email: putri@upm.edu.my*

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ABSTRACT

The use of nitrogen in soilless cultivation, particularly in hydroponics, is pivotal for robust crop growth. This review explores the multifaceted aspects of nitrogen source management in hydroponic systems, scrutinising its sources, deficiency thresholds, optimal concentrations, and the consequences of its toxicity. Understanding the importance of maintaining adequate nitrogen levels for optimal crop production is underscored, emphasising its correlation with yield and quality. A thorough discussion on the factors that contribute to nitrogen toxicity is presented, considering the observable symptoms on crops cultivated in hydroponic systems. Furthermore, this review investigates preventive approaches against nitrogen toxicity in hydroponic setups, highlighting strategies to enhance nitrogen utilisation efficiency while mitigating toxic accumulation. Specifically, the role of urea as a potential mitigator in alleviating nitrogen toxicity is examined, presenting insights into its application and efficacy within hydroponic environments. Moreover, the article discusses the interconnectedness between the usage of nitrogen sources in hydroponics and human health, emphasising the importance of safe and sustainable nitrogen source usage. By gathering information from existing research and methodologies, this review provides a comprehensive guide for practitioners and researchers, aiming to optimise nitrogen source utilisation, foster crop yield, and ensure the safety of both plants and consumers in soilless cultivation systems.

Keywords: Hydroponic, nitrogen source, nutrient, soilless cultivation, toxicity, yield.

INTRODUCTION

Soilless culture (SC) is a broad term that contains all techniques for growing plants in aerated nutrient solution (water culture or hydroponics) or in solid media other than soil (substrate or aggregate culture). Soilless culture techniques can be classified by different types of substrate and container, distribution of nutrient solution to the plant (drip irrigation, sub-irrigation, flowing, stagnant or mist) and the flow of the drainage nutrient solution (open/free-drain or closed/recirculating water). For substrate culture systems, organic (sawdust, wood bark, coconut coir dust, peat and burnt paddy rice) and inorganic (tuff, gravel, perlite, vermiculite, sand, pumice, rockwool and foam mat) substrates are used to provide root support. Meanwhile, hydroponics is a water culture that does not use organic or inorganic substrates but only water (Jones Jr, 2016; Raviv et al., 2019; Resh, 2022; Van Os, 1999).

Hydroponics can only be used for crops with short growing cycles, such as leafy vegetables (e.g.

lettuce, spinach, kale), while substrate culture is commonly used for row crops, such as fruit vegetables (Solanaceae, Cucurbits), strawberries and cut flowers (rose, gerbera, anthurium). Different containers (banquettes, pots, bags, slabs) are filled with inorganic or organic substrates, or a combination of two or three different materials, such as the peat-perlite or peat-pumice mixture. Both techniques have been used successfully by commercial and small farmers (Raviv et al., 2019).

In general, the nutrient solution and specifically its concentration, is the most significant factor that determines the quality and quantity of crop production in the soilless culture (SC) systems. A main disadvantage of open systems that are mostly under substrate culture is that a proportion of the water and nutrients must be allowed to run to waste. This lowers water-use efficiency and contaminates groundwater supplies with salts. There is also a pollution problem arising from the need to dispose of the substrate on an annual or biannual basis (Burrage, 1998). To overcome these matters, many farmers have converted from an open to a close-loop system. This system is known for better results in water use efficiency while maintaining the quality of the yield and reducing the environmental impact of greenhouses and nurseries.

Among the 20 elements required in the nutrient solution, nitrogen (N) is considered as the most important element (Vidal & Gutiérrez, 2008), which is needed in higher quantities for vegetative growth. Furthermore, it is also required in the formation of chlorophyll, amino acids, enzymes, and proteins that are used to develop new cell walls (Barker & Bryson, 2016), as well as stimulating root development and activity, in addition to having a positive effect in the uptake of other nutrients, for instance, potassium (Kant, 2018). This review aims at explaining the importance of nitrogen for crop production hydroponically, as well as providing a brief description of its functions in plants, nitrogen sources in hydroponics and reagents, factors affecting nitrogen toxicity under hydroponics conditions, interaction of nitrogen with other elements and their effects on toxicity, and the symptoms of nitrogen toxicity in vegetable crops. This review also describes the factors affecting the optimisation of nitrogen in hydroponics for vegetable crops.

SOURCES OF NITROGEN IN HYDROPONICS

Nitrogen is available for soilless culture, hydroponics, as well as in soil through various forms and types, such as anionic nitrate (NO_3^-) and cationic ammonium (NH_4^+), which are inorganic nitrogen sources, whereas in urea [$CO(NH_2)_2$], it exists as an organic source. NO_3^- and NH_4^+ are commonly used in vegetable production (Bevan et al., 2021; Marschner et al., 1996). Higher plants take up inorganic nitrogen in the forms of NO_3^- and NH_4^+ through the root system under hydroponics. The source of nitrogen for most of the plants grown in hydroponics is nitrate (Bernstein et al., 2010; Kant, 2018) where plants absorb naturally-occurring nitrates through roots to carry out amino acid biosynthesis (Lairon, 2010). Alternatively, NO_3^- and NH_4^+ are derived from different reagents used to prepare nutrient solutions such as ammonium nitrate, potassium nitrate, ammonium sulphate and ammonium chloride (Jones Jr, 2016). In fertigation process of hydroponics, the water with rich nitrogen is pumped from sources of nutrient solutions and the plants take up nitrates through their roots (Lairon, 2010). Nitrogen pollution from fertiliser discharge is known to have caused severe environmental issues such as eutrophication, air pollution, biodiversity loss, climate change and stratospheric ozone depletion (Kanter et al., 2020). Numerous studies have explored methods to mitigate nitrogen pollution in hydroponic systems (Rufí-Salís et al., 2020; Saxena & Bassi, 2013).

NITROGEN DEFICIENCY, ADEQUACY AND TOXICITY LEVELS IN HYDROPONICS

Nitrogen in both forms such as NO_3^- and NH_4^+ have different levels of deficiency, adequacy, and toxicity levels in soilless culture as well as in hydroponics for every crop. Adequate availability of other nutrients and nitrogen denotes the optimum concentration of elements available for absorption by plants to have good growth from vegetative phase to maturity phase without the depletion of the resources. Each crop has different requirements for nitrogen from both sources i.e. NO_3^- and NH_4^+. During vegetative growth and fruiting phases in hydroponics system, nitrogen has a vital effect on the growth, development, quality, and quantity of vegetable crops especially leafy and fruit crops (Jones Jr, 2016; Marschner, 2011). However, plants have different adequate levels for NO_3^- and NH_4^+ for ideal growth and yield under hydroponics condition, thus, specific information is required for every species in terms of ratio of NO_3^-, NH_4^+ and urea from the total supplied nutrient solution (Savvas et al., 2006).

IMPORTANCE OF NITROGEN ADEQUACY FOR OPTIMAL CROP PRODUCTION IN HYDROPONICS

Nitrogen is crucial for the growth, development, and yield of higher plants (Gastal & Lemaire, 2002), including hydroponically grown vegetables such as lettuce, tomato, cucumber, and strawberry. In hydroponic systems, nitrogen is primarily supplied in the forms of NH_4^+ and NO_3^-, with nitrate being the predominant form utilised by most crops in soilless conditions. This is essential as nitrogen plays a pivotal role in the synthesis of vital plant molecules like chlorophyll and amino acids, which are crucial for photosynthesis and protein formation, respectively (Bernstein et al., 2010; Kant, 2018). The concentration of nitrogen in the nutrient solution significantly influences not only plant growth but also the uptake of other essential nutrients. For example, an optimal concentration of nitrate enhances the absorption of nutrients such as potassium, which is vital for various plant functions including water regulation and enzyme activation (Kant, 2018). The commonly recommended nitrogen concentration in hydroponic nutrient solutions ranges from 100 to 200 mg/L, adjusting lower to below 100 mg/L during the early growth stages to avoid excessive vegetative growth and potential nutrient imbalances (Jones Jr, 2016). Recent research underscores the importance of balancing NH_4^+ and NO_3^- ratios to optimise plant growth and nutrient uptake in hydroponic systems. Studies have found that specific ratios, such as 25:75 NH_4^+ to NO_3^-, are particularly effective. This balance not only stabilises the pH of the nutrient solution but also enhances nitrogen use efficiency, reduces nitrate accumulation in plants, and improves overall plant growth and nutritional quality. For instance, a study on flowering in Chinese cabbage demonstrated that a 25:75 NH_4^+/NO_3^- ratio significantly improved yield and reduced nitrate content in the plants (Zhu et al., 2021). Similarly, another study highlighted that appropriate NH_4^+/NO_3^- ratios positively affected photosynthetic characteristics and dry matter yield in spinach (Wang et al., 2009).

SYMPTOMS OF NITROGEN TOXICITY ON CROPS IN HYDROPONICS

Nitrogen toxicity, characterised by excessively high nitrogen levels in the nutrient solution, poses significant challenges for crops, particularly leafy vegetables and fruit. This condition can severely impede plant growth, often causing them to become spindly and unusually tall. The foliage may appear dark green, and the plants become more susceptible to diseases, pest attacks, and frost damage. Additionally, a common symptom of nitrogen toxicity is the failure of the plant to flower or bear fruit, which generally indicates an overconsumption of nitrogen under hydroponics (Jones Jr, 2016). There are clear symptoms of nitrate and ammonium toxicity through appearances in plants such as root rot, delayed maturity, restricted fruit set, dark green young leaves, and older yellow leaves with necrotic spots. Moreover, the plants with high ammonium toxicity become stunted and exhibit a hollow interior of the roots followed by discoloration and rotting. According to Jones Jr (2016), indications of plant having high nitrogen toxicity are regularly dim green leaves and in the early growth stages, the number of leaves with foliage is higher. Once the toxicity levels are high, the leaves will be shed off. Root framework stays immature or breaks down after some time. The flower and fruit become hindered in growth or twisted in shape. Furthermore, the study by Katalin (2011) reported overwhelming vegetative development combined with dim green shading due to abundance in nitrogen. The vegetative development is drawn out and the crop maturity is postponed to some degree.

Manifestations caused by nutrient deficiencies are by and large distinguished into five classes such as purplish-red shading, chlorosis, hindered development, corruption, and interveinal chlorosis (McCauley et al., 2009). Phipps and Cornforth (1970) determined the symptoms of nitrogen toxicity in tomatoes including roots lignification and chlorosis of the leaves. According to the report by Newcomb (2018), the primary side effect of the nitrogen toxicity in tomatoes is that the plants become big and strong with huge, verdant branches, yet hardly produce any tomatoes. This is due to the abundant nitrogen which prevents the plant from fruiting. Furthermore, high concentration of NH_4^+ in nutrient solution has been reported to affect flower and fruit initiation in tomato and pepper which resulted in the drop in yield and physiological disorders such as blossom end rot in fruits (Jones Jr, 2016).

FACTORS INFLUENCING NITROGEN TOXICITY UNDER HYDROPONICS CONDITIONS

Nitrogen Concentration and Ratio in Nutrient Solution

The excessive accumulation of nitrogen in hydroponic nutrient solutions remains a critical factor contributing to toxicity. As previously discussed, nitrogen is typically introduced into the nutrient solution in the forms of NO_3^- and NH_4^+ through various chemical reagents. Consequently, nitrogen toxicity occurs when there is an overabundance of NO_3^- and/or NH_4^+ beyond optimal levels in the hydroponic system. A study conducted by Kant (2018) corroborated the findings presented by Jones Jr (2016) regarding the optimal ratio of NO_3^- to NH_4^+ to mitigate ammonium toxicity, emphasising a ratio of 75% to 25%. Additionally, Lu et al. (2009) affirmed in their research that tomato plants exhibit maximal root surface area and volume when provided with a similar ratio of 75% NO_3^- and 25% NH_4^+. Kant (2018) asserted that under hydroponic conditions, NH_4^+ as the primary nitrogen source can yield two significant effects, firstly, a reduction in the uptake of other essential elements (Liu et al., 2014; M'rah Helali et al., 2010; Roosta & Schjoerring, 2007) such as calcium (Ca), magnesium (Mg), and potassium (K), and secondly, the potential onset of NH_4^+ toxicity. Moreover, varying ratios between NO_3^- and NH_4^+ exhibit considerable impacts on the uptake of micronutrients (Roosta & Schjoerring, 2007). The NO_3^- /NH_4^+ ratio also affects crops growth and biomass distribution between shoot and root (Guo et al., 2002; Brück & Guo, 2006). In addition, the study by Liu et al. (2014) acknowledged the dramatic decrease of biomass when there was a decrease in NO_3^-/NH_4^+ ratios. Thus, the balanced ratio NO_3^-/NH_4^+ must be sustained in order to avoid accumulation of ammonium that affects optimal growth in a number of species (Ali et al., 2001; Guo et al., 2002).

Furthermore, NH_4^+ toxicity can often occur in different species at high concentrations (Britto & Kronzucker, 2002; Roosta et al., 2009). Liu et al. (2014) demonstrated that NO_3^- outperforms NH_4^+ in supporting watermelon growth, indicating a preference for NO_3^- over NH_4^+ in cultivation. Additionally, their research suggested that watermelon plants exhibit greater sensitivity to NO_3^- compared to NH_4^+. However, some species, such as tea (*Camellia sinensis*), exhibit a preference for NH_4^+ as their primary nitrogen source (Tang et al., 2020). Conversely, other crops display a heightened sensitivity to NH_4^+, whereby the provision of NH_4^+ as the exclusive nitrogen source induces toxic effects, such as diminished root growth and developmental impairments in plants (Ali et al., 2001; Britto & Kronzucker, 2002; Lasa et al., 2001). At the same time, elevated concentrations of NO_3^- within the nutrient solution result in increased NO_3^- uptake by plants, particularly accumulating within the shoot and root structures of vegetables (Cometti et al., 2011). Jones Jr (2016) highlighted the sensitivity of major fruiting crops, such as tomatoes and peppers, cultivated under hydroponic conditions to the ammonium source present in the nutrient solution. This sensitivity spans from flower initiation to the completion of the growth cycle.

pH and Electrical Conductivity

In hydroponic nutrient solutions, each constituent element exerts varying effects on pH fluctuations (Savvas & Adamidis, 1999). Luo et al. (1993) noted that alterations in pH levels significantly impact nitrogen dynamics within hydroponic systems. Abd-Elmoniem et al. (1996) asserted that pH significantly influences the dynamics of nitrogen levels, whether in soil or hydroponic environments. pH level plays a crucial role in determining the availability of nutrients for plants. Given the limited buffering capacity of soilless systems, it is imperative to monitor pH fluctuations daily (Berjon et al., 2004). A report by Storey (2016) elucidated the significance of nitrogen within hydroponic systems, highlighting that deviations from a standardised pH of 4.5 can precipitate nitrogen toxicity. Additionally, within a pH range of 2 to 7, nitrogen compounds predominantly present as NH_4^+. The uptake of NH_4^+ by plants is electrochemically neutralised by the release of protons (H^+) resulting in lowering of pH in rooting zone (Bolan et al., 1991). When the pH exceeds 7, the concentration of NH_4^+ diminishes, concomitant with an increase in NH_3^- concentration (De Rijck & Schrevens, 1997, 1998, 1999). Storey (2016) reported that significant fluctuations in pH conditions can precipitate toxicity within hydroponic systems.

Electrical conductivity (EC) is another influential factor that can significantly affect the nitrogen condition in hydroponic systems. EC serves as an indicator of salt concentration, offering insight into the overall quantity of salts present in a nutrient solution. By analysing EC values, one can gauge the availability of ions within the plant root zone (Nemali & van Iersel, 2004). However, in hydroponic systems, EC values typically range from 1.5 to 2.5 ds/m. As noted by Bond (2017), excessive levels of EC fertiliser salts often lead to nutrient burn. Burton (2018) further highlighted the environmental contamination risks associated with excessive water, which can impact nitrogen levels. Consequently, determining the optimal EC for each crop becomes imperative, with environmental conditions playing a crucial role (Sonneveld and Voogt, 2009). Moreover, elevated EC levels can hinder the uptake of essential elements like nitrogen by increasing osmotic pressure, while low EC levels may significantly compromise plant health and yield (Samarakoon et al., 2006).

Light Intensity

Light intensity significantly affects the concentration and accumulation of nitrate in vegetable leaves through its influence on the regulation of nitrate uptake and reduction processes. This external factors play a pivotal role in controlling the levels of nitrate, thereby mitigating the risk of nitrate toxicity in plants (Albornoz & Heinrich Lieth, 2015; Lillo & Appenroth, 2001; Martínez-Ballesta et al., 2010; Santamaria, 2006). In SC systems, studies indicated that plants tend to accumulate higher levels of nitrate, particularly under conditions of low light intensity. This phenomenon is particularly notable in leafy vegetables, such as lettuce. Furthermore, it is anticipated that nitrate accumulation may potentially reach toxic levels when cultivated in hydroponic environments (Lillo & Appenroth, 2001; Martínez-Ballesta et al., 2010).

Light intensity intricately regulates the accumulation of NO_3^- through specific mechanisms, significantly influencing biochemical activity (Bian et al., 2015; Chen et al., 2017). One such mechanism involves the stimulation of photosynthetic processes, wherein increased light absorption prompts the synthesis of chlorophyll, ATP, and $NADPH_2$ (Wanlai et al., 2013). This heightened synthesis provides crucial resources for nitrate assimilation, including reductants, energy, and carbon skeletons. Specifically, under high light intensity, plants experience accelerated growth, leading to a higher demand for these assimilation materials. Consequently, the photosynthesis rate escalates, driven by the increased availability of chlorophyll, ATP, and $NADPH_2$, facilitating the production of glucose necessary for sustained growth. This mechanism can become disrupted under conditions of low illumination, as the uptake of nitrate by plant roots outpaces the rate at which plants convert nitrate into proteins. An investigation conducted by Anjana and Iqbal (2007) on spinach plants underscored the beneficial impact of high light intensity on nitrate concentrations, which were notably diminished in leaves during midday on sunny days. Consequently, plants tend to accumulate higher levels of nitrate when subjected to low light intensity, potentially leading to toxicity.

Root Zone Temperature

In SC systems, the root zone temperature (RZT) stands as a critical factor influencing both plant growth and the absorption of water and nutrients (Marschner et al., 1996; Sakamoto & Suzuki, 2015a, 2015b; Stoltzfus et al., 1998). Extreme root zone temperatures (RZTs), whether high or low, serve as limiting factors for plant growth. These temperatures affect both root and shoot development in hydroponic systems, particularly during periods of elevated or cold temperatures. Monitoring RZT levels is essential for maintaining optimal conditions in hydroponic environments, as it significantly impacts the growth of various plant species, particularly in regions with fluctuating temperatures such as tropical greenhouses, where temperatures may range from 26°C to 38°C (Tan et al., 2002; Tan et al., 2000; He et al., 2016). In addition, RZT significantly influences the uptake and translocation of nutrients from the nutrient solution, as demonstrated by Yan et al. (2012). Moreover, RZT impacts root growth, development, and cellular differentiation in crops (Marschner, 2011).

Extreme temperatures, either high or low, around the root zone can alter the efficiency of nutrient absorption, such as nitrogen, leading to its accumulation in the hydroponics unit until it reaches toxic levels, potentially resulting in root decay. This phenomenon was confirmed by Yan et al. (2012) in their study on the effects of root-zone temperature and nitrogen availability on nutrient uptake in cucumber (*Cucumis sativus* L.) grown hydroponically. The study found that at a lower RZT of 10°C, compared to 20°C, there was reduced nitrogen uptake from root to shoot, leading to an accumulation of nutrients and increased risk of toxicity. Additionally, Li et al. (2015) explored the effects of RZT on lettuce growth and nutrient content in a hydroponic system. They observed a significant decrease in lettuce production at higher RZTs (30 to 35°C) compared to an optimal 25°C, with the maximum dry mass of lettuce achieved at 24°C. This can be attributed to the reduced nutrient uptake at higher temperatures. Despite the crucial role of nitrogen in photosynthesis, suboptimal RZTs can impede nitrogen absorption through the roots, thereby affecting the photosynthetic rate. However, optimal nitrogen use in photosynthesis helps reduce its accumulation in the plant, thus preventing toxicity. Furthermore, He et al. (2009) found that the photosynthetic rate in *Lactuca sativa* was higher under optimal RZT conditions of 20°C, which facilitated the uptake of nitrogen and other nutrients under hydroponic conditions. Conversely, elevated RZTs can diminish dissolved oxygen levels in deep water culture systems, negatively impacting root growth and development, and consequently reducing nitrogen absorption (Li et al., 2015).

Flow Rate of Nutrient Solution in Hydroponics System

The flow rate of the nutrient solution in hydroponic systems significantly influences the uptake of essential elements like nitrogen, which are critical for optimal plant growth, development, and yield. In hydroponic methods such as the Nutrient Film Technique (NFT), Deep Water Culture (DWC), and media-based systems, optimising the flow rate can substantially increase plant productivity and minimise the risk of nitrogen accumulation, which can cause root damage due to elevated nitrogen levels. The term "flow rate" refers to the velocity at which the nutrient solution is delivered to the plant roots. It is pivotal because it dictates the duration that roots are exposed to nutrients, thereby affecting their ability to absorb essential elements, including nitrogen. An optimal flow rate ensures that plants receive adequate nutrients without flooding the roots, which can lead to oxygen depletion, especially critical in DWC systems.

Oxygen scarcity at the root surface can heighten the susceptibility of plants to diseases and stress, potentially undermining crop health and productivity. Research by Khater and Ali (2015) underscored the impact of flow rate on nutrient uptake in hydroponic systems. Their studies revealed that an increase in flow rate led to decreased uptake of nutrients, adversely affecting the biomass accumulation in both shoots and roots of lettuce. Furthermore, their findings indicated that an increased flow rate resulted in higher concentrations of NO_3^- in the root zone, which can be detrimental to plant health if it accumulates excessively. Adjusting flow rates in hydroponic systems can indeed help mitigate the accumulation of harmful nitrates, thereby optimising nutrient availability and uptake efficiency, enhancing plant health and yield. Research shows that tailored flow rates, especially using techniques like the Modified Intermittent Nutrient Film Technique (NFT), can significantly reduce nitrate concentrations in lettuce leaves without compromising yield. This technique involves adjusting the nutrient supply schedules to optimise the period of nutrient exposure, effectively balancing growth needs and minimising nitrate buildup (Tabaglio et al., 2020).

Interaction of Nitrogen with Other Element

Nutrients in hydroponic systems, such as iron and magnesium salts, are crucial for plant growth. However, excessive levels of these salts can alter the environment and potentially lead to nitrogen toxicity. For example, Phipps and Cornforth (1970) identified factors contributing to nitrogen toxicity, including shortages of iron and magnesium, and inadequate root aeration. Further research by Abd-Elmoniem et al. (1996) examined the presence of ions that induced nitrogen toxicity in hydroponic systems, highlighting the unique challenges of hydroponic cultivation compared to soil-based planting.

A common mistake in hydroponics is the assumption that synthetic forms of nitrogen suitable for soil are also appropriate for hydroponic use. In hydroponic systems, most of the nitrogen must be supplied in the form of NO_3^- because ammonium ions can quickly become toxic. For instance, hydroponic plants can tolerate nitrogen levels (as nitrate) up to approximately 250 ppm, but can only withstand NH_4^+ concentrations up to about 30 ppm. This is why urea is not typically used as a nitrogen source in hydroponics. Bond (2017) noted that nutrient burns often occur when fertiliser salt levels are too high. Additionally, Bessa et al. (2017) identified compounds such as polysaccharides, alkaloids, and phenolic compounds in hydroponics that can influence nitrogen toxicity. Hassan et al. (2008) found that prolonged exposure to increased nitrogen and mineral levels significantly reduced all plant growth parameters, including photosynthetic rate, chlorophyll content, and fluorescence efficiency. Another critical aspect highlighted in the literature is the interactions between nitrogen and potassium, calcium, and magnesium. High levels of potassium, for instance, can decrease the uptake of calcium and magnesium, indicating antagonistic relationships among these ions. This is significant because the balance of these nutrients affects overall plant health and growth, particularly in hydroponic systems where nutrient levels can be precisely controlled (Al Meselmani, 2022; Bevan et al., 2021).

Environmental Conditions

Controlled environment agriculture has a significant impact on nitrogen levels in plants. Research by McKeehen et al. (1996) found that such environments increase the total non-protein nitrogen content in plant biomass, especially in leafy parts and roots. While nitrate levels are higher in hydroponically-grown vegetative tissues, they are excluded from edible grains and tubers, underscoring the importance of managing nitrogen levels for safe and nutritious crop production in systems like Controlled Ecological Life-Support Systems (CELSS).

Environmental changes such as fluctuations in air temperature and humidity significantly influence nitrogen toxicity in plants. Studies have highlighted the effects of environmental changes on nitrogen toxicity. For instance, elevated temperatures have been shown to increase transpiration rates in plants like basil, leading to increased nitrogen uptake. This can result in nitrogen toxicity if not carefully monitored and managed. Hydroponic systems, in particular, demonstrate how controlled high temperatures can enhance nutrient uptake and overall plant growth, yet they require diligent monitoring to prevent nutrient excess (Geary et al., 2015; Hendrickson et al., 2022). Additionally, a study on sweet pepper in hydroponic systems revealed that temperature not only affects water use efficiency but also influences how nutrients are absorbed by plants. Lower temperatures were shown to alter the uptake rates of key nutrients differently than higher temperatures, impacting overall plant health and yield (Ropokis et al., 2019).

The balance of microbial communities is crucial for managing nitrogen levels effectively. In aquaponics which is a combination of aquaculture and hydroponics, microbial communities, including nitrifying bacteria, play a vital role. These microbes convert fish waste, which contains ammonia, into nitrates that plants can utilise, thereby preventing the buildup of harmful ammonia levels that can be toxic to both fish and plants. Kasozi et al. (2021) and Day et al. (2021) highlighted the importance of maintaining a balanced bacterial ecosystem to prevent fluctuations in water quality that could lead to nutrient imbalances or toxicity. The presence of heavy metals like cadmium can also affect nitrogen management in plants. Masclaux-Daubresse et al. (2010) noted that under cadmium stress, plants adopt a metabolic safeguard strategy through an amino acid storage mechanism to cope with nitrogen toxicity. This dynamic response of plants to environmental stressors highlights the intricate relationship between environmental conditions and nitrogen metabolism, emphasising the need for an in-depth understanding of these factors for plant survival and adaptation.

Plant Genotype

The impact of genotype on nitrogen uptake and utilisation is significant, particularly in soilless cultures where precise nutrient management is crucial. Studies such as those by Santamaria et al. (1998) and Beatty et al. (2010) demonstrated that different genotypes within the same species can exhibit considerable variation in their nitrogen absorption capabilities and efficiency. For instance, in chicory, the 'Clio' cultivar showed higher nitrogen uptake and produced more dry matter per unit of nitrogen absorbed compared to 'Frastagliata'. This indicated that genotype-specific differences can directly influence plant growth and biomass production in controlled environments. Additionally, the genotype of a plant affects its growth responses and metabolic profiles under varying nitrogen conditions. Beatty et al. (2010) found that in barley, amino acid concentrations in plant shoots varied significantly among genotypes when exposed to high and low nitrogen levels, affecting overall nitrogen use efficiency. This suggested that certain genotypes may be better suited for specific environmental conditions or agricultural purposes, highlighting the importance of understanding these genetic factors in optimising growth strategies and nutritional outcomes.

Moreover, the interaction between genotype and microbial communities, such as rhizobia in legumes, plays a crucial role in nitrogen fixation. Previous studies on bean genotypes showed significant genotype-rhizobia interactions, which influence the efficiency of nitrogen fixation (Reinprecht et al., 2020). This interaction is pivotal in reducing fertiliser use and enhancing sustainability in agriculture. Thus, selecting and breeding genotypes that exhibit high nitrogen use efficiency and optimal interactions with beneficial microbes can lead to more sustainable agricultural practices, better crop yields, and reduced environmental impact. The variability in genotype responses to nitrogen suggests a potential for selective breeding to enhance nitrogen use efficiency. For instance, the research by Farid and Navabi (2015) highlighted bean cultivars with potential for higher nitrogen fixation under reduced nitrogen fertilisation conditions. Such breeding programs could focus on selecting genotypes that not only yield well but also use nitrogen more efficiently, thereby supporting sustainable agricultural practices.

MEASURES TO PREVENT NITROGEN TOXICITY IN HYDROPONICS AND TO ACHIEVE OPTIMAL NITROGEN USE EFFICIENCY

Hydroponics offers significant advantages for modern agriculture by allowing precise control over the growing environment, which can lead to higher quality and yield of crops. However, optimising nitrogen use is crucial to prevent toxicity and ensure efficient nutrient uptake. The following measures are essential for achieving these goals:

1. System Selection

Choosing the appropriate hydroponic system is fundamental. Closed systems are particularly recommended for their efficiency in nutrient management and environmental sustainability. These systems recycle nutrient solutions, thereby reducing waste and minimising environmental impact (Velazquez-Gonzalez et al., 2022).

2. Understanding Plant-Specific Requirements

Different plant species and their growth stages require specific nutrient profiles. For instance, NO_3^- and NH_4^+ need to be supplied in balanced ratios tailored to the plant developmental phase. Recent studies highlighted the benefits of predominantly using nitrate in hydroponic solutions to avoid pH imbalances and reduce the risk of ammonium toxicity (Schiefloe et al., 2023; Kudirka et al., 2023).

3. Environmental Monitoring

Consistent monitoring of environmental parameters such as light intensity, air temperature, and humidity, alongside water quality parameters like pH and electrical conductivity (EC), is vital. These factors significantly influence nutrient uptake and utilisation by plants (Solis-Toapanta et al., 2020).

4. Managing Nutrient Solution pH

The pH of the nutrient solution is crucial for nutrient solubility and availability. Maintaining the pH within an optimal range ensures efficient nutrient absorption. A study on lettuce demonstrated that precise pH management using buffering agents significantly improved growth and nutrient uptake (Kudirka et al., 2023).

5. Utilising Advanced Technologies

Implementing precision agriculture technologies such as sensors and automated monitoring systems can greatly enhance nutrient management. These technologies provide real-time data on crop performance and environmental conditions, enabling informed decision-making to optimise nutrient supply and prevent toxicity (Velazquez-Gonzalez et al., 2022).

ROLE OF UREA IN REDUCING NITROGEN TOXICITY UNDER HYDROPONICS

In hydroponics and open field culture, nitrogen is the chief nutrient because of its important role in metabolism and is required in large quantities (Masclaux-Daubresse et al., 2010; Warner et al., 2004). Nitrogen is usually supplied to plants as NO_3^- and NH_4^+ together in nutrient solution (Jones Jr, 2016). However, urea is the highest nitrogen source i.e., 46% and known as an organic source though it is not usually preferred in hydroponic system for vegetable production. Urea can be supplied to hydroponics culture but not as source for nitrogen. Urea can be applied in hydroponics and it may not have any effect on ionic and cation imbalance in ion uptake since it has no ions which means stable pH. It was also reported by two studies (Gunes et al., 1994; Zhu et al., 1997) that urea, when supplied together with NO_3^- is effective to reduce NO_3^- accumulation in leafy vegetables. However, the effect of urea was tougher than NO_3^- on lettuce production in NFT where replacement of 20% nitrate by urea in the nutrient solution did not have effects on the yield (Gunes et al., 1994). Zhu et al. (1997) in the study on pak choi, reported that the replacement of 25% and 50% of nitrate with urea stimulated the growth and the yield. Ikeda and Tan (1998) investigated the role of urea as an organic nitrogen source with comparison to inorganic nitrogen sources for hydroponically-grown tomatoes. The study concluded that urea is a good nitrogen source when it is supplied together with nitrate and has positive effects on pH stability. Another study was conducted by Tan et al. (2000) about the uptake of nitrogen source such as urea, nitrate or ammonium by tomato plants grown hydroponically at different plant growth stages. This study concluded that urea can be used as a source of nitrogen for tomato plants at reproductive growth stages because the absorption, translocation and assimilation of urea is as fast as that of nitrate at reproductive growth stages after seedling stage. This concludes that the urea can be used for leafy crops such as lettuce and spinach.

HEALTH IMPLICATIONS OF NITRATE ACCUMULATION IN HYDROPONIC VEGETABLES

Under hydroponic conditions, both commercial and small-scale growers produce a variety of edible vegetables, commonly known as salad vegetables. However, when growers apply high nitrogen concentrations in the form of nutrient solutions, it can lead to the accumulation of nitrates in plant tissues. This occurs due to an imbalance between the absorption and assimilation of nitrate and ammonium, resulting in excess nitrogen being stored in the vacuoles of plants. Several factors influence nitrate accumulation in hydroponic vegetables beyond high nitrogen concentration, including genetic factors, harvesting time, and light intensity. When these factors are not properly managed, nitrate levels can reach toxic levels.

Research has shown that high concentrations of nitrate in vegetables are linked to serious health risks, such as methemoglobinemia (also known as "blue baby syndrome") and an increased risk of gastric cancer (Hung et al., 2004; Santamaria, 2006; Vahed et al., 2015). Methemoglobinemia occurs when nitrates are converted to nitrites in the body, which then interfere with the oxygen-carrying capacity of hemoglobin. This condition is particularly dangerous for infants. Furthermore, nitrates can react with amines in the stomach to form nitrosamines, which are potent carcinogens linked to gastric cancer. Additionally, excessive nitrate levels have been associated with other diseases such as hypertension, thyroid disorders, and increased risks of colorectal cancer (Gupta et al., 2017; Ward et al., 2018; Katan, 2009). Given these health risks, regulatory bodies like the European Union have established maximum permissible levels of nitrate in vegetables. For winter crops, the limits are set between 3,500 to 4,500 mg N-NO_3^- per kg fresh weight, while for summer crops, the limit is 2,500 mg N-NO_3^- per kg. These limits vary depending on cultivation methods and environmental conditions (Du et al., 2007; Liu et al., 2014).

ISSUES, CHALLENGES AND WAY FORWARD FOR HYDROPONICS

Nitrogen is a major element in preparing nutrient solutions for soil cultivation, hydroponics, and aquaponics. It is essential for the optimal growth, development, and maximum yield of higher plants, especially vegetables such as lettuce, tomato, cucumber, and strawberry, regardless of whether they are grown in soil or hydroponic systems. When NO_3^- is used as the primary nitrogen source in high concentrations in fertilisers, it raises health concerns due to its potential impacts. The accumulation of NO_3^- in vegetables has been linked to several health issues, including methemoglobinemia and an increased risk of gastric cancer (Salehzadeh et al., 2020, Santamaria, 2006). Understanding the factors that influence nitrogen toxicity, particularly in the forms of NH_4^+ and NO_3^-, under hydroponic culture is crucial. This knowledge will help identify key points to optimise nitrogen management in hydroponic systems.

Optimal nitrogen management in hydroponics involves recognising that each species has a specific optimal range for NO_3^- and NH_4^+ in the nutrient solution. Achieving this range requires understanding various factors. First, the type of species (e.g., leafy greens, fruiting plants, herbs) must be considered. Most species prefer NO_3^- as the nitrogen source, with an ideal nutrient solution ratio of 75% NO_3^- to 25% NH_4^+. However, some species, such as tea, prefer NH_4^+ as the sole nitrogen source (Tang et al., 2020). Knowing the genotype and phenotypic properties of crops is also essential, as these factors influence their physiological responses to NH_4^+ and NO_3^- toxicity. Additionally, selecting the appropriate hydroponic system, such as Nutrient Film Technique (NFT) or Deep Water Culture (DWC), is crucial for optimal growth, especially for leafy species like lettuce and spinach (Kumar et al., 2023).

Technical considerations are also vital to prevent nitrogen toxicity in hydroponic culture. Regularly checking the quality of the nutrient solution, including pH, EC, and RZT, is critical. It is important to avoid using wastewater to prepare nutrient solutions. Furthermore, environmental conditions such as light intensity, air temperature, and humidity significantly affect nitrogen toxicity under hydroponic conditions. Future intervention strategies should consider partial replacement with urea and amino acids. This approach can reduce NO_3^- concentration, thereby mitigating nitrogen toxicity. By implementing these strategies, growers can produce safer hydroponic vegetables with lower nitrate levels, thus reducing the associated health risks for consumers.

AUTHORS CONTRIBUTION

PEMW and ARMA conceived and designed the work. PEMW and ARMA performed the analysis. PEMW, MHCO and ARMA wrote the paper. PEMW and MHCO checked and approved the submission.

CONFLICT OF INTEREST

All authors have read the manuscript and declare no competing interest.

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