EFFECT OF COMPOST AND MINERAL FERTILIZER RATES IN MID-TERM VEGETABLE SUCCESSION

by

JENNY SHRESTHA

(Under the Direction of Dorcas H. Franklin)

ABSTRACT

A study was conducted at the University of Padova, Italy, from 2020 to 2022 to determine the impacts of mineral and organic fertilizers in a mid-term vegetable succession. The 5 fertilization treatments, i. T0 (control), ii. TMIN (100% mineral N), iii. T50 (50% mineral N 50% compost N), iv. T100 (100% compost N), and v. T200 (200% compost N), were replicated 4 times in a randomized block design. Results show the highest values for yield, quality, and nitrogen use efficiency (NUE) for TMIN. As the experiment progressed, a positive impact of compost fertilization was observed for T50 and T200, both performing better than T100. Hence, integrated application of organic and mineral fertilization or the application of double the dose of organic fertilizer is recommended while transitioning from mineral to organic fertilization to minimize the steep reduction in yield, quality, and nitrogen use efficiencies.

INDEX WORDS: Yield, Quality, Nitrogen use efficiency, Vegetable succession, Compost, Mineral fertilizer, Integrated application, Transition

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BS, Agriculture and Forestry University, Nepal, 2018

A Thesis Submitted to the Graduate Faculty of The University of Georgia in Partial Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE

ATHENS, GEORGIA

2023

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August 2023

DEDICATION

Dedicated to my family, friends, and advisors.

TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

INTRODUCTION

With increasing awareness about environmental protection and the development of various modern agricultural technologies, the scope of sustainable agriculture is ever-growing. One of the major objectives of sustainable agriculture is to maintain and improve soil quality while satisfying the food demand and quality (Rowley, 2018). Due to the extensive use of mineral fertilizers in the past to fulfill the increased food demand for an increasing population, along with heavy tillage, mechanization, and use of pesticides and monocultures, soil qualities have deteriorated, along with increased greenhouse emissions, reduced soil biodiversity, and groundwater contamination (Ju et al., 2009; Wauters et al., 2010). Sustainable agriculture focuses on maintaining soil health, diverse functional microbial populations, and improving soil physical and chemical properties while providing additional nutrients (Rady et al., 2016). Hence, carbon-rich fertilizer is applied to the soil to amend the soil properties and increase the organic matter content of the soil and biodiversity within the soil. Although organic fertilizer has holistic benefits in the long run, it provides limited nutrients that are slowly released, hence, limiting crop yield to its full potential.

Studies suggest that the combined application of organic and mineral fertilizers is more effective in terms of nutrient availability and use efficiency and is considered a viable alternative to conventional fertilization (Khamwichit et al., 2006), especially for the first few years of transitioning from mineral fertilization to organic fertilization. Positive interaction between organic and mineral fertilizers has resulted in crop yield greater than when each is applied independently (Pincus et al., 2016). Previous studies have verified that the combined application of organic and chemical fertilizers has a positive cumulative effect on soil properties, nutrient availability, crop growth, and overall yield. Similarly, studies suggest that prolonged application of organic fertilizers leads to a self-sufficient N supply in vegetable crop production. Often in these studies, a single application rate for all kinds of fertilizers is used. With this study, we assessed the impact of varying rates of organic and mineral fertilizers in a vegetable crop succession, and thereafter, determined if mineral fertilization could be replaced by organic fertilization assuring satisfying yield and quality of produce, while promoting a sustainable agricultural system.

FERTILIZATION IN VEGETABLE CROPS

Fertilization is one of the most important soil and crop management practices, greatly influencing soil quality (Chander et al., 1998). Fertilizers are external inputs mainly supplied by chemical or organic materials that are needed to restore the nutrients in the production system that are removed from the soil to produce marketable yields (Sambo & Nicoletto, 2017). Various chemical and carbon-rich fertilizers are commercially available for agricultural use and are applied based on crop and soil requirements. Plants, however, can uptake the nutrients from the soil mainly in inorganic forms, meaning that nutrients within soil organic matter, present or applied, must first be mineralized before they can be absorbed by the plants (Sambo & Nicoletto, 2017). Thereafter, minerals, organic matter, and microorganisms should be considered as a united system in close association and interactions with soil environments rather than as separate entities (Mohammadi et al., 2011). Depending on the physical, chemical, and biological properties of soil and the amendment applied, and ecological factors, the effectiveness of an applied amendment can vary widely.

Primarily plants require oxygen, carbon dioxide, and water. In addition to that, plants require 14 mineral elements for proper growth and development. Primary mineral elements, nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), sulfur (S), and magnesium (Mg) are required in large amounts. In contrast, chlorine (Cl), iron (Fe), manganese (Mn), boron (B), copper (Cu), nickel (Ni), zinc (Zn), and molybdenum (Mo) are required in smaller amounts and are called the secondary minerals (Singh and Sapkota, 2022). Chemical fertilizers supply one or a combination of the primary and secondary plant nutrients at higher rates, while organic fertilizers supply all the necessary plant nutrients in varying and less readily available amounts.

MINERAL FERTILIZER

Mineral fertilizers, also known as inorganic fertilizers, are substances with inorganic properties that consist of essential nutrients which when applied to soil, enhance the phyto-availability of different kinds of nutrients to the soil, improving the quantity and quality of crop (White & Broadley, 2009; Savci, 2012). Mineral fertilizers are chemical components that contain essential elements for plant growth and development. Mineral fertilizers are used to achieve the required yield potential to feed the world’s population, and the global consumption of these fertilizers has increased greatly. Chemical fertilizer's effect on the soil depends on rates and application methods. The rate, chemical formula, and fertilizer application method can influence the effectiveness of chemical fertilizers and vary depending on soil type and health. Forms of chemical fertilizers that are being used provide either a single nutrient or a compound/multi-nutrient fertilizer provides several nutrients. Compound fertilizers can be produced by a combination of two or more ingredients with specific reaction processes and another by blending two or more granular fertilizers (Singh & Sapkota, 2022).

The most important mineral fertilizers supply nitrogen, phosphorus, and potassium. N-fertilizers are manufactured from gaseous nitrogen (N_2) involving an energy-intensive Haber–Bosch process. The roots of plants can readily uptake and transport both NH_4^+ and NO_3^- ions (IFASTAT, 2021). Phosphatic fertilizers are produced from different rock phosphates using sulphuric acid, and potassium (K) is mined from ores of large marine origin (Lægreid et al., 1999). The rocks which contain fluorapatite and hydroxyapatite are sources of phosphorus for fertilizers. These rocks are treated with strong acids, and those phosphorous-containing minerals are converted to soluble phosphorous salts. The commonly used K fertilizers are potassium chloride/ muriate of potash and potassium sulfate. Sometimes, potassium nitrate can also be used in plants to supply potassium. The mines with rock deposits left by evaporates are the sources of potassioum (Singh & Sapkota, 2022). Plants readily absorb phosphorus as phosphate ion $H_2P0_4^-$, and potassium as an exchangeable K^+ ion (Walker, 2013). There is extensive use of reserves of sulfates and phosphate rocks which are depleting rapidly and are being projected to be exhausted within 25- 100 years (Kesler, 2007).

The increasing population and pressure of development works have created an extensive overuse of energy and raw materials, leading to the increased cost of fertilizers, maximizing uncertainty in their availability. Furthermore, to ensure food security for upcoming generations, nitrogenous fertilizers have huge subsidization by governments which creates overuse of these fertilizers to reduce the risk of loss in yield. This creates negative impacts on agricultural prosperity and sustainability. Chemical fertilizers are a source of pollution and contribute to different environmental and health hazards. The manufacture and use of N fertilizers contribute to emissions of greenhouse gases. Similarly, they are also responsible for the eutrophication of water bodies (Galloway et al., 2008; Smith et al., 2008).

For both economic and sustainable reasons, it is obvious that mineral fertilizers should be manufactured and used with great caution. For crop production for future food security, we require a viable and sustainable fertilizer management process and system, which should include advanced and sophisticated decision support tools, better agronomic practices, and crops that require less fertilizer input (Conley et al., 2009; White & Hammond, 2009).

Nitrogen

Nitrogen is one of the essential nutrients, which plays a vital role in building the proteins necessary for plants to convert solar radiation to carbohydrates resulting in higher yields (Singh & Sapkota, 2022). It is often required in large quantities by the crop depending on its growth pattern and initial availability in soil. The most used N fertilizer is urea, and when applied to soil, it is easily hydrolyzed, producing NH_4^+ and carbon dioxide by enzymes in the soil. The NH_4^+-N that is produced from the hydrolysis of applied urea or through applied NH_4^+ fertilizers is either taken up by the plant, converted to NO_3^- through the nitrification process involving various bacteria, or consumed by the soil biomass which can result in immobilization of N. This process is soil moisture, temperature, pH, and aeration dependent. In well-aerated soils, NH_4^+-N is readily converted to NO_3^--N from days to weeks (Singh & Sapkota, 2022). Nitrate leaching is frequently the most important loss process in horticulture because large inputs of N fertilizers are applied to maintain high productivity (Thompson et al., 2007), the roots of many vegetable crops are superficial (Thompson et al., 2020), and the N remaining in the field as crop residues after harvest is a large fraction of the plant N uptake. Because of this, risks associated with high nitrate concentrations in water leaving the root zone are prominent negatively impact environmental health (Agostini et al., 2010; Cameira and Mota, 2017; Thompson et al., 2020). Hence, it is important to optimize the use and management of nitrogen fertilizer in vegetable crops from both agronomic and environmental points of view (Sambo & Nicoletto, 2017).

Synchronization of N mineralization with crop N demand is an important strategy to increase N use efficiency (Tei et al., 2020). N use efficiency is maximum when N mineralization is synchronized with the crop N demand. N mineralization in the soil is affected by various abiotic factors like soil temperature and moisture content, which in turn depends on weather conditions and location on Earth. When N mineralization is lower than the crop N requirement, additional fertilization could easily fill the gap. However, if the case is reversed, high N loss is possible (Neve, 2017). Various studies have been conducted to identify immobilizing materials which could lightly bind or retain soil inorganic N concentrations in soil like paper waste (Rahn et al., 2003; Vinten et al., 1998), straw, sawdust, immature green waste compost (Chaves et al., 2005b), and tannic acid (De Neve et al., 2004) when soil inorganic N is high, and N crop demand is low.

Similarly, materials like vinasses, molasses, dairy sludge, and malting sludge are being studied as remineralization agents which could boost N content in soil when crop N demand increases. The results of various studies about the effectiveness of these materials are vary (Chaves et al., 2007; Rahn et al., 2003; De Neve et al., 2004), which could be attributed to the weather, soil, and the physical, chemical, and biological condition of the added materials, so further in-depth experiments should be conducted to properly define the roles of such materials in different crop, soil, and climatic conditions. The overuse of amendments and fertilizers can cause losses to the environment also for nutrients other than N (Sylvain & Thomas, 2013; Veneklass et al., 2012).

The nitrogen balance method determines the N fertilizer recommendations by considering all sources of N inputs and outputs. Inputs are subtracted from the crop N demand, giving the value for mineral N fertilizer as a difference (Thompson, 2017). The total N outputs considered in this method include N uptake by crop, N losses (NO_3^- leaching, denitrification, NH_3 volatilization, immobilization), and estimated N remaining in the soil. The following table represents all the inputs and outputs considered by this method.

Table 1.1. Nitrogen balance method to determine the appropriate N application rates in vegetable crops

N inputs	**N outputs**
Initial soil mineral N ($N_{\text{min-ini}}$)	Crop N (N_{crop})
N mineralized from soil OM ($N_{\text{mins-OM}}$)	N losses (N_{loss})
N mineralized from crop residues ($N_{\text{mins-crop res}}$)	
N mineralized from manure ($N_{\text{mins-man}}$)	Final soil mineral N ($N_{\text{min-fin}}$)
N applied in irrigation (N_{irr})	
Mineral N fertilizer (N_{fert})	
Total N Inputs (∑Inputs)	**Total N Outputs (∑Outputs)**

CARBON-RICH FERTILIZER

Organic fertilizers are derived from natural sources like plant residues, animal excreta, and agriculture and agro-industries byproducts (Lin et al., 2019). Organic fertilizer increases the organic matter content in the soil, which is a key factor in improving soil fertility (Fageria, 2012). Soil organic matter (SOM) is dynamic and is affected by changes in soil management, tillage, and plant production techniques (Baker et al., 2007). SOM consists of living parts of the plant parts, dead forms of organic materials, and soil organisms in different stages of decomposition (Mohammadi et al., 2011). Organic fertilizers are highly efficient and can increase crop yield without compromising soil quality, contributing to long-term food security and the preservation of the environment (Cen et al., 2020). Thereafter, the benefits of organic fertilizers are often described as having long-term effects on soil fertility and crop performance by increasing soil organic matter content and subsequently improving soil structure, water-holding capacity, nutrient pool, and microorganism density (Zhang et al., 2020; Guo et al., 2016; Liu et al., 2010). In addition to increasing crop yield and soil nutrients, compost application can provide better resistance to diseases, and increase water use efficiency, nutrient cycling, and microbial density of soil (Stewart-Wade, 2020).

Farm-yard manure and compost are the traditionally used organic fertilizers that increase soil organic matter and enhance soil quality by improving soil's physical, chemical, and biological properties (Mohammadi et al., 2011). However, currently, organic fertilizers can be industrially manufactured by processing municipal solid wastes, sewage sludge, anaerobic digestion residues, by-products of mushroom cultivation, animal carcasses, feathers, wools, and bones (Sambo & Nicoletto, 2017; Sequi et al., 2017). Bulky organic fertilizers have relatively less nutrient concentration and are applied as base dressing, whereas more concentrated commercial organic fertilizers are applied to correct the nutrient supply based on crop requirements (Tei et al., 2020). They improve the soil aggregates (Hati et al., 2008), increase micropores (Schojonning, 1992) and macropores (Yang et al., 2011), decrease bulk density, and maintain good tilth to facilitate better germination and root development (Edwards and Hailu, 2011; Rowley, 2018). Nutrients are slowly released when compost is applied, which can benefit long-term nutrient availability by minimizing nutrient leaching associated with irrigation and rainfall (Paulin and Peter, 2008) and extending fertilization effects compared to mineral fertilizers (Larcheveque et al., 2011).

Long-term application of organic fertilizer contributes to environmental sustainability (Hui et al., 2017) and reduces eutrophication and climate change impacts (Kustermann et al., 2008). Application of organic fertilizer can change the soil bacterial population and their activities including the N-cycling microbiome community (Li et al., 2014; Yu et al., 2014), releasing nutrients in plant-available forms and hence, promoting plant vegetative growth and crop productivity (Kallenbach & Grandy, 2011; Jackson et al., 2012). The activities of soil enzymes are generally higher in organic fertilizer treatments than in chemical fertilizer and unfertilized treatments (Mohammadi, 2011), which is subjected to a combined effect of increased microbial biomass with increased soil carbon concentration and a higher degree of stabilization of enzymes to humic substances (Mohammadi et al., 2011).

SOURCES OF CARBON-RICH MATERIALS

On-farm sources

Plant and animal residues available on agricultural land are the on-farm sources of organic matter. These residues get decomposed within the soil by microorganisms under favorable conditions and are mineralized in plant-available forms (Mohammadi et al., 2011). Plants are called primary sources and animals, usually are the secondary sources of organic matter (NO, 2010). To keep the nutrient cycling system in balance, the rate of addition of organic matter in the form of plant residues, manure, or any other sources must be equal to the rate of decomposition, plant uptake, and losses by leaching, volatilization, and erosion (Bot & Benites, 2005).

- Plant materials

Since the harvest index, a ratio of commercial yield to the total yield, of the vegetable crops is often low, a large amount of plant material is left unharvested as residue on the field. These crop residues could be a good source of N for the subsequent crop if they are properly incorporated into the soil, facilitating the decomposition and mineralization of the organic matter. The value of N content in the soil could vary drastically depending on the individual vegetable crop, which is why these values must be acknowledged while planning the fertilizer application from an external source. If we fail to do so, there might be cases of over-fertilization and N losses (Tei et al., 2002). The amount of crop residues varies drastically among vegetable crops. For example, for leafy vegetables like spinach and lettuce, when measured as N, is usually 25-30 kg N/ha, and for crops like cabbages it could be as high as 250-300 kg N ha^{-1} (Chaves et al., 2007; De Neve, 2017; Tempesta et al., 2019). In the case of cauliflower, the N requirement of the subsequent crop could be well met by the N mineralization of its residues (Rahn et al., 2001).

Depending on the crop grown, under good climatic and soil conditions, over 80% of the mineral N present in the crop residues can be released within 9 weeks of soil incorporation, as shown in a Western European study (Tremblay et al., 2001).

- Animal materials

Animal manure is a common source of organic matter, especially in a vegetable production system, applied traditionally as farmyard manure (Neve, 2017). Currently, the form, nutrient content, and role of manures are very diverse based on where it is generated i.e., feedlots, dairy and beef farms, horse operations, poultry operations, and open-range ranches and the management of those facilities. The assimilative capacity and degradability are also dependent on the agronomic and environmental contexts in which the manure is introduced (Mohammadi, 2011). Animal manure is broadly categorized as liquid (slurries) and solid (farmyard manure). Liquid manure contains a greater amount of inorganic N than organic N, and the organic N is easily mineralized, totaling approximately 70% of the N fraction. Contrastingly, solid manure usually has less inorganic N and the mineralization of organic N varies greatly, resulting in only 40% to less than 0 readily available N (immobilization) (Neve, 2017). Solid manures usually have a high C: N ratio (20-30) and have limited N release in the first year of application whereas liquid manures like vinasse (2-3) or digestates (2-7) have low C: N ratio and hence, have higher and fast N availability (Moller, 2018).

Off-farm sources

Most of the off-farm sources of OM are recycled waste from agricultural industries introduced as organic manures and nutrition, aiming to improve resource use efficiency and waste minimization in the agricultural sector. Some sources are sludges from dairy factories, breweries, gelatin production, slaughterhouses, the deep freeze industry, the paper industry, municipal solid waste, etc. The major processing events include composting, digestion, and pyrolysis. The efficient use of these processed organic materials is an important challenge for future research, notably for predicting N availability (Neve, 2017).

COMPOST

Compost is a decomposed heterogeneous organic waste that is usually locally available and is a source of multiple nutrients essential for plants (Khaliq et al., 2006). Composting is a biochemical process of solid waste fermentation during which diverse groups of microorganisms mainly aerobic thermophiles and nematodes, play crucial roles (Pietronave et al., 2004) in maintaining the nutrient content of compost and its effect on crop productivity (Pepe et al., 2013). An additional advantage of microbial communities in compost includes the control of soil-borne pathogens in plants due to the combined effect of the production of antimicrobial compounds, heat release, and competition with the pathogens influencing the viability, thereby inhibiting the development of plant diseases (Mehta et al., 2014). In other words, composting is a technique of treating carbon-rich waste which otherwise would be incinerated or deposited in landfills (Zhang & Sun, 2014) into a value-added product (Qian et al., 2014) and eliminates the possibility of the negative effects that could have resulted from the direct application of organic waste in the soil (Onwosi et al., 2017).

Compost contains essential nutrients and organic matter, making it desired organic fertilizer among farmers (Adugna, 2016) that is in total agreement with sustainable and circular agriculture (Adbrecht et al., 2011). Depending upon the raw materials used, there are differences in the quality and nutrient availability among the available composts. However, composts guarantee a conspicuous amount of nutrient supply, an estimated 20% of the nutrients are released in the first year of its application (Sambo & Nicoletto, 2017). Similarly, the effectiveness of compost varies drastically based on soil properties like porosity, pH, oxygen availability, initial organic matter content, clay, and iron oxide (Courtney & Mullen, 2008; Forte et al., 2009).

Municipal solid waste (MSW) compost

In many European countries including Italy, municipal solid wastes are composted with potential agricultural use to improve soil organic fertility restoration while limiting the amount of waste going to final disposal, hence providing economic and environmental benefits (Fagnano et al., 2011). MSW composting is identified as an effective form of recycling wastes and is expected to play a more important role in waste management operations in the future (Arvanitoyannis, 2008) as it creates a product suitable for agricultural purposes at a relatively low-cost (Wolkowski, 2003). MSW might also contain non-food domestic biowastes like garden biowastes (Hargreaves et al., 2008) and the decomposable packaging material of food and non-food products (Waldron & Nichols, 2009), and together with food wastes, contributes to 55-70% by weight to the community's residential waste (Arvanitoyannis, 2008). Usually under suitable degradative conditions, a controlled composting process completes within 3 months; however, under normal conditions, it takes around 1-2 years (Kaiser et al., 1995).

The compost, hence prepared, is rich in organic matter and improves soil structure by enriching it with humic substances but the concentration of key nutrients is very low compared to commercial fertilizers (Arvanitoyannis, 2008). However, with the increasing interest in organic agriculture, the prospect and production of organic MSW compost for agricultural uses are also increasing owing its positive impact on the physical, chemical, and biological soil properties (Iglesias-Jimenez & Alvarez, 1993). In the Mediterranean area, along with compost and digestate, municipal solid waste gave appreciable yields in tomatoes, zucchini, and lettuce (Montemurro et al., 2010; Alburquerque et al., 2012).

Factors affecting the composting process

Composting is completed in three major stages with different microbes at each stage according to different physiochemical conditions (Bhatia et al., 2013; Mehta et al., 2014). Mesophiles are the first to appear in moderate temperatures. Increased temperature due to metabolic activities and the growth of mesophiles lead to the appearance of thermophilic microorganisms that decompose polysaccharides, proteins, and fats. The final stage shows a predominance of mesophiles again, making compost mature, cooled, and stabilized, which becomes ready for field application (Bhatia et al., 2013; Pepe et al., 2013). The various factors affecting the composting process are described below.

- Temperature

Temperature is the foremost factor to determine the effectiveness of the composting process as it determines the relative advantage of some microorganisms over others to make sure of the absence of harmful microbes. Temperature above 55 °C is essential to eliminate parasites and pathogens allowing maximum sanitary conditions (Ravindran and Sekaran, 2010). Compost in more than 72 hours of thermophilic phase can get rid of weed seeds and pathogens (Zhang & Sun, 2014). Caution is required at temperatures above 65 °C as it can be detrimental to beneficial microbes leading to the cessation of the process (Imbeah, 1998). Hence good composting temperature is best at 40-65 °C (Rigby et al., 2016). The temperature of the composting material gives an indication of composting phase as well as the real-time condition of microbial degradation (Awasthi et al., 2014).

- Aeration

Next to temperature, aeration is another important factor in composting (Chen et al., 2015), through which oxygen is consumed, and carbon dioxide and water are released (Awasthi et al., 2014). Oxygen is necessary to oxidize organic materials, evaporation of surplus moisture from the substrate, and regulate temperature across composting mass (Petric & Selimbasic, 2008). Aerobic microbial activities rely on aeration, the degree of which can affect the quality of the compost (Gao et al., 2010).

Higher aeration could increase evaporation and the cooling rate (Sundberg & Jonsson, 2008) during the thermophilic stage and can prevent the decomposition process (Gao et al., 2010).

- Moisture

Moisture content during composting has been observed to influence the degree of aeration, oxygen uptake rate, temperature, free air space, and microbial activities (Petric et al., 2012). Moisture content shows an inverse relationship with the gas diffusion rate i.e., the higher the moisture content, the lower the rate of gas diffusion which could result in the poor oxygen supply needed for the metabolic activities by the microorganisms (Mohammad et al., 2012). On the other hand, very low moisture could decline the distribution of soluble nutrients (Guo et al., 2012) and in addition, would cause dehydration at the early stages of composting process hindering the biological process (Makan et al., 2013). Moisture content has been found to differ among different materials which needs initial adjustment accordingly. For example, composting of poultry and wheat straw requires 70% initial moisture content (Petric & Selimbasic, 2008), and pig slurry requires 60-70% moisture content (Ros et al., 2006). Food waste is high in moisture content and thus requires suitable adjustment. Optimal moisture content for effective composting has been the topic of discussion for years (Bernal et al., 2009; Onwosi et al., 2017) yet no concrete conclusions have been revealed.

- C: N ratio

Carbon, nitrogen, and potassium are the major nutrients microorganisms demand for composting (Darby et al., 2016) which are acquired by breaking down organic compounds that release energy for metabolism (Chen et al., 2015). Since C is an energy source and N is the constituent of the building cell structure, C and N are particularly crucial (Chen et al., 2015; Iqbal et al., 2015). In the lack of N, microbial growth will be constrained, resulting in the reduced decomposition of the C (Igoni et al., 2008).

Compared to the conversion rate of N, microorganisms use C 30-35 times faster (Igoni et al., 2008). In case of a lower C: N ratio, huge amounts of soluble basic salts are released, unfavorable for plant growth (Awasthi et al., 2014), and N will be released as NH_3 emissions. In other cases of a higher C: N ratio, the composting process is delayed due to insufficient N required for microorganisms' growth (Chen et al., 2015). Since the initial C: N ratio will affect both the mineralization of organic matter and nitrification processes (Ros et al., 2006), bulking agents such as rice husk, wood chip, peanut shells, and urea are proposed to be added to adjust the ratio (Wang et al., 2015; Zhang et al., 2016; Zhang et al., 2016).

Besides these factors, particle size, pH, and degree of compaction have also been observed to influence the composting process (Juarez et al., 2015; Li et al., 2013). The most pronounced advantages of composting include the reduction of greenhouse gases, improvement of soil properties by use of nutrient-rich compost (Bernstad, Canovas & Valle, 2017; Garg, Gupta & Satya, 2006), increased yield, sustainable cultivation, and improved nutrition. Also, composting is a simple biological process that is easy to understand and produces stabilized and sanitized products and nutrients. Despite these immense advantages and possibilities, the production of compost fertilizer and its use seems underrated. The possible reason behind this may be the lack of assurance among people regarding its fertility (Lupton, 2017) and/or the toxicity of fertilizers (Lekfeldt, Kjaergaard & Magid, 2017). Further, competitive prices between chemical and organic fertilizers might be a concern for people (Case et al., 2017; Dannehl et al., 2016). Current attitudes of people towards the use of compost fertilizer are knowledge gaps, assumed and/or actual technical defects such as contaminants, price advantages, and cultural barriers are possible reasons for its slow adoption.

MINERAL VS. CARBON-RICH FERTILIZER

Mineral fertilizer alone is insufficient to maintain an adequate level of fertility and soil function; organic matter should be added to maintain a satisfactory level of water, nutrients, and soil fertility. If the soil has limited organic matter, yield response is limited even if artificial fertilizer is sufficiently applied (Madeleine et al., 2005). This is because continuous use of chemical fertilizers deteriorates soil health and fertility with the advancement of time and intensification of agricultural activities (Savci, 2012; Cassman et al., 1997). Though mineral fertilizer increases crop yield, negative impacts are, but not limited to decreasing organic matter content, loss of soil aggregates, soil acidification, loss of soil biodiversity, groundwater pollution, and greenhouse gas emissions (Koch & Stockfisch, 2006; Zhu et al., 2017; Ju et al., 2007; Meng et al., 2000; Clark & Tilman, 2008; McGill, 2015). Prolonged application of mineral fertilizer often reduces soil pH and leads to soil acidification in vegetable-producing soil (Meng et al., 2000). Excessive mineral fertilizer application combined with excessive irrigation, increases the accumulation of soil nutrients resulting in reduced N fertilizer efficiency, in most cases only up to 30-50% (Norse, 2005) and less than 10% in some cases are up taken by plants, thereafter, increasing losses of those nutrients in forms of gases or leaching to shallow groundwater (Ju et al., 2007).

The negligence in the use of chemical fertilizers and excessive reliance upon them has caused the exhaustion of soil nutrient reserves along with the emersion of various soil health problems (Norse, 2005). In addition to this, with the rise in the prices of chemical fertilizers and growing awareness of environmental safety concerns in recent years, the public interest has shifted towards organic produce and opened the scope for research works in the organic production sector (Berova et al., 2010). However, organic fertilizer when applied independently provides insufficient nutrients to support expected yield, healthy crops and maintain soil fertility (Giller et al., 1997) because nutrient released from organic manure is dependent on soil microorganisms and environmental conditions all of which affect the rate and timing of nutrient mineralization (Rowley, 2018). Because, as of now, the unreliability of carbon-rich amendments to supply a known amount of N and other nutrients when needed especially in the context of fulfilling the ever-increasing food demand, the use of chemical fertilizers cannot be fully eliminated (Adesemoye & Kloepper, 2009). Though the nutrient use efficiency was higher, the yields were 20 % lower in organic fertilizer treatments than in conventional systems as reported in the study conducted by Mader et al. in 2002 is one such example.

Vegetable crops require a continuous adequate supply of nutrients for their proper growth and development. The effect of organic fertilizer is variable and rather slow, and its management is labor-intensive and expensive compared to mineral fertilizers (Maggio et al., 2008), thereafter, farmers prefer conventional mineral fertilization to organic fertilizers to maintain crop yield (Smith et al., 2008). When only organic fertilization is practiced, owing to the low mineralization rate of soil organic matter, often a high quantity and continuous application of compost are applied (Chang et al., 2007). However, other factors like climate and soil type affect the release and storage of nutrients, than just the quantity applied. The ratio of compost mixed with soil is also important in determining the nutrient supply and properties of soil including texture, bulk density, pH, EC, organic carbon, and nitrogen content of the soil (Isa et al., 2021). Due to the physical properties of compost, mainly high bulk density and low plant available moisture, salinity, biological oxygen demand, pH, and degradation rate, the high amount of compost in the soil is often limited to less than 50% (Raviv, 2011).

Often, compost is applied based on the N requirements of the crop and while doing so, other nutrients may be applied in excess as the inorganic N content of the compost is lower (Hargreaves et al., 2008). When compost was applied at more than the appropriate rate, in addition to not providing further enhancement of the microbial population and soil enzyme activities, the yield did not increase compared to the control in a study conducted by Chang et al., 2007 in 24 different vegetable crops. It further can alleviate the adverse effect of soluble salt on crop growth (Chang et al., 2007). This shows that despite having numerous benefits, a high amount of compost application is neither beneficial nor sustainable in the long run. This compromises sustainability in the agricultural system, and many studies suggest that there is a need for an improved method of nutrient supply with minimum negative environmental impacts while still satisfying the food demand of the growing population (Godfray et al., 2010; Foley et al., 2011).

INTEGRATED APPROACH

Chemical fertilizers meet the mineral nutrient demand of plants and microorganisms, but not the carbon demand, which is also essential to regulate the nutrient cycle in the soil as carbon is a major component of the microbial cells. So, the integrated application of chemical and organic fertilizers is taken into consideration to provide a balanced supply of mineral nutrients and carbon (Mohammadi et al., 2011). An approach to integrating compost application with mineral fertilizer is a good strategy for sustainable farming (Gete et al., 2010), resulting in a synergistic effect and synchronized uptake of nutrients by crops (Palm et al., 2001). Combined application of organic and mineral fertilizers is an integrated soil fertility management (ISFM) approach that increases fertilizer use efficiency (Pincus et al., 2016, Donovan & Casey, 1998; Hua et al., 2020), while still resulting in improved yield benefits, soil organic carbon, and total nitrogen content compared to either of them applied independently (Gai et al., 2018; Mucheru-Muna et al., 2007; Nziguheba et al., 2002; Pincus et al., 2016).

When compost is applied with mineral fertilizers, planting shock is reduced for plants along with a continuous nutrient release (Larcheveque et al., 2006), it improves soil structure and creates the favorable environmental condition for root development (Larcheveque et al., 2011; Pagliali et al., 1981), even when mineral fertilizer is applied at a low rate (Kapkiyai et al., 1998), checking the total leachable N from applied mineral fertilizers (Rowley, 2018). Hence, the judicious application of mineral and organic fertilizer is essential to maintain soil health and sustain productivity (Rana & Sharma, 1993). A study conducted by Ye et al., 2020, concluded that organic fertilizer when applied with a reduced rate of chemical fertilizer, gives a yield equivalent to the yield obtained by using 100% chemical fertilizer, hence proving that the application rate of chemical fertilizers can be reduced while maintaining better yield, quality, and economic efficiency. The soil physical conditions were improved through better soil aggregation, saturated hydraulic conductivity, reduced mechanical resistance, and bulk density in the study conducted by Hati et al., 2006 when farm-yard manure was applied with chemical fertilizer in a soybean-mustard crop rotation. Also, a study conducted by Caris-Veyrat et al., in 2004 reported that nutrient content in vegetable crops grown with ISFM had higher nutrient contents including carotenoids, polyphenols, and Vitamin C than when conventional fertilization was done.

NITROGEN USE EFFICIENCY

The nutrient use efficiency of plants refers to the ability of plants to acquire, transport, store, and use the nutrients from the soil depending upon the level of nutrient supply to produce dry matter/grain or a commercial product (Ciarelli et al., 1998) to the maximum potential (Gonzalez-Fontes et al., 2017). Plants with high nutrient use efficiency perform better even when nutrient availability is limited (Tilman et al., 1997). Extended monoculture practices deplete the nutrients taken up by the individual plant but neglect other essential nutrients that other plants within a planting sequence could have taken advantage of (Benincasa et al., 2017). Nutrient use efficiency can be dependent on root growth and architecture (Pietro et al., 2017). But it is also vaguely affected by external factors like climate, soil, biological interaction among soil microorganisms, soil, and plants (Gonzalez-Fontes et al., 2017), and agronomic management practices like fertilizer application and irrigation (Panhwar et al., 2019). Due to the continuous global food demand, the need for fertilizer application has also increased, however, fertilizer is a limited resource, the cost for its production and distribution is increasing, and the public concern related to nutrient use side effects is growing (Panhwar et al., 2019).

The increased use efficiency of nutrients helps to reduce the quantity applied of the external inputs and limits the probable environmental impacts due to the application (Tuomisto et al., 2012). Similarly, improvement of nutrient use efficiency is an essential prerequisite in the present context when there is limited productive land and a dire need for expansion of crop production even from the marginal lands with low nutrient availability (Adhikari et al., 2023). Factors such as the source of nutrients, crop requirements, application rate, placement, and their interactions with one another along with the crop, the environment, and agronomic management practices must be taken under consideration to identify the most efficient nutrient management system (Panhwar et al., 2019). Nitrogen (N), being the fundamental element regulating the growth and development of plants, is the most explored nutrient for efficiency studies. The inorganic and organic-N uptake systems have evolved in the plants to adjust to the diverse N availability in the soil (Pietro et al., 2017). Vegetable crops in particular, due to their short growing cycles and superficial rooting, have a relatively low nutrient use efficiency compared to other arable crops (Greenwood et al., 1989; Thompson et al., 2020). Nutrient use efficiency is usually estimated for major nutrients like N, P, and K, and has been reported to be lower than 50% for N, less than 10% for P, and about 40% for K (Baligar et al., 2001).

Generally, nitrogen use efficiency (NUE) considers two main components, N uptake efficiency which means the ability of crops to take up N from the soil (Burns, 2006; Greenwood et al., 1989), and the efficiency to use the absorbed N to grow and produce yield (Janssen, 1998; Schenk, 2006). N-use efficiency is measured using various parameters and is also influenced by various crops, soil, and environmental factors. Usually, both fertilizer-N and soil-N are considered though they are considered nearly equivalent (Greenwood et al., 1989) while measuring total N-use efficiency as they may be available differently in time and space (Burns, 2006). The use efficiency of absorbed N is calculated by considering the total crop dry weight accumulated per kilogram of absorbed N excluding the roots (Benincasa et al., 2011). However, in vegetables, the actual marketable yield can be different from the potential yield (Van Eerd, 2007), so the marketable dry weight is often considered to calculate N efficiency parameters (Benincasa et al., 2011). Crop management also plays an important role in determining N use efficiency of crops (Neeteson et al., 1999) which includes but is not limited to land management (i.e. harvesting method, tillage, and/or rotation) crop density and spatial arrangement of plants in the field (Shapiro & Wortmann, 2006), fertilization rate and application methods (Li, 2003; Linaje et al., 2005), water management, fertigation (Battilani et al., 2003; Remie et al., 2003), and use of microorganism and plant growth promoters (Chen et al., 2003; Gadagi et al., 2004). Also, the interactions between any of the above-mentioned factors can significantly impact on N use efficiencies.

Agronomic Efficiency (AE)

AE is the efficiency of applied nutrients used in increasing the commercial yield (Brouder & Volence, 2023) and is calculated as the increase in yield per unit nutrient applied.

$$AE\ (kg\ kg^{-1}\ N)\ = \frac{Gf - Gu}{Na}$$

Where, Gf = Commercial yield of a fertilized plot

Gu = Commercial yield of an unfertilized plot

Na = Amount of nutrient applied

Physiological Efficiency (PE)

PE is defined as the yield increase in the aboveground part of the plant due to crop uptake of nutrients and is mainly used for research purposes (Brouder & Volence, 2023). It is the total biomass yield obtained per unit of fertilizer contributed.

$$PE\ (kg\ kg^{-1}\ N)\ = \frac{Byf - Byu}{Nf - Nu}$$

Where, Byf = Biomass yield of a fertilized plot

Byu = Biomass yield of an unfertilized plot

Nf = Nutrient taken up in biomass of fertilized plot

Nu = Nutrient taken up in biomass of unfertilized plot

Apparent Recovery Efficiency (ARE)

ARE is the proportion of the nutrient applied as fertilizer that plants take up and are influenced by fertilizer management and crop nutrient needs (Brouder & Volence, 2023).

$$ARE\ (\%) = \frac{Nf - Nu}{Na} * 100$$

VEGETABLE CROP CYCLE

Vegetable crop rotation is a common practice implemented to improve soil fertility management in conventional and organic systems, whether in a specialized or non-specialized production system (Benincasa et al., 2017). Increasing nutrient use efficiency, and self-sufficiency is often practiced, especially in the vegetable cropping system. Crop rotation helps improve soil fertility by exploring available soil nutrients in different depths (Gardner & Sarrantonio, 2012; Pedersen et al., 2009) and by establishing a symbiotic relationship with soil organisms having high nutrient extraction/fixation ability. Rotating crops with different root depths and structures increases nitrogen use efficiency (Thorup-Kristensen, 2002) and allows them to recover and recycle P and other nutrients (Sylvain & Thomas, 2013). Usually, after the fertilizer incorporation, high N-demanding vegetables should be planted first so that they can best utilize the available nutrients. In contrast, low N-demanding vegetables should be grown later, whose requirements could be fulfilled by the residual N availability (Poltronieri et al., 2013). Nutrient use efficiency could be increased by cultivating an appropriate sequence of vegetable crops (Benincasa et al., 2017) in a combined fertilization system including both mineral and carbon-rich fertilizers as carbon-rich fertilizers enhance soil N retention capacity and mineral fertilizers ensures N supply in the short-term (Evanylo et al., 2008; Morra et al., 2013). The study conducted by Moccia et al., 2006 showed that the soil organic C and total N increased by 37% and 22%, respectively, in four years in an organic farming system with crop rotation than the monocropping system, guaranteeing long-term nutrient availability and crop yields in the carbon-rich system.

QUALITY PARAMETERS OF VEGETABLES

One of the major factors contributing to nitrate accumulation on raw vegetables is the application of nitrate-based fertilizers in the production system. Nitrate is the most important form of N taken up by most plants (plant preferring soil pH >5.5). When the plant's nitrate uptake exceeds N requirements, the excess N is stored in the leaves compared to the bulbs, seeds, fruits, roots, and tubers. Hence, leafy vegetables are prominent nitrate-accumulating plant species (Maynard et al., 1976; Santamaria, 2006). Almost 80% of human exposure to nitrate is related to the raw consumption of vegetables (EFSA, 2008). Hence, it makes the regulation of nitrate accumulation in vegetables a rather important issue of discussion. The acceptable daily dose of NO_3^- set by the European Union is 3.7 mg kg^{-1} body weight per day, and the fatal adult dose is 7-35 g per day (Petersen & Stoltze, 1999).

High nitrate accumulation in leafy vegetables is one of the important health risks posed by the combination of high crop N demand, low N fertilizer recovery rate by vegetable crops, and excessive irrigation (Thompson et al., 2007; Thorup-Kristensen et al., 2012). In crops like lettuce, the highest level of toxicity was reported when chemical fertilizers were applied and were almost twice that of lettuce fertilized with carbon-rich fertilizers (Pavlou et al., 2007). For crops in which the leaf is not a commercial product, other edible portions of the crops should be considered to estimate the potential toxicity (Hargreaves et al., 2008) based on its consumable parts. The sustainability of the vegetable production sector depends on the willingness and ability of the producers to effectively reduce N losses to the environment by adapting to more efficient N management systems (Quemada et al., 2013). In light of this, many researchers are now focusing on improving the N management in vegetable cropping systems to reduce the negative environmental and health impacts (Tei et al., 2017; Padilla et al., 2018; Kristensen & Stavridou, 2017). Research suggests that municipal solid waste compost application does not result in the accumulation of undesirable metals in tomato and squash (Ozores-Hampton & Hanlon, 1997). However, it is suggested to consider a variety of plant species for a comparative trial to ensure that they are safe for human consumption (Hargreaves et al., 2008).

OBJECTIVES OF THE STUDY

The objective of our study was to evaluate the impact of different rates of compost and mineral fertilizers on the yield, quality, and nitrogen use efficiencies of the vegetable crops grown in succession to determine if the integrated application of the compost and mineral fertilizers or the increased rate of application of compost as a fertilizer performed well enough to be accepted as an alternative to mineral fertilization without having to compromise the yield and quality while making the transition from a conventional to an organic fertilization vegetable succession system.

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CHAPTER 2

EFFECT OF COMPOST AND MINERAL FERTILIZER RATES ON YIELD AND QUALITY OF MID-TERM VEGETABLE SUCCESSION[1]

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[1] Shrestha, J., Sambo, P., Nicoletto, C., Franklin, D., & Cabrera, M. To be submitted to Agronomy Journal.

ABSTRACT

Continuous use of mineral fertilizers to fulfill the growing food demand can potentially harm human and environmental health. Shifting from mineral to organic fertilization has been suggested as a sustainable solution to maintain and improve soil health while satisfying food demand and quality. However, previous studies also suggest that using only organic fertilizer during the initial years of conversion limits crop yield to its full potential. A study was conducted at the experimental farm of the University of Padova, Italy, in a three-year vegetable crop succession from 2020 to 2022 to evaluate the impacts of different rates and combination ratios of mineral and compost fertilizers on the yield and quality of vegetables. Our study aimed to determine if the combined application of mineral and organic fertilizer or an increased application rate of compost fertilizer could be a viable solution to the abovementioned problem. The 5 fertilization treatments, i. T0 (control), ii. TMIN (100% mineral N), iii. T50 (50% mineral N and 50% compost N), iv. T100 (100% compost N), and T200 (200% compost N), were replicated 4 times in a randomized block design. The commercial yield and the total biomass of most vegetable crops were higher for TMIN followed by T50 and T200. The significant differences among the treatments for yield were obtained for processing tomatoes, cabbage, and lettuce, and for the total biomass, only caramba cabbage had significant differences. As for the quality parameters, positive results for total soluble solids and electrical conductivity emerged in favor of compost treatments, especially T200. However, only a few data were significant. The indifferent results between the fertilized and non-fertilized treatments indicate the presence of initial soil fertility that influenced the actual impact of the applied fertilizers. Moderate results were obtained for T50 throughout the experimental period. However, noticeable positive impacts on yield,

biomass, and quality of vegetables in the later stages of succession were obtained for compost after continuous application.

INTRODUCTION

Fertilizers are external inputs needed to restore the nutrients in the production system, which are removed from the soil to produce marketable yields, mainly supplied by chemical or organic materials (Sambo & Nicoletto, 2017). Mineral fertilizers are conventional fertilization inputs that increase crop yield and are extensively used to fulfill the growing food demand of an increasing global population. However, the continuous use of chemical fertilizers deteriorates soil health and fertility, causing numerous harmful impacts on human and environmental health (Koch & Stockfish, 2006; Zhu et al., 2017). As a solution, an organic farming system has been proposed to produce food with minimal harm to ecosystems, animals, or humans (Mclntyre, 2009; Schutter, 2011). Soil managed under organic systems has better water-holding capacity and infiltration rates in addition to a higher yield than the conventional systems under drought conditions (Colla et al., 2000; Lotter et al., 2003). Organic fertilizers, however, provide insufficient nutrients to support the expected yield (Giller et al., 1997) and their management is labor-intensive and expensive compared to mineral fertilizers (Maggio et al., 2008).

Organic fertilizers are usually applied in bulk to meet the N demand of the crop because organic systems are N-limited, whereas conventional systems are not (Seufert et al., 2012). Moreover, often due to environmental and soil factors, the release of plant-available mineral N from organic fertilizers like compost or animal manure is slow and does not correspond to the crop N demand when plant requirements are greatest (Pang & Letey, 2000; Berry et al., 2002). Because of these reasons, in the context of fulfilling the increasing food demand, the use of chemical fertilizers cannot be fully eliminated (Adesemoye & Kloepper, 2009), especially because high yields are popularly considered essential to sustainable food security on a finite land basis (Godfrey et al., 2010). An integrated nutrient management system combining mineral and organic fertilizers could be a viable solution to sustainable and cost-effective soil fertility management, resulting in increased productivity without having considerable environmental impacts (Roba, 2018). Many studies suggest that the integrated application of mineral and organic fertilizers results in improved yield and quality benefits, soil organic carbon, and total nitrogen content compared to either of them applied independently (Gai et al., 2018; Mucheru-Muna et al., 2007; Pincus et al., 2016).

Most of these studies are focused on an individual crop and for a short cropping duration. Moreover, in this study, the application of compost is considered a fertilizer and not a soil improver, differently from what has been considered in many studies previously cited, partially or completely replacing mineral fertilization. The objective of this study was to evaluate the impacts of different rates of compost and mineral fertilizers on the yield and quality of vegetables in a mid-term vegetable succession.

MATERIALS AND METHODS

This three-year study was conducted at the "L. Toniolo" Experimental Farm of the University of Padova, Legnaro (PD) from the year 2020 to 2022 in open field conditions. The soil of the experimental field was characterized as a Fluvi-Calcaric Cambisol (CMcf) with clay-texture (IUSS Working Group WRB, 2014), capacity of field and wilting point respectively equal to 34% (v v^{-1}) and 13.5% (v v^{-1}), and bulk density of 1.45 Mg m^{-3}. The chemical characteristics of the soil at different depth based on dry matter basis is represented in **Table 2.1**. The 5 fertilizer treatments used in this experiment were based on nitrogen supply to satisfy crops needs: i. T0 (control), ii. TMIN (100% mineral N), iii. T50 (50% mineral N and 50% compost N), iv. T100 (100% compost N), and T200 (200% compost N). Each experimental plot was of dimension 12 m*8 m (96 m^2 per unit area). The treatments were arranged in a randomized block design with 4 replications, totaling 20 plots. The plots were timely irrigated based on the water requirements of each crop. The crops were planted in succession for three years, and are represented in **Table 2.2**.

Table 2.1. Chemical properties of the soil of the experimental field at 0-0.20 m depth and 0.20-0.40 m depth

Soil Depth	pH	EC (µS cm^{-1})	NH_3^--N (mg kg^{-1})	NH_4^+-N (mg kg^{-1})	K (mg kg^{-1})	P (mg kg^{-1})
0–0.20 m	7.35	250	101	49	94	100
0.20–0.40 m	7.3	250	87	24	61	213

Table 2.2. List of crops in succession and their transplantation and harvest dates

Year	Crops	Plant density (plants m^{-2})	Transplantation date	Harvest date
2020	Processing tomato (Solanum lycopersicum HEINZ 1281 F1)	4	6th May	5-6th / 17-18th August
	Chard (Beta vulgaris Apulian type) and Catalogna chicory (Cichorium intybus L., Catalogna Group variety Katrina)	9.2	28th August	10th November
2021	Cabbage (Caramba and Alfaro) and Cauliflower	4	2nd April	18th June
	Radicchio (Castelfranco, Chioggia, Verona, Treviso)	7.4	12th August	10-25th January (2022)
2022	Lettuce (Gentile and Red lollo)	9.2	7th April	25th May
	Pumpkin (Delica and mini moscata)	1	24th June	3-4th October

The compost was produced and supplied by the S.E.S.A Societa Estense Servizi Ambientali S.P.A company based at Via Comuna, 1, 35042 Este PD, after which the trail 'SESA' is named. The chemical composition of the compost was determined before its application and is shown in **Table 2.3**.

Table 2.3. Chemical properties of the compost on a dry weight basis

	N	P	K	% dry matter
	% dw			
Year 1	1.65	0.53	1.98	50
Year 2	1.99	0.64	2.65	58
Year 3	1.65	0.53	1.98	54

At the beginning of each crop year, the crop's requirement for N, P, and K was calculated to determine the amount of compost and mineral fertilizer inputs depending on the treatments applied as represented in **Table 2.4**. The obtained amount of compost was the fresh weight of compost that was required to supply the proportion of crop N requirement (inorganic N) based on the treatments applied assuming complete mineralization.

Table 2.4. Application rates of the compost (fresh weight), and N, P, and K fertilizers for fertilization treatments applied to vegetable crops in succession. Application rate for compost (Mg ha^{-1}) was calculated by dividing the N application rate by compost % dry weight and % N of compost dry weight time 10, for each year (Table 2.3.). For compost treatments, mineral P and K fertilization were only applied in case the applied compost could not satisfy the total P_2O_5 and K_2O requirements.

	T0	TMIN	T50	T100	T200
Year 1 (Processing tomato) requirement					

Compost (Mg ha^{-1}) (Fresh weight)	-	-	10.75	21.25	42.5
N (kg ha^{-1})	-	170	85	-	-
P_2O_5 (kg ha^{-1})	-	130	64.4	-	-
K_2O (kg ha^{-1})	-	260	132	7.1	-
Year 2 (Cabbage and Cauliflower) requirements					
Compost (Mg ha^{-1}) (Fresh weight)	-	-	4.33	8.66	17.32
N (kg ha^{-1})	-	100	50	-	-
P_2O_5 (kg ha^{-1})	-	70	-	-	-
K_2O (kg ha^{-1})	-	160	-	-	-
Year 2 (Radicchio) requirements					
Compost (Mg ha^{-1}) (Fresh weight)	-	-	3.03	6.06	12.12
N (kg ha^{-1})	-	70	35	-	-
P_2O_5 (kg ha^{-1})	-	60	-	-	-
K_2O (kg ha^{-1})	-	110	-	-	-
Year 3 (Lettuce and Pumpkin) requirements					
Compost (Mg ha^{-1}) (Fresh weight)	-	-	9.6	19.2	38.5
N (kg ha^{-1})	-	170	85	-	-
P_2O_5 (kg ha^{-1})	-	140	88	12.4	-
K_2O (kg ha^{-1})	-	375	243	110	-

Both compost and mineral fertilizers were applied (1-2 days before the transplantation of the samplings) and incorporated in the soil by the rotavator. Before that incorporation, tillage was done to a depth of 30 cm, followed by harrowing. Mulching was provided for tomatoes, lettuce, and pumpkins.

Sampling and harvesting

A pre-harvest was done for processing tomatoes by selecting 3 sample plants at their marketable maturity to determine the total biomass production (marketable and waste biomass) and harvest index (HI).

$$\text{Harvest Index (HI)} = \frac{\text{Marketable fresh biomass (kg)}}{\text{Total fresh biomass (kg)}}$$

Ethrel® was sprayed to induce a uniform ripening at the rate of 2.5 L ha^{-1} to facilitate the final harvesting. In the case of cabbages and cauliflowers, the first non-destructive sampling was performed after 30 days of transplantation to count the number of leaves and measure the SPAD (Chlorophyll meter SPAD-502 Plus) value, indicating the chlorophyll content in leaf tissues and the vegetative vigor of seedlings. After another 30 days, another non-destructive sampling was done to assess the production potential of the sample plants. Two non-destructive samplings were carried out for lettuce to measure the chlorophyll content in the leaves using SPAD. Similarly, Dualex (Dualex 4 Horta Ltd.) was used to measure the anthocyanins and flavonoid content in the leaves. As for pumpkins, one non-destructive sampling was done to measure the chlorophyll content in the leaves by using SPAD.

For all vegetables in succession, the final harvest was done when the crops reached their commercial maturity to determine eac crop's commercial yield and total biomass for all fertilizer treatments by selecting plants within the 10 m^2 area of the central row of each plot. Two sub-samples of the harvest were taken for each crop, the first one to determine the dry matter percentage by dehydrating the samples at 65^{o}C for 48 hours, and another sample was stored at -18^{o}C to be later used for qualitative analysis. For the pumpkin, three representative fruits from each plot were selected to measure the equatorial and polar diameters, the flesh's thickness, and the flesh's color.

Due to the unwarranted weather conditions during the flowering season, there were no commercial harvests for cauliflower varieties to carry out further measurements. The crop residues after harvest were shredded and buried by two successive harrowing to take advantage of the residual fertility present in the soil.

Laboratory analysis

The dry matter of the vegetable samples was determined by taking a difference between the weight of the fresh sub-sample separated during harvest and its weight after being dried by placing it in an oven at 65°C for 48 hours. pH and electrical conductivity (EC) were measured using a portable pH conductivity meter (model HI Hanna Instrument) on the thawed sample juice of the vegetables. Similarly, a drop of the thawed juice was used to measure the total soluble solids content (TSS) (°Brix) by using a portable digital refractometer (HI 96801). Titratable acidity (TA) was determined according to the standard ISO 750:1998 (E) method, which involves taking a known volume of cell juice (10 ml) to which 40 ml of demineralized water is added. Using the STEROGLASS s.r.l. Titrex Act automatic titrator, the sample was titrated. The mL of 0.1N soda ash (NaOH) needed to reach the pH threshold value at 8.2 of the solution composed of the sample plus the citric acid was then noted. Then the titratable acidity in grams of citric acid per 100 g of fresh product was defined by the following formula.

$$Z = V * N * mEqwt * 100 / Y$$

Where:

Z= g of acid per 100 g of sample

V= volume in ml of NaOH (sodium hydroxide) used for titration

N=normality of NaOH (0.4 g l^{-1})

mEqwt = milliequivalents of acid (0.064 citric acid)

Y= volume in ml of sample

The determination of antioxidants and phenols was carried out by using the methods given by Kang et al. (2002) with appropriate adjustments to adapt the method to the matrix to be analyzed. 2 g of powdered frozen, dried sample was mixed with 20 ml methanol and filtered with filter paper (589 Schleicher diameter 125 mm). For antioxidants determination, 100 µ of the extract was added to 1900 µ of FRAP reagent and homogenized by shaking for 4 minutes at 20°C. The absorbance was read at 593 mm in the spectrophotometer, and the reading was compared with the calibration curve of ferrous ammonium sulfate solutions with concentrations from 0 to 1200 µ ml^{-1}. The final antioxidant value was expressed as mg Fe^{2+} equivalents (Fe^{2+} E) per kg of dry and fresh samples. For phenol determination, 200 µ of extract was added to 1000 µ of Folin-Ciocalteau reagent and 800 µ of 7.5% anhydrous sodium carbonate, followed by shaking for 15 minutes and resting for 30 minutes at room temperature. The spectrophotometer reading was at 765 mm, and the absorbance values were compared to the known concentrations of gallic acid (0-300 µ ml^{-1}). The phenol content was expressed as mg gallic acid equivalents (GAE) per kg of dry and fresh samples.

Statistical analysis

The data obtained were analyzed with Statgraphics 19 Centurion software by means of ANOVA. In the case of significant F-values, the means were compared with Tukey's HSD test at the significance level of $p < 0.05$.

RESULTS

Processing tomato

The total weight of ripe fruits per plant for tomato was significantly higher for T0, TMIN, T100, and T200, with the highest value of 1.52 kg for T200 than the lowest value of 1.17 kg for T50 **(Figure 2.1.)**. However, the total weight of unripe fruits was significantly higher for T200 (2.37 kg) than for all other fertilization treatments. The tomato crop's total biomass and HI were not significantly different for the treatments; however, the highest biomass yield was for the treatment T200 and HI for T100. For the qualitative traits, no significant differences were found among the treatments for the dry matter %, TSS, pH, TA, antioxidants, and phenolic value for the processing tomatoes. However, significant differences were found for the EC, the highest value was for T200 and the lowest for TMIN.

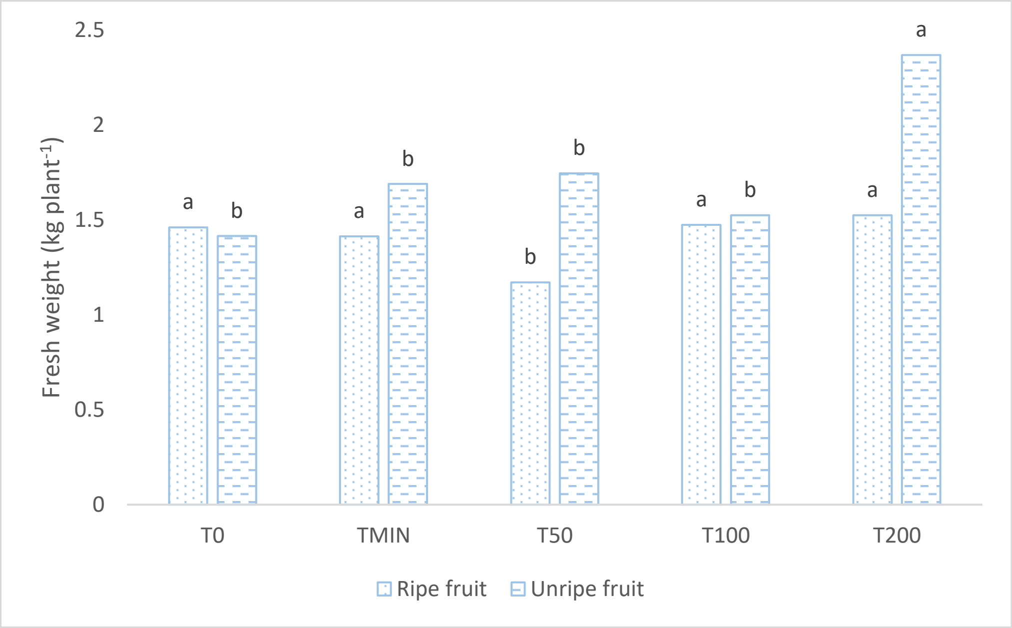

Figure 2.1. Fresh weight of ripe and unripe fruits of processing tomato for different fertilization treatments. Different alphabets in the graph indicate the significance under HSD Tukey's test $p < 0.05$.

Chard and Chicory

The commercial and biomass yield of chard and chicory was not significantly different among fertilization treatments. The prominent contributor to biomass is their commercial product, leaf. The dry matter, pH, TSS, and TA values were also not statistically significant for either.

Cabbage

The first survey was conducted 32 days after the transplantation (DAT) of cabbage and showed that in both varieties (Caramba and Alfaro), the number of leaves per plant values varied significantly with fertilization treatments. The values were significantly higher for TMIN and T50, followed by T100 and T200. However, during the second survey at 64 DAT, there were no differences among the treatments. The SPAD readings were statistically significant at both sampling periods for the caramba variety; the highest values were for T50 and TMIN at 32 DAT and 64 DAT respectively. In the case of the Alfaro variety, significant differences among the treatments for SPAD values were at 64 DAT only; the highest value was observed for TMIN.

For the Caramba variety of cabbage, the commercial yield per plant and the total biomass values were significantly greater than the control but not different from the compost treatments. The highest values were obtained for TMIN, 1.161 kg for commercial yield per plant **(Figure 2.2.)** and 94.95 kg ha^{-1} for biomass yield **(Figure 2.3)**. As for the Alfaro variety, only the commercial yield per plant value was statistically significant from the control and the highest value was for T50 (1.41 kg) (**Figure 2.2.**). Also, for the caramba cabbage, the values for dry matter %, pH, TSS, EC, and TA were not significantly different among the treatments.

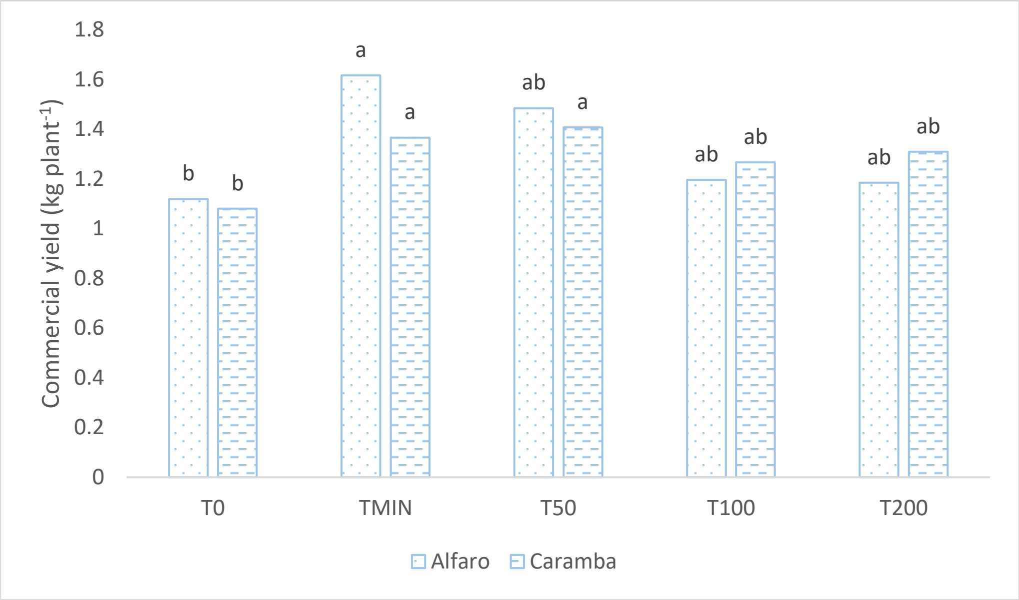

Figure 2.2. Commercial yield per plant of Alfaro and Caramba varieties of cabbages for different fertilization treatments. Different alphabets in the graph indicate the significance under HSD Tukey's test $p < 0.05$.

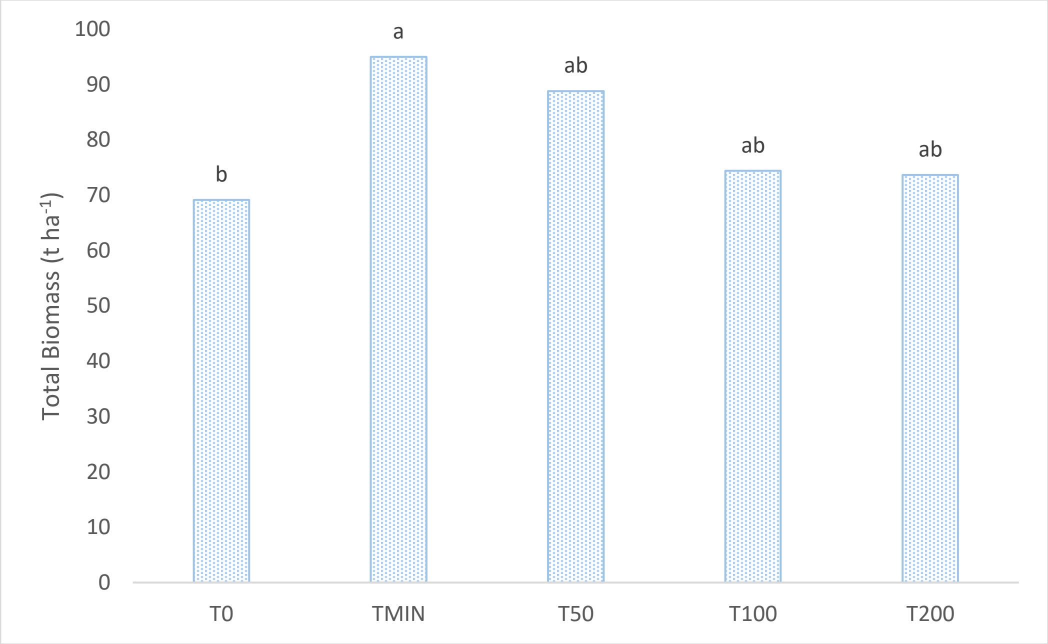

Figure 2.3. Total biomass yield of Caramba variety of cabbage. Different alphabets in the graph indicate the significance under HSD Tukey's test $p < 0.05$.

Cauliflower

As for the cauliflower varieties, the number of leaves and the SPAD values were significantly different among the fertilization treatments for both sampling periods. Graffiti and Flame star, both had the highest number of leaves for TMIN at both 32 DAT and 64 DAT, while the lowest number was recorded for T200 and T100, respectively. The SPAD value was the highest for TMIN and T50, for Graffiti and Flame Star respectively for both survey dates.

Radicchio

The commercial yield and the total biomass values were not statistically significant for all varieties of Radicchio. Also, the pH, TSS, and TA contents did not differ statistically among the fertilization treatments for all varieties of Radicchio. However, EC values were significantly different for fertilizer treatments in Verona and Chioggia varieties; both varieties had the highest value for T200, which are 3.84 mS cm^{-1} and 3.21 mS cm^{-1}, respectively (**Figure 2.4.**).

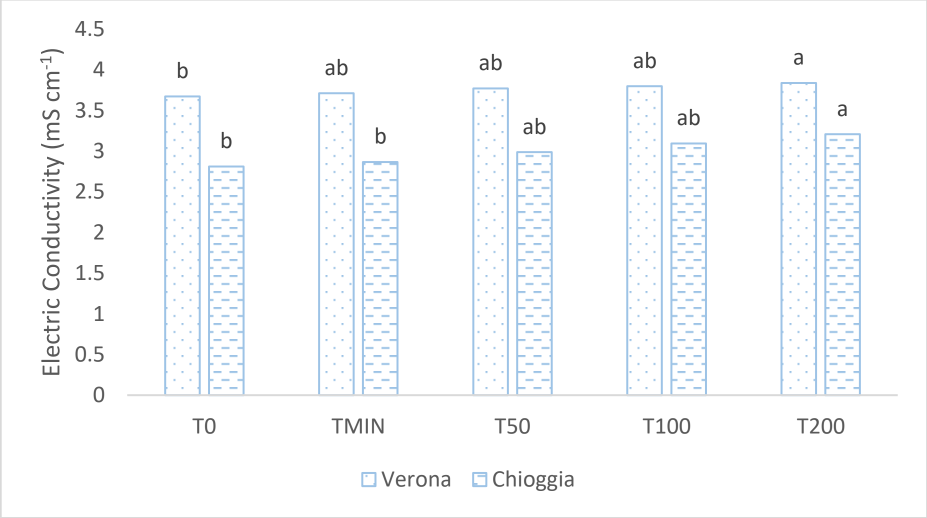

Figure 2.4. Electrical Conductivity values of Verona and Chioggia varieties of Radicchio for different fertilization treatments. Different alphabets in the graph indicate the significance under HSD Tukey's test $p < 0.05$.

The total antioxidant and phenolic values were also not significant for all varieties; however, differences were seen in the values among the varieties. The higher values were recorded for Verona and Chioggia, followed by Treviso, and the lowest was for Castelfranco.

Lettuce

Based on the readings taken in April, the highest chlorophyll content for the gentile variety of lettuce was obtained for T200 with 12267 µg cm^{-2}, which was not significantly different from other fertilization treatments except for TMIN, which had the lowest value of 6549 µg cm^{-2} (**Figure 2.5.)** Similarly, the flavonoid content was significantly higher for T0, T100, and T200, with the highest value for T0 (1113 µg cm^{-2}) (**Figure 2.6.**). The anthocyanin content was highest for T0 (0.4050) and the lowest for TMIN (0.3722) (**Figure 2.7.**). The values for chlorophyll, flavonoid, and anthocyanin were not statistically significant for gentile lettuce in May readings. The chlorophyll content in the lollo rosso lettuce was significantly different for the fertilization treatments based on April's readings but not for May. In April, the highest value was for T200 (15182 µg cm^{-2}), followed by T0 (14030 µg cm^{-2}), and the lowest value was for TMIN (6984 µg cm^{-2}) (**Figure 2.5.**). The flavonoid content was significantly different for April; the highest value was for T0 (935 µg cm^{-2}), followed by T200 and T100, while the lowest value was for TMIN (430 µg cm^{-2}) (**Figure 2.6.**). The anthocyanin content was significantly higher in T0 (771 µg cm^{-2}) and T200 (742 µg cm^{-2}), followed by T100, T50, and T0 with the significantly lowest value (324 µg cm^{-2}) for April (**Figure 2.**7), and the values were not significantly different for May. The SPAD, antioxidant, and phenol values were not significantly different for both readings taken during May for both lettuce varieties.

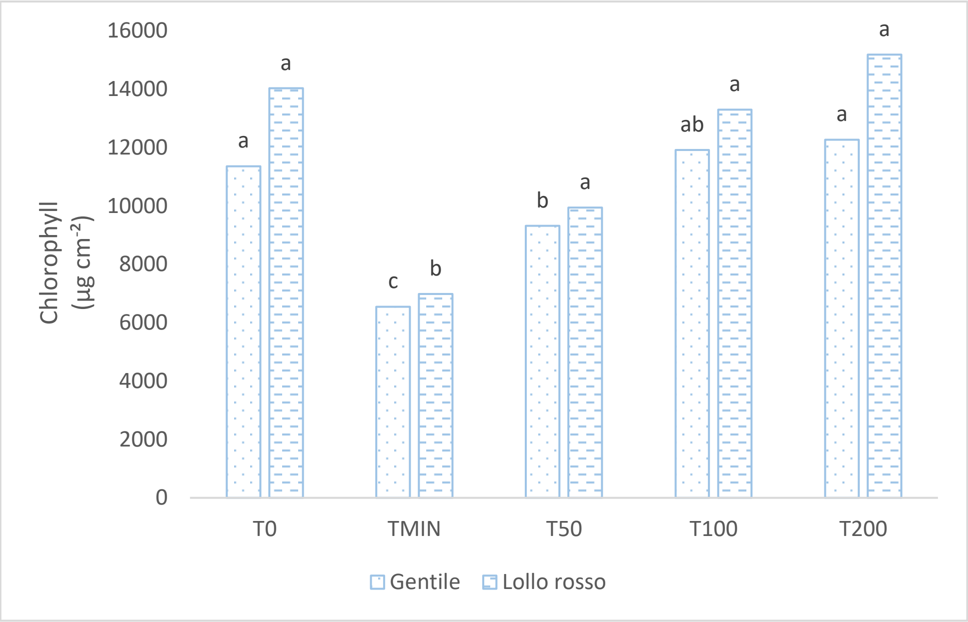

Figure 2.5. Chlorophyll content in Gentile and Lollo rosso variety of Lettuce in April reading for different fertilization treatments. Different alphabets in the graph indicate the significance under HSD Tukey's test $p < 0.05$.

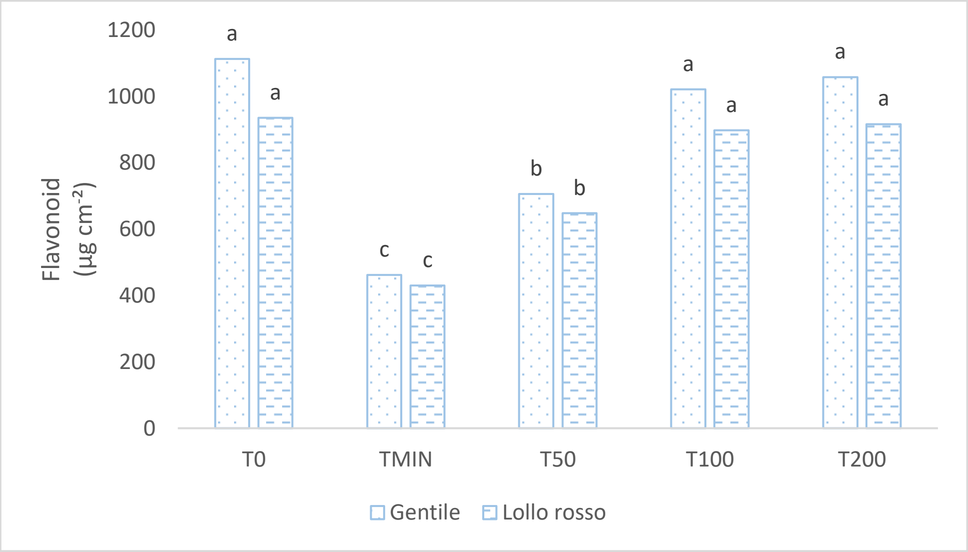

Figure 2.6. Flavonoid content in Gentile and Lollo rosso variety of Lettuce in April reading for different fertilization treatments. Different alphabets in the graph indicate the significance under HSD Tukey's test $p < 0.05$.

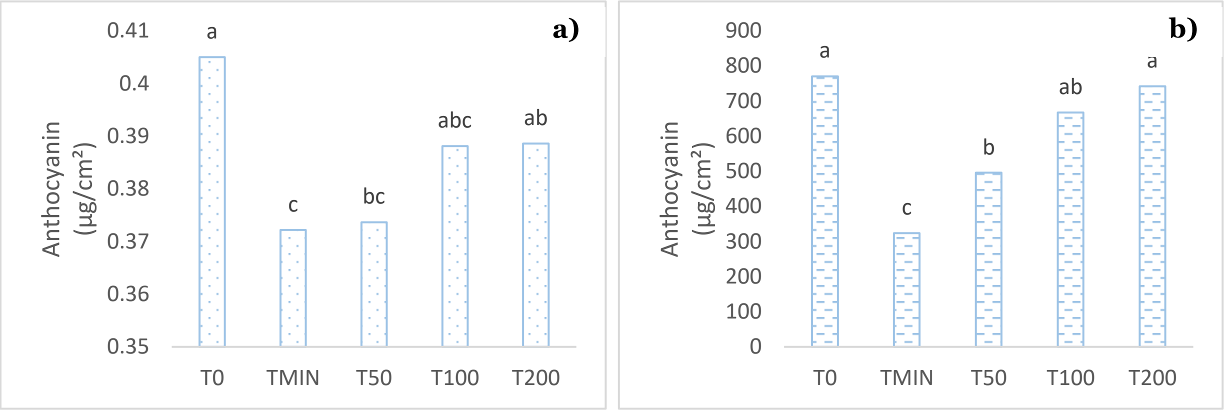

Figure 2.7. Anthocyanin content in **a)** Gentile and **b)** Lollo rosso variety of Lettuce in April reading for different fertilization treatments. Different alphabets in the graph indicate the significance under HSD Tukey's test $p < 0.05$.

The total biomass for both gentile and lollo rosso lettuce was not significantly different for the fertilization treatments, but the yield per plant was statistically significant for both lettuce varieties.

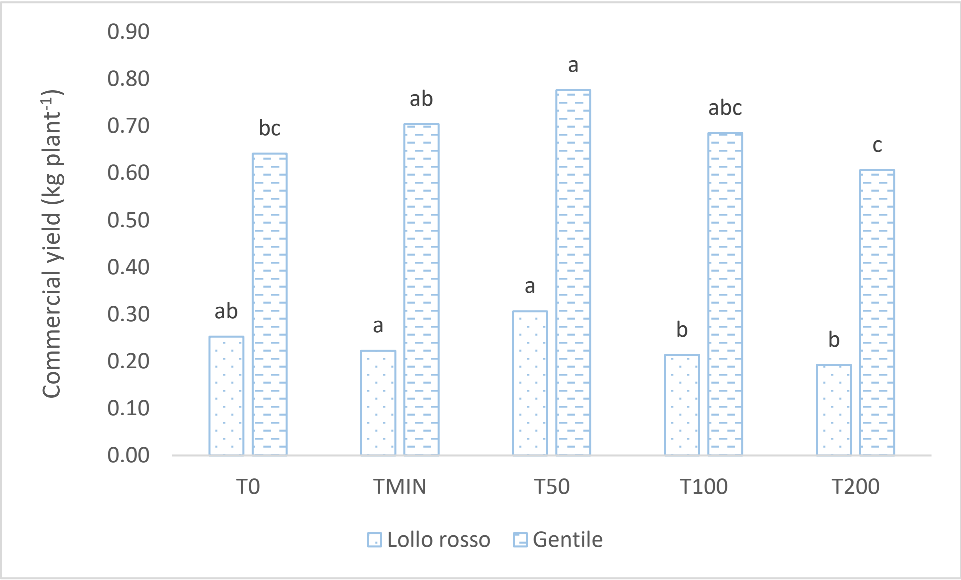

Figure 2.8. Commercial yield per plant of Gentile and Lollo rosso varieties of Lettuce for different fertilization treatments. Different alphabets in the graph indicate the significance under HSD Tukey's test $p < 0.05$.

For both varieties, the highest yield was for T50 and the lowest was for T200. However, a yield gap was seen between the two varieties. On average, the yield per plant of lollo rosso was 64.71% lesser than the gentile variety. For both varieties, the average values for the dry matter %, TSS, pH, EC, and TA were not statistically significant for the fertilization treatments.

Pumpkin

The SPAD values were not significantly different for Delica and Mini moscata pumpkin varieties. Additionally, the commercial yield and the total biomass values were not significantly different among the fertilization treatments for both pumpkin varieties. For the delica variety, the highest yield values were obtained for T200; on the contrary, mini moscata had the lowest yield values for T200.

The average fruit weight, diameter, and pulp thickness were found not significant to the treatments, but the values were higher for delica pumpkin than for the mini moscata for all parameters. Though the percentage of the dry matter was not significant for both pumpkin varieties, the values ranged from 14.25% - 20.38 % for delica and 10.45% - 13.60% for mini moscata. Different fertilization treatments influenced the soluble solid contents of only delica pumpkin, the highest value being 8.19 ^{o}Brix for TMIN (**Figure 2.9.**). EC values were significant for mini moscata pumpkins, the highest being 7.48 mS cm^{-1} for T200, followed by T100 and TMIN (**Figure 2.10**). pH, TA, antioxidant, and phenolic values were not significantly different for both delica and mini moscata pumpkins.

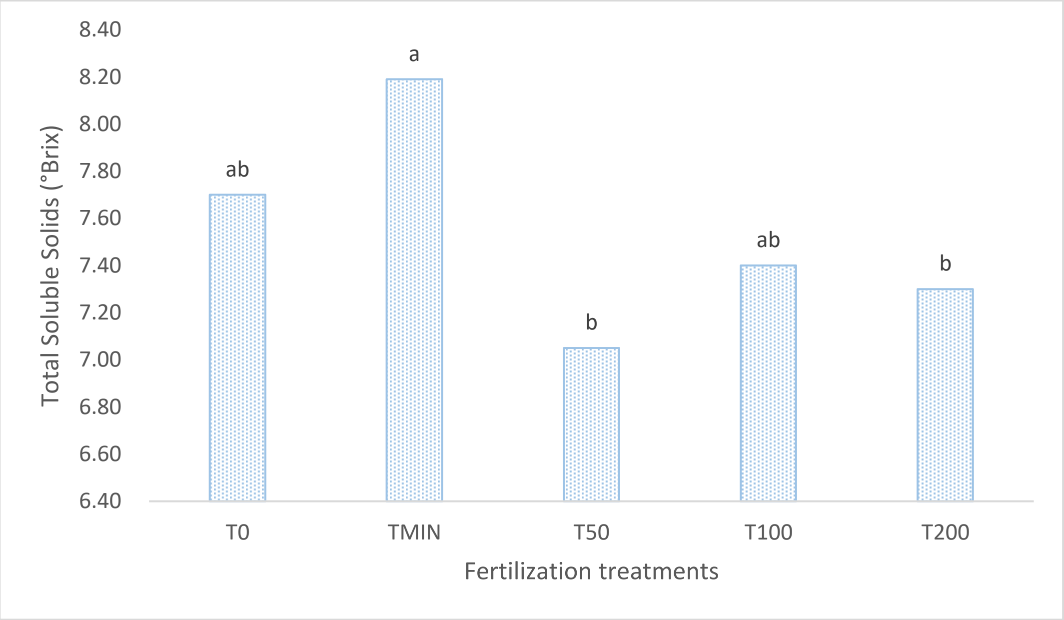

Figure 2.9. Total soluble solids (TSS) values of Delica Pumpkin for different fertilization treatments. Different alphabets in the graph indicate the significance under HSD Tukey's test $p < 0.05$.

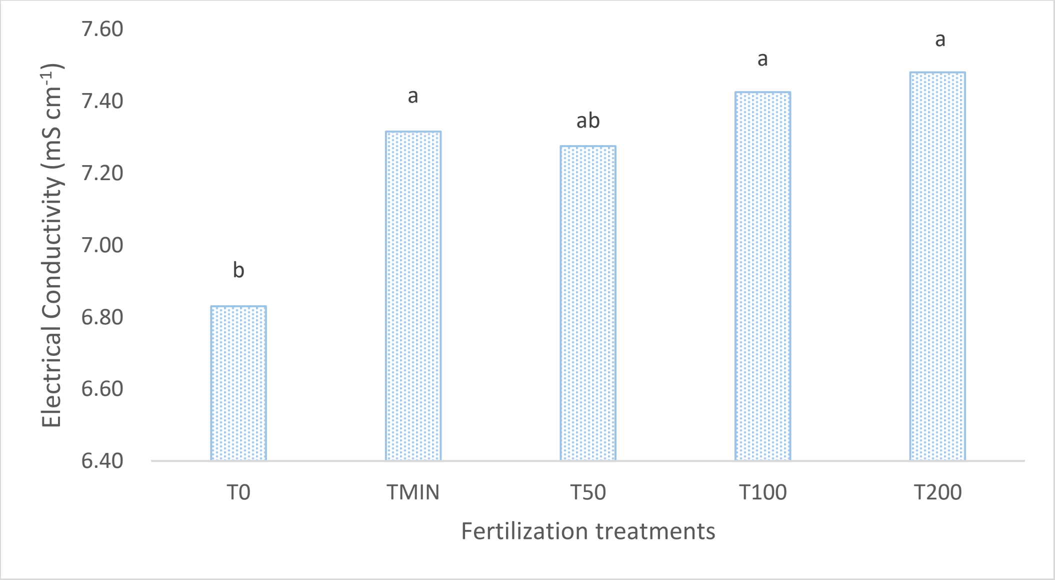

Figure 2.10. Electrical conductivity (EC) values of Mini moscata Pumpkin for different fertilization treatments. Different alphabets in the graph indicate the significance under HSD Tukey's test $p < 0.05$.

DISCUSSION

The commercial yield for most of the vegetable crops was observed highest in treatment TMIN, where all the total N requirement of the crop was supplied in mineral form, followed by T50, where half of the cop requirement was supplied in mineral form and the other half in organic form. The yield values were significant only for processing tomatoes, cabbage, and lettuce. For tomatoes, the yield value was the highest in T200, which was not significantly different than TMIN, T100, T0, but all of them were higher than T50. This result is contrary to the results obtained by Ghorbani et al. (2008), where the yields from the organically fertilized tomato plants were significantly lower than the yield obtained from mineral-fertilized plants. An increase in the microbial biomass due to compost application leading to the production of hormones and humates that act as plant growth regulators could also be the reason for the improvement in plant growth and increases in fruit yields (Arancon et al., 2003; Tu et al., 2006).

On the contrary, for cabbage and lettuce, the highest yields were obtained with treatment T50, and the yield decreased with increasing compost application. Dadomo et al. (1994) and Parisi et al. (2003) in their study mentioned that there should be a significant increase in yield between no N application and increasing N application. The reason behind lower yield values for these crops, even with the higher application of compost could be the unfavorable weather conditions for organic N mineralization.

The mineralization of N is also temperature dependent; with the decreasing temperature, the activities of microorganisms slow down. Hence, N uptake from organic sources decreases leading to lesser production from organic treatment and higher production in the treatments with mineral fertilization. So, spring-summer crops benefit from high temperatures that promote the mineralization of compost and crop residues from earlier crop cycles. The lowest yield result for TMIN in lollo rosso lettuce was contrary to many studies; however, it was similar to the results obtained by Saha et al. in 2017, who recorded their highest yield with the compost and lowest yield with the mineral fertilizer, which was not significantly different from the yield for non-fertilized treatments. Our result of no significant difference between T0 and other fertilized treatments contradicts Dadomo et al. (1994) and Parisi et al. (2003), who mentioned that there should be a significant increase between no N application and increasing N application. The reason behind this could be the good initial fertility of the soil, which masked the effect of different fertilization rates and methods, during the early stages of crop succession. The total yield for both the pumpkin varieties was below the standard average, because of heavy weed infestation, powdery mildew attack, and the extreme high temperatures throughout the crop cycle. The increased temperature might have affected the N uptake in quality and form, in addition to negatively impacting nutrient and water uptake and root growth (Chatterjee et al., 2020).

The total biomass values were not statistically significant for all vegetables except the caramba cabbage, where the highest biomass was obtained for TMIN followed by T50. For all vegetables, the biomass values improved with increased compost application in greater proportion than the commercial yield values which could also be attributed to the higher presence of N that stimulated the vegetative vigor of the crop (Heeb et al., 2006). The overall effects of inorganic N released might have surpassed the slow-release effect, resulting in abundance availability to the plants, higher biomass, and delayed maturity of fruits. Diallo et al. (2020) reported that the biomass production levels in the organic and mineral treatments were mostly similar irrespective of the proportion of applied nitrogen dosages. Despite showing improvements, the values of total biomass were still lower for treatments with only compost fertilization. This result was backed by another study conducted by Hammermeister et al. (2006) when they showed that due to the slow mineralization kinetics of organic fertilizer, the crop yield did not systematically increase with the amount of organic matter applied in their study.

The highest HI of tomato, 35% for T100, was much lower than the 65% reported by Ho (1984) and 61.4% reported by Moccia et al. (2006); however, it was complementary to the results of Agele et al. (2008), who mentioned that the lower HI of tomatoes was due to the unfavorable climatic conditions during the growing season and the onset of fruit formation as we faced with high temperature and low rainfall conditions during our study.

The SPAD values were within the range of 60 and 75 and followed a similar pattern to the number of leaves. Similarly, for the lettuce varieties, during the first Dualex reading in April, differences were seen among the treatments, which were reduced in the May reading. The results are based on the plant's pigment concentrations, which might have been influenced by the weather conditions during the cropping period, especially the rainfall. There were some days with rainfall before the first reading in April which may have diluted the pigments, and no rainfall during the second reading in May, making the differences not significant. Similarly, the SPAD values did not vary with treatments but showed a similar trend as the chlorophyll content.

There were some influences of fertilization treatments in the qualitative parameters; however, the effect of fertilization varied for different vegetables in succession. The average dry matter of the processing tomato was 5%, which was consistent with the findings of Moccia et al. in 2006. The TSS values obtained in this study were within the recommended range of commercial tomatoes of 4.7-6.0 °Brix by Barrett et al. in 2007; however, since the highest value was recorded for TMIN, our results were in contradiction with that of Barrett et al. (2007), Bilalis et al. (2018), and Sharpe et al. (2020). Higher TSS values for the processing tomatoes are preferred to decrease the costs during the processing to evaporate the water to reach the ideal amount of soluble solids (Chand et al., 2021). Similarly, the values for EC were higher for treatments of compost fertilization than the mineral and control, which may suggest that the flavor component of compost-treated tomatoes was better than the mineral fertilized tomatoes (Suhandy et al., 2014). However, the results differed from that of

Petropoulos et al. (2020), where the highest EC was for mineral fertilizer treatment. The major contributor to the acidic flavor of tomatoes is citric acid, which contributes to the taste and aroma of the fruits. However, the TA value of T50 was higher than other treatments though not significantly different. TSS and TA of tomatoes are used to determine the taste index and maturity, which are very critical parameters for industrial processing (Navez et al., 1999). The pH values are preferred between 4 to 5, as shown by our results, except for T50. The fertilization treatments did not significantly affect the quality parameters of chard, upholding the results of a study conducted by Kolota and Czerniak in 2010. The dry matter content in their study of 7.41% was similar to the value obtained in our study of 7.87%.

As for chicory, a study conducted by Khaghani et al., in 2012 reported that mineral fertilizer, particularly urea, improves quality parameters significantly than other combinations of fertilizers, contrary to our study, where the different fertilizer combinations did not significantly influence the quality of chicory. The study conducted by Haque et al. (2006) reported that different combinations of nitrogen and phosphorus fertilizers had a significant influence on the TSS and TA of the cabbage varieties but not on pH. In our study, the fertilizer treatments did not impact all quantitative parameters of the cabbage varieties. In their study, the highest values for TSS and TA were obtained for the maximum fertilizers applied, contrary to our study, where the highest values were obtained for the control treatments. Very few differences were found in the quality parameters among the four varieties of radicchio. Only for Verona and Chioggia varieties, the differences among the fertilizer treatments were significant, where the highest values were for the treatments with greater amounts of organic fertilizers applied. The anthocyanin content of both varieties of lettuce showed similar patterns for the different fertilization treatments, with the highest values for non-fertilized treatment. Among the fertilized treatments, it can be observed that compost treatments performed better than the mineral fertilizer treatment. The huge gap between the values of two varieties of lettuce is due to the color of the leaves. Since, Lollo rosso is a red-colored variety of lettuce, the anthocyanin content was higher than that of the green-colored Gentile variety.

While the yield was proportional to the nitrogen applied in the pumpkin varieties, the individual fruit size and diameter did not increase with the increase in N applied differing from the results of Walters (2020), where quadratic relationships were found for fruit size and diameter with the increasing N rates from 0 to 224 kg ha^{-1}. In our case, T0 had the highest diameter value for both varieties, the highest average fruit weight in mini moscata, and the second highest in delica. The pulp thickness was constant between the treatments in both varieties. The higher TSS value for TMIN in the delica variety could be due to the higher N availability and higher protein production with an increase in soluble solids. The mini moscata variety had a non-significantly different but lower value than delica, which could compromise the market value as the sweetness in the taste is its peculiarity. The pH of both varieties of pumpkins was not significantly different but was in line with the results reported by Xue et al. (2020). The significant EC values in mini moscata for compost and mineral fertilizers could be because of the presence of higher salt content, which is reflected in the parameter. In a study conducted by Oloyede et al. in 2012, fertilizer application rates significantly influenced the antioxidant and the phenolic activities in pumpkin fruits, and it was shown that there was a consistent decrease in values of those parameters as fertilizer rates were increased. In our study, fertilizers neither significantly affected the antioxidant and phenolic values, nor did the parameters follow a similar trend with varying fertilization rates.

CONCLUSIONS

The treatments significantly influenced the yield parameters only for processing tomato, cabbage, and lettuce varieties, which were the first crop in succession for each experimental year. The crops were grown in the spring season, where the mineralization of organic N must have been influenced by the weather parameters showing significant differences among the fertilization treatments. As for the processing tomato, being the first crop in succession, significantly higher yield even without any fertilization signifies the important presence of initial fertility of the soil which might have resulted in the non-significant differences in yield among the treatments for crops that came later in succession. For most other vegetables, T50 had the closest yield values to the TMIN, indicating a possibility of replacing half of the mineral fertilization requirement with compost. This could help the plant and soil dynamics to get acquainted with compost treatments while maintaining the yield and eventually, in the long run, we may be able to replace mineral fertilization completely. Only some of the quality parameters were significantly different among the treatments, and where there were significant, the higher values were mostly for the compost treatments. Electrical conductivity was the highest in T200 for Verona and Chioggia varieties of radicchio and mini moscata variety of pumpkin, chlorophyll, flavonoid and anthocyanin values of lettuce varieties were also the highest for T200, and total soluble solids of the delica pumpkin was the highest for TMIN.

It should be considered that the application of compost takes time to obtain detectable effects in the soil. In this three-year study, the observed effects nevertheless allowed us to verify an important production consistency among the mineral treatment and those applying compost. A study like this is particularly important from a practical point of view to understand the impact of compost and mineral fertilizers in farmer's fields, considering different rates of nutrients applied to a single crop, and a succession of crops in changing climatic conditions. Despite variations in results, compost application had noticeable positive impacts on vegetable crops for yield and quality parameters. A suggestion for farmers who intend to start using an organic fertilization plan could be to use an organic-mineral fertilization in the first two years and subsequently use only the compost as a fertilizer, thus maintaining yield while transitioning from mineral fertilization to organic fertilization.

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CHAPTER 3

EFFECT OF COMPOST AND MINERAL FERTILIZER RATES ON NITROGEN EFFICIENCIES AND NITROGEN BALANCE OF MID-TERM VEGETABLE SUCCES[2]

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[2] Shrestha, J., Sambo, P., Nicoletto, Franklin, D., & Cabrera, M. To be submitted to Agronomy Journal.

ABSTRACT

Fertilization is one of the most important soil and crop management practices, especially for a high-nutrient-demanding crop like vegetables due to their low nitrogen use efficiency (NUE) and variability in N storage and losses from soil. A field experiment was conducted to study the impacts of compost and mineral fertilizers on the NUE and N balance of vegetable crops in succession in an experimental farm at the University of Padova, Italy for three years. The 5 fertilization treatments, i. T0 (control), ii. TMIN (100% mineral N), iii. T50 (50% mineral N 50% compost N), iv. T100 (100% compost N), and T200 (200% compost N), were replicated 4 times in a randomized block design. The commercial yield, total biomass, and plant N uptake were evaluated to estimate agronomic efficiency (AE), physiological efficiency (PE), and apparent recovery efficiency (ARE) to finally calculate the utilization efficiency (EU) of each vegetable in succession. The efficiency parameters were significantly influenced by the treatments only for chard, chicory, and lettuce. On average, the AE was the highest for TMIN, as the mineral fertilizers resulted in the highest values of commercial yield for most vegetable crops, whereas PE was the highest for T50, as the additional application of compost fertilizer improved the total biomass yield of the vegetable crops. The ARE was the highest for TMIN, followed by T50 as mineral N was readily available for plants to uptake and utilize to produce marketable yield as well as total biomass yield. The overall EU, thereafter, was the highest for TMIN, especially, in the earlier years of the experiment. As the experiment progressed, the efficiencies of the treatments with compost fertilizers gradually increased to become comparable to that of the mineral fertilizer treatment. N removals across the crop succession were also estimated, only cabbage had a significant N removal for different fertilization treatments among all crops in succession. The highest cumulative N removal was found in TMIN, T50 and

T200 had moderate values, whereas T100 and T0 had the lowest values. Henceforth, the lowest and the highest N content in soil was for TMIN and T100 respectively. The soil's nitrogen and organic carbon distribution were significantly influenced by the soil's depth and the treatments applied when analyzed at the end of the third experimental year. The results showed a higher amount of nitrogen and organic carbon at the top 40 cm of compost-fertilized fields. On the top 20 cm of soil, the amount of nitrogen and organic carbon stored was significantly influenced by the fertilization treatments, and the highest value was obtained for T200 plots.

INTRODUCTION

The vegetable sector represents a large economic share in Europe despite having a relatively small land area coverage and production (EUROSTAT, 2019). Usually in the vegetable production sector, N fertilizer is applied more than the actual crop demand (Thomson et al., 2007). Vegetables represented 2.3% of the total fertilizer consumption (11Mt N) while only 1.2 % of the total cultivated area was under vegetable crops in 2014-2015 (Heffer et al., 2017). This is mostly because of the low nutrient efficiency of vegetables compared to other arable crops due to their short growing cycles and superficial rooting (Greenwood et al., 1989; Thompson et al., 2020). Nitrogen use efficiency (NUE) of plants refers to the ability of plants to uptake the nitrogen from the soil to produce dry matter/grain or a commercial product (Ciarelli et al., 1998). Hence, two main components of NUE are, N uptake efficiency which means the ability of crops to take up N from the soil (Burns, 2004; Greenwood et al., 1989), and the efficiency to use the absorbed N to grow and produce yield (Janssen, 1998; Schenk, 2004). The use efficiency of absorbed N is calculated by considering the marketable yield, total biomass yield, and the nitrogen content in total crop dry weight accumulated per kilogram of absorbed N excluding the roots (Benincasa et al., 2011). In vegetables, the actual marketable yield can be different from the potential yield (Van, 2007), so the marketable dry weight is often considered to calculate N efficiency parameters (Benincasa et al., 2011).

NUE is vaguely affected by external factors like climate, soil, biological interaction among soil microorganisms, soil, and plants (Gonzalez-Fontes et al., 2017), and agronomical management practices like fertilizer application and irrigation (Panhwar et al., 2019). There can be variations in both N uptake and use of absorbed N based on the crop species and cultivars as every individual genotype has its own morphological and functional characteristics (Schenk, 2004; Throup-Kristensen & Sorensen, 1999). Also, the same genotype can show different N use efficiencies when exposed to different environments, they affect either crop growth and development or the availability of N from the soil by affecting the mineralization of organic N or N losses (Agostini et al., 2010). Similarly, it also depends on the different levels of N availability and studies show that crop N use efficiency is higher when the fertilizer-N rate is relatively low (Burns, 2004). Nonetheless, due to the high demand for vegetable crops, N fertilizers are often considered a cheap indemnity against yield loss caused due to soil, climatic, and management factors (Thomson et al., 2007).

High N fertilizer application is frequently followed by excessive irrigation (Throup-Kristensen et al., 2012), increasing the environmental risk due to high nitrate concentrations in groundwater sources (Agostini et al., 2010; Cameira & Mota, 2017; Thompson et al., 2020) and health risk due to nitrate accumulation in the leafy vegetables (Colla et al., 2018). Hence, it is important to consider all the possible inputs and outputs of N, through a detailed N balance method to avoid any excess application of N fertilization throughout the crop growing season. The potential inputs are initial soil mineral N, N Mineralized from soil organic matter and added organic materials, N supplied from irrigation, atmospheric N deposition, and mineral N application. And the outputs are N taken up by the crop and N losses due to denitrification, volatilization, leaching, and immobilization (Tei el al., 2020). Various studies compared the mineral and organic fertilizer applications and showed that N-efficiency can be improved by shifting toward an organic farming system, as it slows down and checks the availability of mineralized organic N over a long period of time while improving organic soil carbon and microbiomes within the soil. Often these studies consider a uniform rate of fertilizer application and a single crop cycle that runs throughout the year or for multiple years (Nicoletto et al., 2014). In our study, we assessed the impact of compost and mineral fertilizers at different rates on the yield, biomass, and nitrate accumulation in the biomass of vegetable crops in succession to estimate the various nitrogen use efficiency parameters. We also evaluated the soil nitrogen content at the end of each experimental year, to understand the nitrogen balance, storage, and movement within the soil at different depths.

MATERIALS AND METHODS

The three-year experiment was conducted at the "L. Toniolo" Experimental Farm of the University of Padova, Legnaro (PD) from the year 2020 to 2022 in open field conditions. The soil was characterized as a Fluvi-Calcaric Cambisol (CMcf) with clay-texture (IUSS Working Group WRB, 2014), with field capacity of 34% (v v^{-1}), wilting point of 13.5% (v v^{-1}), and bulk density of 1.45 Mg m^{-3}. The chemical characteristics of the soil at different depths on dry matter basis are represented in **Table 3.1**.

Table 3.1. Chemical properties of the soil of the experimental field at 0-0.20 m depth and 0.20-0.40 m depth

Soil Depth	**pH**	**EC (µS cm^{-1})**	**NH_3^--N (mg kg^{-1})**	**NH_4^+-N (mg kg^{-1})**	**K (mg kg^{-1})**	**P (mg kg^{-1})**
0–0.20 m	7.35	250	101	49	94	100
0.20–0.40 m	7.3	250	87	24	61	213

The 5 fertilization treatments were, i. T0 (control), ii. TMIN (100% mineral N), iii. T50 (50% mineral N 50% compost N), iv. T100 (100% compost N), and T200 (200% compost N). The treatments were arranged in a randomized block design and were replicated 4 times, making a total of 20 plots. Each experimental plot was of dimension 96 m^2. The vegetables were planted in succession for three years, their varieties, and growth periods are presented in **Table 3.2**. The crops were timely irrigated based on their irrigation requirements.

Table 3.2. List of crops in succession and their transplantation and harvest dates

Year	Crops	Plant density (plants m^{-2})	Transplantation date	Harvest date
2020	Processing tomato (Solanum lycopersicum HEINZ 1281 F1)	4	6th May	5-6th / 17-18th August
	Chard (Beta vulgaris Apulian type) and Catalogna chicory (Cichorium intybus L., Catalogna Group variety Katrina)	9.2	28th August	10th November
2021	Cabbage (Caramba and Alfaro) and Cauliflower	4	2nd April	18th June
	Radicchio (Castelfranco, Chioggia, Verona, Treviso)	7.4	12th August	10-25th January (2022)
2022	Lettuce (Gentile and Lollo rosso)	9.2	7th April	25th May
	Pumpkin (Delica and Mini moscata)	1	24th June	3-4th October

The compost was produced and supplied at the beginning of each experimental year by the S.E.S.A Societa Estense Servizi Ambientali (SESA) S.P.A company based at Via Comuna, 1, 35042 Este PD. The properties of compost applied for each experimental year are shown in **Table 3.3.**

Table 3.3. Chemical properties of the compost on a dry weight basis

	N	P	K	% dry matter
	% dw			
Year 1	1.65	0.53	1.98	50
Year 2	1.99	0.64	2.65	58
Year 3	1.65	0.53	1.98	54

At the beginning of each crop year, the recommended amount of N_2, P_2O_5, and K_2O was calculated to determine the amount of compost and mineral fertilizer inputs depending on the treatments applied (**Table 3.4.**). Both compost and mineral fertilizers were applied 1-2 days before the transplantation of the saplings and incorporated in the soil by the rotavator.

Table 3.4. Application rates of the compost (fresh weight), and N, P, and K fertilizers for fertilization treatments applied to vegetable crops in succession. Application rate for compost (Mg ha^{-1}) was calculated by dividing the N application rate by compost % dry weight and % N of compost dry weight time 10, for each year (Table 2.3.). For compost treatments, mineral P and K fertilization were only applied in case the applied compost could not satisfy the total P_2O_5 and K_2O requirements.

	T0	TMIN	T50	T100	T200
Year 1 (Processing tomato) requirement					
Compost (Mg ha^{-1}) (Fresh weight)	-	-	10.75	21.25	42.5
N (kg ha^{-1})	-	170	85	-	-
P_2O_5 (kg ha^{-1})	-	130	64.4	-	-
K_2O (kg ha^{-1})	-	260	132	7.1	-
Year 2 (Cabbage and Cauliflower) requirements					

Compost (Mg ha^{-1}) (Fresh weight)	-	-	4.33	8.66	17.32
N (kg ha^{-1})	-	100	50	-	-
P_2O_5 (kg ha^{-1})	-	70	-	-	-
K_2O (kg ha^{-1})	-	160	-	-	-
Year 2 (Radicchio) requirements					
Compost (Mg ha^{-1}) (Fresh weight)	-	-	3.03	6.06	12.12
N (kg ha^{-1})	-	70	35	-	-
P_2O_5 (kg ha^{-1})	-	60	-	-	-
K_2O (kg ha^{-1})	-	110	-	-	-
Year 3 (Lettuce and Pumpkin) requirements					
Compost (Mg ha^{-1}) (Fresh weight)	-	-	9.6	19.2	38.5
N (kg ha^{-1})	-	170	85	-	-
P_2O_5 (kg ha^{-1})	-	140	88	12.4	-
K_2O (kg ha^{-1})	-	375	243	110	-

Harvest and measurements

After the crops reached their commercial maturity, harvesting was done to determine the commercial yield and total biomass of each vegetable crop for all treatments within the 10 m^2 area of the central row of each plot. The dry matter % of each vegetable biomass was determined by dehydrating the samples at 65°C for 48 hours. 700 mg of dehydrated sample was used to determine the nitrogen content in the dry matter following the Kjeldahl method. Thus, obtained values were used to determine the nitrogen use efficiency parameters for the vegetable crops.

Nitrogen Use Efficiencies

Agronomic efficiency (AE): AE is defined as the commercial product achieved per unit nutrient applied.

$$AE\ (kg\ kg^{-1}\ N) = \frac{Gf - Gu}{Na}$$

Where, Gf = Commercial yield of a fertilized plot

Gu = Commercial yield of an unfertilized plot

Na = Amount of nutrient applied

Physiological efficiency (PE): PE is defined as the total biomass yield obtained per unit of fertilizer contributed.

$$PE\ (kg\ kg^{-1}\ N) = \frac{Byf - Byu}{Nf - Nu}$$

Where, Byf = Biomass yield of a fertilized plot

Byu = Biomass yield of an unfertilized plot

Nf = Nutrient taken up in biomass of fertilized plot

Nu = Nutrient taken up in biomass of unfertilized plot

Apparent recovery efficiency (ARE): ARE is defined as the amount of nutrient absorbed per unit of nutrient contributed.

$$ARE\ (\%) = \frac{Nf - Nu}{Na} * 100$$

Utilization efficiency (EU): EU is the product of PE and ARE.

$$EU\ (kg\ kg^{-1}\ N) = PE * ARE$$

Soil analysis

Soil sampling was done 4 times to understand the nutrient dynamics established in the soil due to different fertilization treatments, particularly in the root zone throughout the experiment period. The first sampling was done before the beginning of the experiment and after that one sampling at the end of each experimental year. All the samplings except the last were carried out at two depths. The first depth was 0-20 cm, the layer most affected by root development of the vegetable crops and the second depth was 20-40 cm, to assess nutrient losses if there were any. For the final sampling, a total sample depth of 100 cm with a 20 cm interval (0-20 cm, 20-40 cm, 40-60 cm, 60-80 cm, and 80-100 cm) was taken to do a more immersive study of nutrient movement in the soil. The surface crop residues were removed beforehand and then the sampling cores were drilled using a special drill to the desired depth. The collected samples were air-dried and sieved with a 2 mm mesh, to obtain 100 g of samples ready for laboratory analysis, the results of which were used to determine the N balance parameters.

Nitrogen balance

N removals across vegetable succession in the different fertilizer treatment was calculated by measuring the N taken up in the commercial yield of each vegetable for all treatments. Thus, obtained values were added after each succession to the previous values for all vegetables and fertilization treatments to get cumulative removal of N from the soil. Also, to compare the cumulative amount of N applied to the soil based on crop requirements for every crop cycle across all fertilization treatments, the total N applied for each crop in succession was added over the three years of the experiment. Finally, the soil N content was determined to understand the N storage and movement pattern within the different depths of soil.

Statistical analysis

The data from the field surveys and laboratory analysis were statistically analyzed with Statgraphics 19 Centurio software by means of ANOVA. In the case of significant F-values, the means were compared with Tukey's HSD test at the significance level of $p < 0.05$. For the N balance parameters, the values for different varieties of each crop were averaged instead of calculating separately to show the values for crop succession on a yearly basis.

RESULTS AND DISCUSSION

Commercial and biomass yields

The commercial yield per plant of the processing tomato, cabbage, and lettuce was significantly influenced by the fertilizer treatments, but the yield of other vegetables was not significantly different among the fertilizer treatments (**Table 3.5.**). The yield of processing tomato was significantly higher in T200, T100, T0, and TMIN than in T50.

The non-significant difference in yield among the mineral, compost, and non-fertilized treatments was contrary to the results obtained by Ghorbani et al. (2008), where the yield obtained with mineral fertilizer was significantly higher than the organically fertilized and non-fertilized treatments. Similarly, Dadomo et al. (1994) and Parisi et al. (2003) also mentioned in their report that there should be a significant increase in yield between no N application and increasing N application.

The reason behind the indifferent yield result from T0 could be the good initial fertility of the soil, which masked the effect of different fertilization rates and methods, during the early stages of crop succession. For caramba cabbage, TMIN and 50 had significantly higher yields than T100, T200, and T0, and for Alfaro cabbage, T50, and TMIN had the highest yield but were not significantly different from T100 and T200, which in turn was not different than T0. Lettuce had the greatest yield for the T50 but both varieties were only significantly different from T200. As for the other vegetables, though the values were not significant, the commercial yield was higher in treatment TMIN and T50, where the crop's total or partial N requirement was supplied in the readily available mineral form.

Table 3.5. Commercial yield of vegetable crops in succession for different fertilization treatments. Different alphabets in the graph indicate the significance under HSD Tukey's test $p < 0.05$

	Commercial yield (kg plant^{-1})				
Vegetables	T0	TMIN	T50	T100	T200
Processing Tomato	1.46^{a}	1.41^{a}	1.17^{b}	1.47^{a}	1.52^{a}
Chard	0.45	0.62	0.54	0.48	0.61
Chicory	0.46	0.59	0.48	0.47	0.46
Cabbage (Caramba)	1.12^{b}	1.62^{a}	1.48^{a}	1.20^{b}	1.18^{b}
Cabbage (Alfaro)	1.08^{b}	1.37^{a}	1.41^{a}	1.27^{ab}	1.31^{ab}
Radicchio (Castelfranco)	0.36	0.41	0.39	0.32	0.39
Radicchio (Chioggia)	0.47	0.51	0.42	0.45	0.39
Radicchio (Verona)	0.15	0.14	0.17	0.13	0.13
Radicchio (Treviso)	0.45	0.44	0.42	0.39	0.39
Lettuce (Gentile)	0.64^{bc}	0.70^{ab}	0.78^{a}	0.68^{abc}	0.61^{c}
Lettuce (Red lollo)	0.25^{ab}	0.22^{b}	0.31^{a}	0.21^{b}	0.18^{b}
Pumpkin (Delica)	1.63	1.57	1.34	1.56	1.83
Pumpkin (Mini Moscata)	1.41	1.32	1.17	1.23	0.94

Total biomass yield was statistically significant for fertilization treatments only for the caramba cabbage, where the highest biomass was obtained for TMIN which was only statistically different from T0 (**Table 3.6.**). For most of the other vegetables, the highest biomass yield was also in TMIN, but the overall values were impressive for the compost treatments too. For example, for processing tomato, chard, and delica pumpkin, the highest biomass yield was recorded for T200. The reason behind the higher biomass yield for T200 could be the increased amount of nitrate availability in the soil due to the application of a double dose of organic N, which stimulated the vegetative vigor of the crop. The mineralization of applied organic N is also temperature dependent. During summer, microbial activities are increased due to high temperatures, improving N mineralization. Because of this, we can see that the organic yield of the summer vegetables is comparatively better than that of the winter vegetables. The lowest value was obtained for T0, which was not significantly different from TMIN, unlike other vegetables. The study conducted by Saha et al. in 2017 justifies this result, where the authors reported that the compost yield was the highest and the mineral fertilizer yield was the lowest, which was not significantly different from the non-fertilized yield. Due to the unfavorable climatic conditions for the cauliflower, no commercial yield was obtained for both varieties.

Table 3.6. Total biomass yield of vegetable crops in succession for different fertilization treatments. Different alphabets in the graph indicate the significance under HSD Tukey's test $p < 0.05$

	Total biomass yield (t ha^{-1})				
Vegetables	T0	TMIN	T50	T100	T200
Processing Tomato	173.54	190.7	180.9	168.92	223.28
Chard	53.82	72.06	71.24	61.15	77.19
Chicory	45.26	58.95	48.06	46.97	46.93
Cabbage (Caramba)	69.12^{b}	94.95^{a}	88.79^{ab}	74.35^{ab}	73.61^{ab}
Cabbage (Alfaro)	75.04	89.52	94.45	88.56	80.81
Radicchio (Castelfranco)	52.36	60.06	58.14	46.68	56.74
Radicchio (Chioggia)	51.57	56.22	47	50.37	44.57
Radicchio (Verona)	15.1	15.33	16.37	12.76	12.15
Radicchio (Treviso)	54.35	58.89	55.04	50.98	51.63
Lettuce (Gentile)	58.88	64.63	71.25	62.84	55.63
Lettuce (Red lollo)	23.19	20.41	28.12	19.59	17.65

Pumpkin (Delica)	16.3	14.43	13.41	15.68	18.4
Pumpkin (Mini Moscata)	14.14	12.1	11.79	12.32	9.41

Plant N uptake

The concentration of N on a dry weight basis was calculated to determine the N taken up by the total biomass of each vegetable crop, to further estimate the nitrogen use efficiencies. The values were not statistically significant for any of the vegetable crops in succession, however, the values obtained can we utilized to understand the pattern of N utilization in the biomass of the vegetables based on treatments applied (**Figure 3.1.**). For the processing tomato, the highest uptake of N in leaf biomass and in fruits for dry weight basis was significant to the fertilization treatments. The highest values were seen in T50 (2.4% leaf and 3.32% fruit) followed by TMIN (2.2% leaf and 3.31% fruit). The highest value of N taken up by total biomass was for T200 (448 kg ha^{-1}) followed by TMIN (419 kg ha^{-1}), and T50 (408 kg ha^{-1}). For chard, the highest % N in the biomass was obtained for T50 (3.90%) the highest N uptake values by the total plant biomass was by TMIN followed by T50, whereas, for Chicory, the highest values for both parameters were obtained for T50 (2.71% and 128 kg ha^{-1}).

The % N content for both varieties of cabbages, Alfaro and Caramba, was around 2 %. N absorbed by the total biomass was maximum for TMIN (132.44 kg ha^{-1} for caramba and 206.86 kg ha^{-1} for Alfaro) and minimum for T0 (102.72 kg ha^{-1} for caramba and 150 kg ha^{-1} for Alfaro). The Treviso variety of radicchio had a higher % N value ranging from 8.6-9.6% compared to 4.2-4.4% for Verona and 2.7-2.9% for Chioggia and Castelfranco. The values varied impressively among the varieties for the N in total biomass as well i.e., for TMIN the values were 250 kg ha^{-1}, 200 kg ha^{-1}, 150 kg ha^{-1}, and 50 kg ha^{-1} for Castelfranco, Chioggia, Treviso, and Verona respectively. The % N was the highest in TMIN for both lettuce varieties, 3.48% in gentile and 3.24% in lollo rosso. However, the total N content in the biomass was the highest for T50 for both varieties, 86.54 kg ha^{-1} for gentile and 58.22% for lollo rosso. The % N values for Mini moscata (2.6%) were higher in all cases than the Delica varieties (2.1%). The total N content in the pumpkin biomass was the highest for T0 compared to all other treatments, 62.41 kg ha^{-1} in delica and 43.46 kg ha^{-1} in mini moscata. For almost all vegetables in this succession, the values of % N in dry matter and total N uptake by the biomass were the highest for TMIN and T50. Nevertheless, the values for compost and no fertilization increased in the final year of the experiment. The variation in results could be subjected to the N mineralization potential of soils and the high N release of incorporated vegetable crop residues, complicating the N supply and N demand synchronization (Tei et al., 2020).

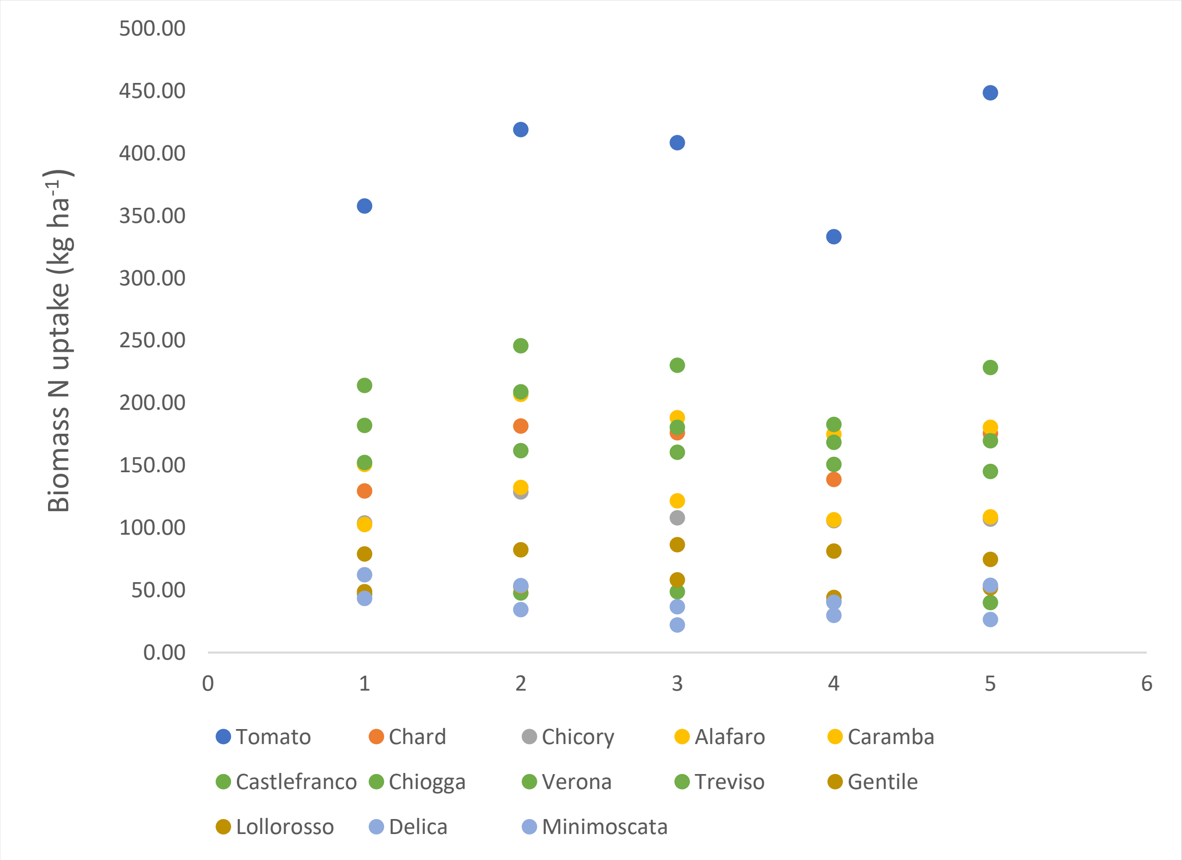


Figure 3.1. N uptake by the total biomass of each vegetable crop in succession

Nitrogen use efficiency

Different parameters were evaluated to analyze the nitrogen use efficiency of the vegetable crops in succession, i.e., AE, PE, ARE, and EU. The different treatments had statistically significant effects on AE and ARE for Chard. AE was significantly higher for TMIN (90.51 kg kg^{-1} N) and T200 (86 kg kg^{-1} N) than for T50 (46.81 kg kg^{-1} N) and T100 (16.64 kg kg^{-1} N) **(Figure 3.2.a.)**. ARE was significantly higher for TMIN (30.64 %), T200 (27.45 %), and T50 (27.20 %) than for T100 (5.49%) **(Figure 3.2.b.)**.

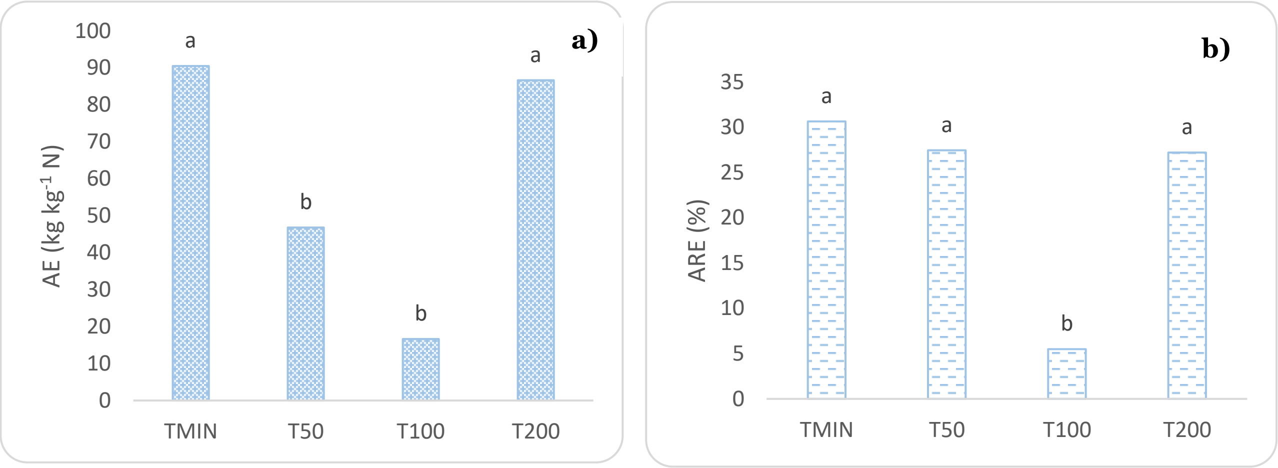
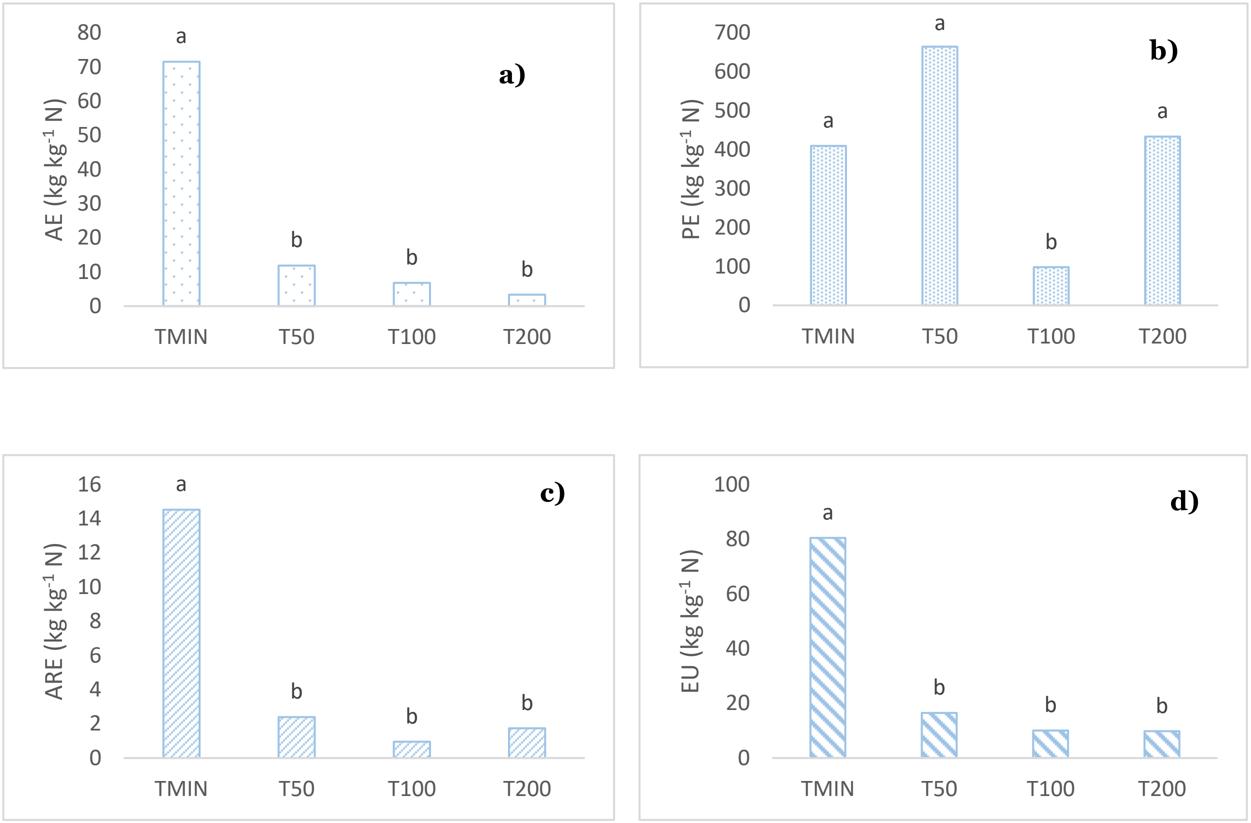


Figure 3.2. a) Agronomic efficiency (AE) and **b)** Apparent recovery efficiency (ARE) of chard for various fertilizer treatments. The different alphabets in the figure represent the significance at $p < 0.05$ for Tukey's HSD Test

As for Chicory, all parameters were significantly influenced by the treatments applied. AE was significantly higher for TMIN than all other treatments with a value of 71 kg kg^{-1} N supplied (**Figure 3.3.a**). The PE values for TMIN (409.41 kg kg^{-1} N), T50 (664.73 kg kg^{-1} N), and T200 (433.64 kg kg^{-1} N) were not different from one another but were significantly higher than T100 (97.95 kg kg^{-1} N) (**Figure 3.3.b.**). ARE (**Figure3.3.c.**) and EU (**Figure 3.3.d.**) values were also significantly higher for TMIN than other treatments with a value of 14% and 80.50 kg kg^{-1} N respectively.



Figures 3.3. a) Agronomic efficiency (AE), **b)** Physiological efficiency (PE), **c)** Apparent recovery efficiency (ARE), and **d)** Utilization efficiency (EU) of chicory for various fertilizer treatments. The different alphabets in the figure represent the significance at $p<0.05$ for Tukey's HSD Test

For the lollo rosso variety of lettuce, significant differences among the treatments were only found for PE, where the highest value was obtained for T50 (603.19 kg kg^{-1} N), which was statistically different from TMIN (106.21 kg kg^{-1} N), but not from T100 and T200 (**Figure 3.4.**). As for the delica variety of pumpkin, T200 (3.99 %) had significantly higher ARE than all other treatments (**Figure 3.5.**).

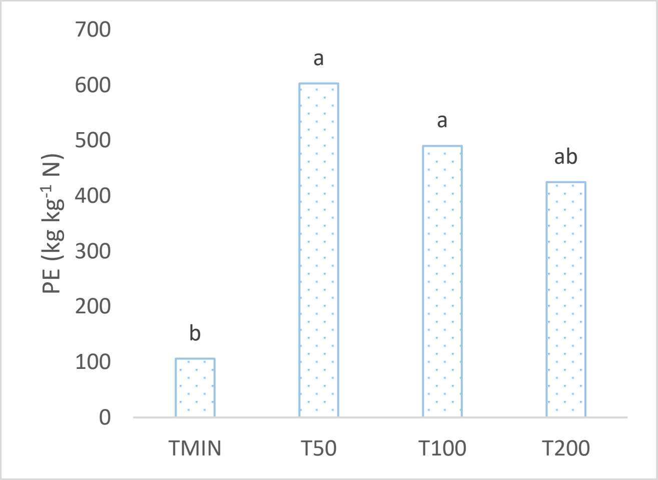


Figure 3.4. Physiological efficiency of lollo rosso lettuce for various fertilizer treatments. The different alphabets in the figure represent the significance at $p<0.05$ for Tukey's HSD Test

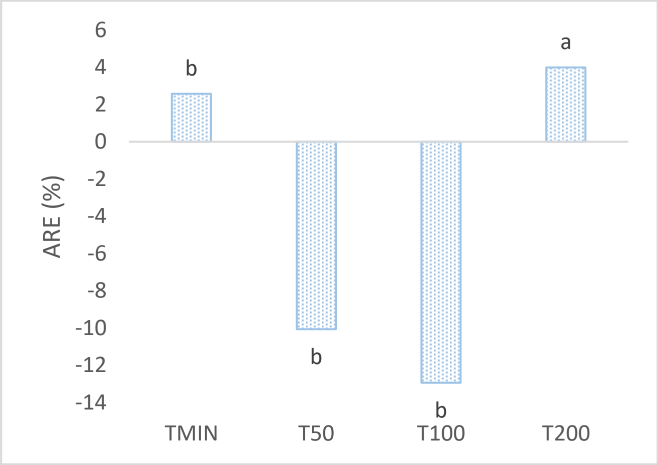


Figure 3.5. Apparent recovery efficiency of delica pumpkin for various fertilizer treatments. The different alphabets in the figure represent the significance at $p<0.05$ for Tukey's HSD Test

From the results, we can see that the AE of Chard and Chicory was the highest for TMIN, though for Chicory the values were not statistically different for TMIN from T200, corresponding to the commercial yield of both vegetables. In both cases, a significantly lower value was obtained for T100. The results are in contradiction to the study conducted by (Tosti, 2008; Tosti et al., 2008; Farneselli et al., 2009), where the nitrogen use efficiency of the organic fertilizer was constant and very high regardless of the N supply, whereas, in the case of mineral N supply, the efficiency decreased considerably with an increasing N application rate. However, the results were not supported by many authors afterward considering the comparison between the green manure N and mineral fertilizer N is not immediately understandable and hence, can lead to misinterpretation (Benicasa et al., 2011).

When PE was compared, significant differences were obtained only for Chicory and Lollo rosso variety of lettuce. For both of them, the highest value was obtained for T50 followed by T200, indicating that addition of compost improves the uptake of N in the total biomass of the vegetables. The ARE of Chard, Chicory and Delica pumpkin were higher for TMIN followed by T200, indicating that from the applied fertilizers, the highest amount of N was able to be recovered when either mineral fertilizer was applied or when higher amount of compost was applied. We can also observe from the significant result of Chicory for EU, that it follows the pattern of AE and ARE. As for the other vegetable crops in succession, statistically significant differences among the treatments were not noticed, meaning that the nitrogen use efficiencies of those vegetables were not influenced by the type and rate of fertilization applied. Nevertheless, the values were inconsistent with previous studies making it difficult to derive concrete conclusions. There is variability in the results obtained in the comparative studies related to N use efficiency and N losses between the organic and mineral fertilization systems, mainly due to the diversities in management practices within both organic and mineral farming systems and lack of consistency in the interpretation of results (Tei et al., 2020).

The study conducted by Tei et al., 1999 reported that increasing the N rate in vegetables increased the N accumulation in the shoots but decreased the apparent recovery of N fertilizer. This concept was supported by another study conducted by Tei et al., in 2002b, where the author reported that the N fertilization rate has little or no effect on the total biomass production and N-accumulation, however, very high N rates can increase the non-commercial biomass yield in crops like tomatoes, (Tei et al., 2002a), because of which AE decreases. The authors also suggested that the efficiencies value can vary among the two cultivars of the same vegetables, justifying the results of our study where two varieties of lettuce, pumpkin, and cabbage, and four varieties of radicchio showed distinguished values for different efficiency parameters.

A study conducted by Thorup-Kristensen et al. (2012) suggested that plant nutrition and N use efficiency, both could be improved in vegetable cropping systems when non-legume/legume cover crops are combined with crop rotation based on varying cropping depth and N demand as a replacement of N fertilization. In addition to this, the less explored techniques like intercropping, reduced tillage, and controlled traffic farming could be further explored to potentially increase N use efficiencies (Tei et al., 2020). Hence, rather than considering just whether the management practices are organic or mineral, we can suggest that the change in fertilizer input, plant cover, and rotation designs are more important factors in securing high yields and low nitrate leaching (Thorup-Kristensen, 2006). Since nitrogen use efficiencies of vegetable crops are affected by various factors, all aspects should be carefully taken into consideration and the scientists should be able to share the data with the farmers so that they could obtain complete information and compare their results (Benincasa et al., 2011).

Nitrogen Balance

Cumulative N supplied over three years of experiments to individual crops as a function of treatments

Depending upon the crop requirement, nitrogen was added to the soil either as a mineral or a compost fertilizer at different rates. The graph below (**Figure 3.6.**) represents the cumulative amount of nitrogen supplied to each experimental plot as the vegetable succession proceeds from the first to the third year.

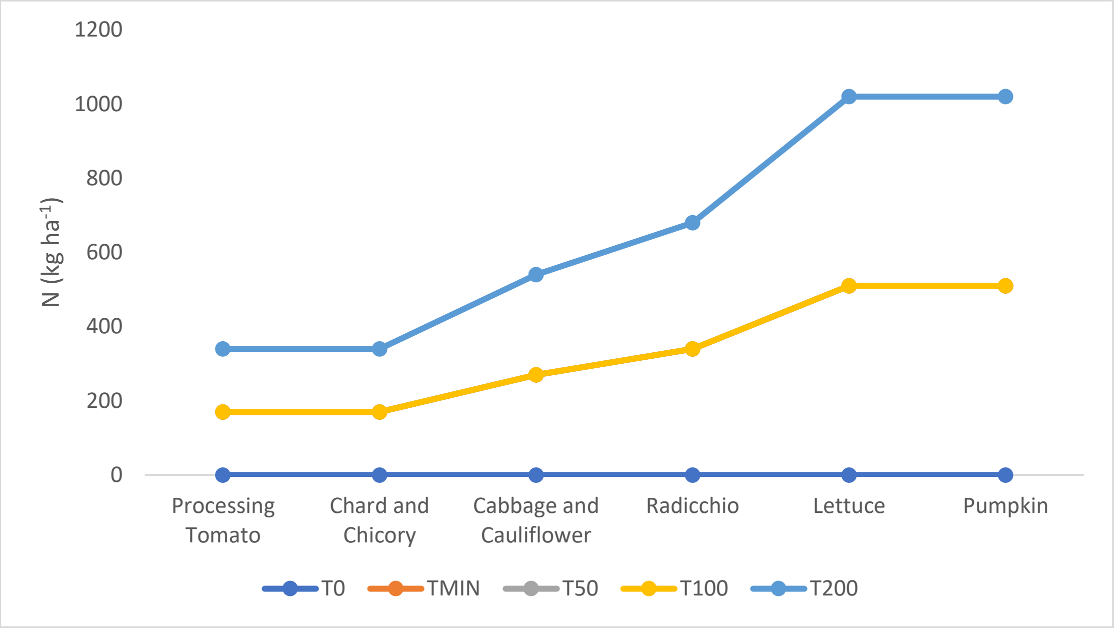


Figure 3.6. Cumulative N supplied for the different vegetable crops over three-year succession for various fertilization treatments. For TMIN, T50, and T100, the amount of N applied was the same, hence represented by an overlapped yellow line in the graph.

N removals across crop succession in the different fertilizer treatment

Varying amounts of nitrogen were removed by the vegetables, based on their individual needs and treatments applied. The statistically significant nitrogen removal among the treatments was observed only for the Cabbage (**Figure 3.7.**). However, the highest removal of nitrogen among the individual crops was seen in Chicory with about 120 kg N ha^{-1} and the lowest was in Pumpkin with about 50 kg N ha^{-1}, which resonates with the lowest biomass per hectare production for Pumpkin as shown in **Table 3.4.**

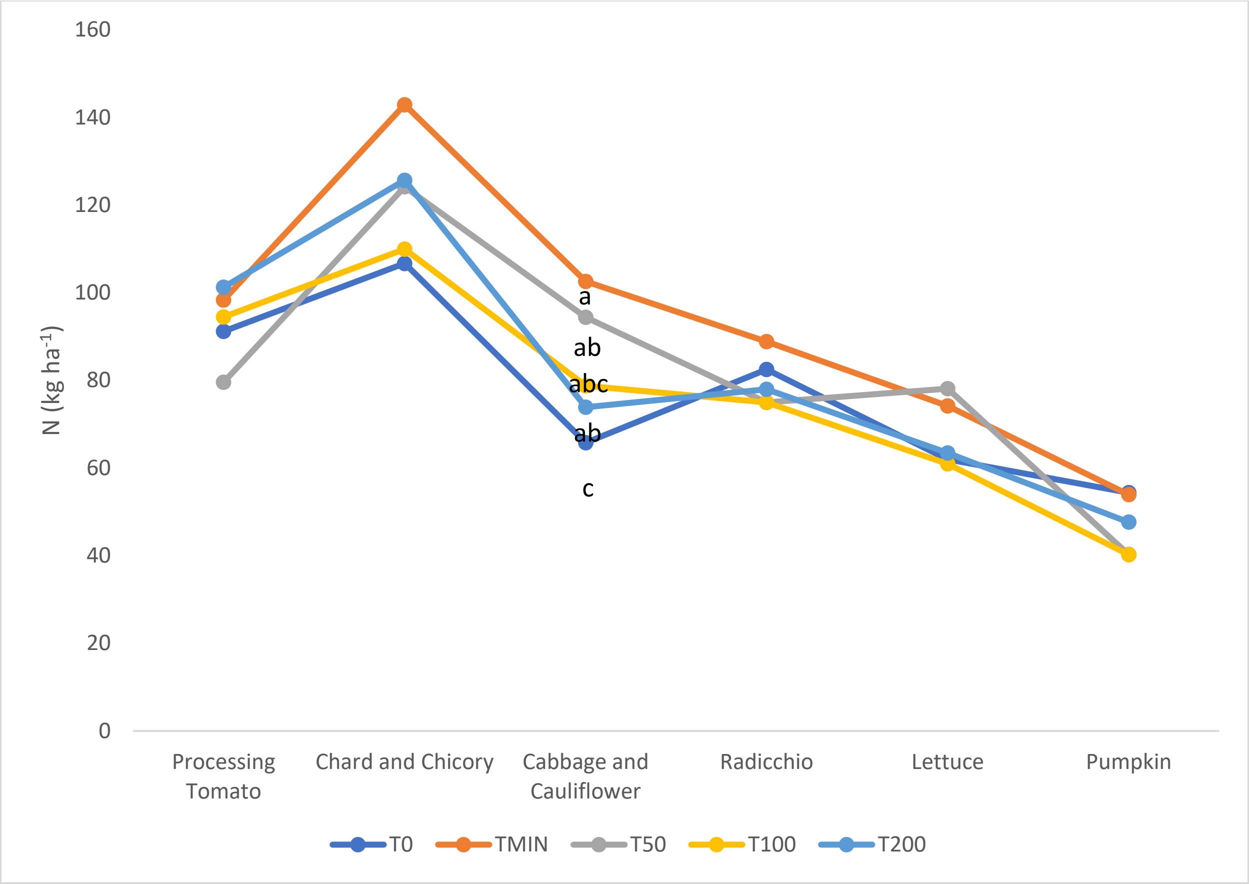


Figure 3.7. N removal from the soil for various treatments in each vegetable crop succession for various fertilization treatments. The alphabets in the figure represent statistical significance for $p < 0.05$ when compared with Tukey's HSD test

N removal for lettuce was more than the pumpkin for all treatments although the yield and biomass for lettuce is far lower than that of pumpkin. The reason behind this could be the trend of storing a high amount of absorbed N in the leaves as nitrate by lettuce, which is not involved in growth processes (Maynard et al., 1976). For each individual crop, the higher removal from TMIN is understandably due to immediate nitrogen availability in plant-absorbable form, but the interesting finding is that T0, without any fertilizer inputs, provided a comparable amount of N to other treatments. And at the end of the three years of the experiment, we can see that the value of T0 is as high as the value of TMIN. This is due to the improved N availability in soil due to crop residue incorporation in addition to the residual fertility present in the soil.

Figure 3.8. represents the cumulative export of nitrogen which refers to the total amount of nitrogen removed from the soil after every crop in succession. We can see in the graph that the cumulative amount of nitrogen value starts to show some differences immediately after the second crop, and with time the treatment with the highest removal of nitrogen is TMIN totaling 539 kg N ha^{-1}, while the lowest removal is from the treatment T100 with a value of 455 kg N ha^{-1}. T50 and T200, both have moderate values, with satisfactory yield (**Table 3.3.**), giving hopeful results for possible adaptation by the farmers.

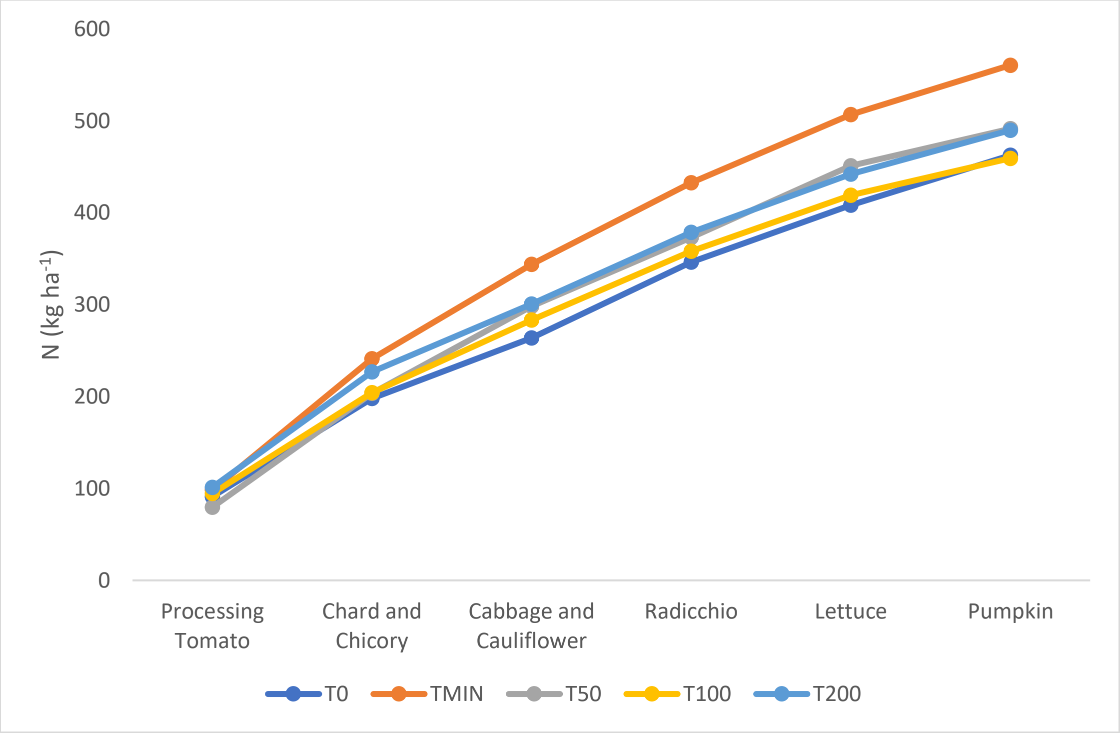


Figure 3.8. Cumulative N removal from vegetable crop succession for various fertilization treatments

Soil N content over the time

Figure 3.9. shows the amount of nitrogen present in the soil at different stages of the experiment for different fertilization treatments at the depth of 0-40 cm. At the end of the first-year experiment, we can see a very steep increase in nitrogen content for T200, and the value gradually drops with the decrease in the amount of compost applied. There is no difference in nitrogen content in TMIN at the end of the first year, but the value starts to decrease by the end of the second year along with all the other treatments. The soil N value of T200 was higher than all other treatments until the end of the second year but it decreased very sharply in the third year, making the soil N value of T100, the highest at the end of the experiment.

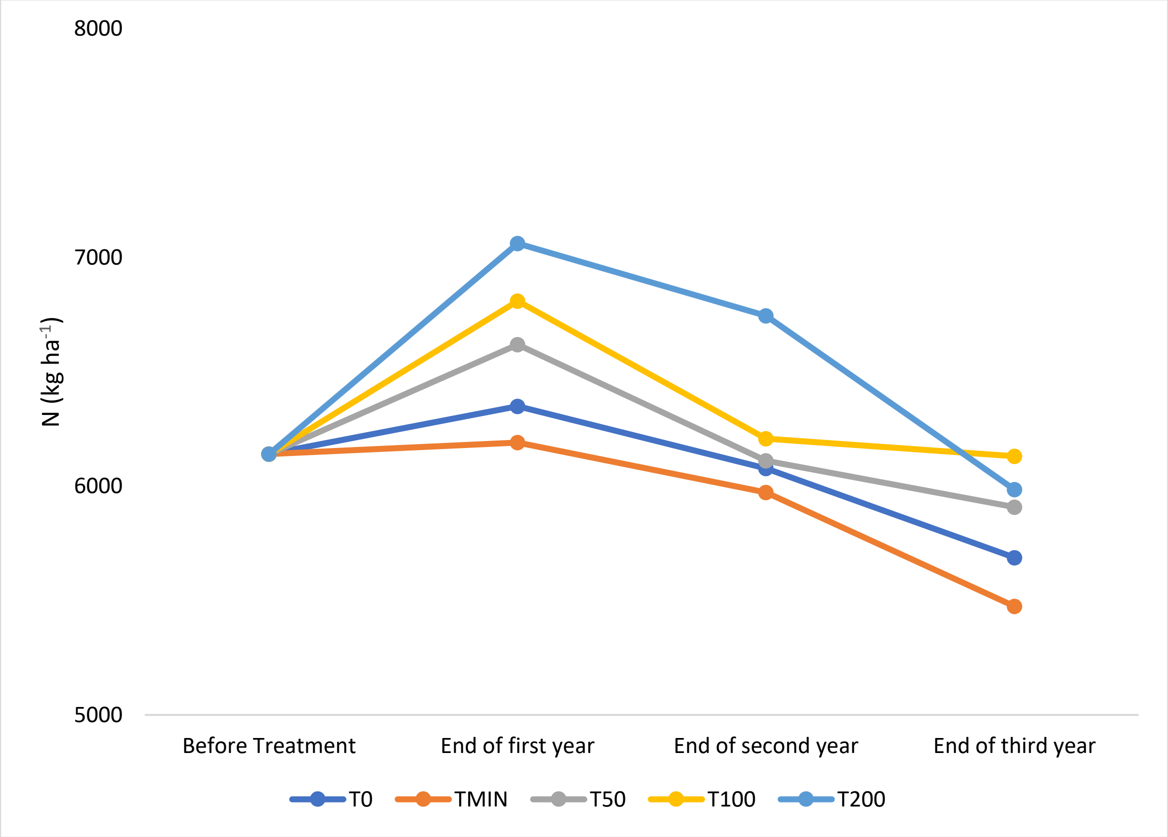


Figure 3.9. Soil N content over the three-year experiment of vegetable crop succession for various fertilization treatments

The results suggest that the N content in the soil is higher for organically treated fields either due to the slow release of nitrates and improved storage ability of soil or due to less nitrate loss due to leaching. A similar result was concluded by Benoit et al. (2014) when studied across 37 fields with 8 crop rotations. Nitrate leaching loss in organic and conventional fields were 0.2+-0.1 kg N kg^{-1} N $year^{-1}$ and 0.3 +-0.1 kg N kg^{-1} N $year^{-1}$ respectively. Another reason for this could be the immediate availability of mineral fertilizer for plants to produce yield and biomass. A study conducted by Tei et al. in 1999 concluded that when the available N is required to obtain the maximum marketable yield, the N left in the soil at harvest is considerably low. In our study, higher commercial yields were obtained for plants applied with mineral fertilizer treatments throughout the experiment period, and in later stages, the yield was impressively improved for both T200 and T0.

Distribution of nitrogen and carbon along the depth of the soil

For the last set of soil samples, the values of nitrogen, organic carbon, and inorganic carbon were studied to understand the pattern of nutrients stored at different soil depths in relation to the treatments applied (**Figure 3.10.**). The nitrogen and organic carbon values were highly significant for both the fertilization treatments and the soil depth; however, the values were non-significant in the case of inorganic carbon. The organic carbon was the highest for T100, which was not statistically different from T50, T200, and T0, and the lowest value was observed for TMIN. Mohammadi et al. (2011), also suggested that though the mineral fertilizer fulfills the nutrient demand of plants and microorganisms, it does not fulfill the carbon demand, so organic fertilizer is required to provide a balanced supply of nutrients and carbon.

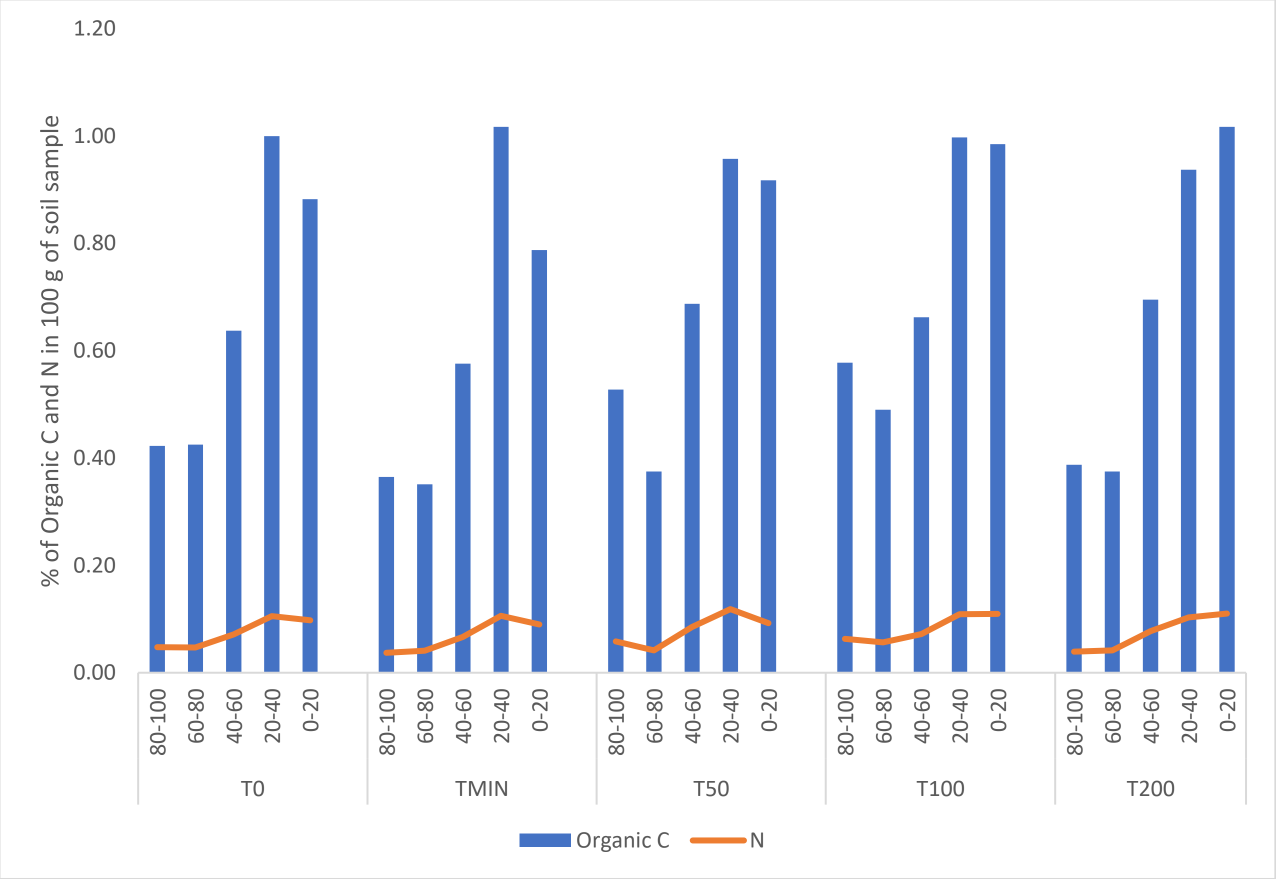


Figure 3.10. Nitrogen and organic carbon content at depths 0-20 cm, 20-40 cm, 40-60 cm, 60-80 cm, and 80-100 cm for different fertilization treatments

Similarly, the nitrogen content was the highest for T100 followed by T50. These values were not statistically different from those obtained for T200 and T0, which in turn were not statistically different from the lowest value obtained for TMIN. Both nitrogen and organic carbon values were significantly higher in depths 0-20 cm, 20-40 cm, and 40-60 cm than in 60-80 cm and 80-100 cm. The interaction between the treatments and the soil depth was not significant for the measured nutrients. Within each interval of depth, the nitrogen and organic carbon content were statistically significant among different treatments only at 0-20 cm (**Figure 3.11.**). At this depth, T200 had the highest content of organic carbon and nitrogen, which was not statistically different from T100, T50, and T0, however, was different from TMIN.

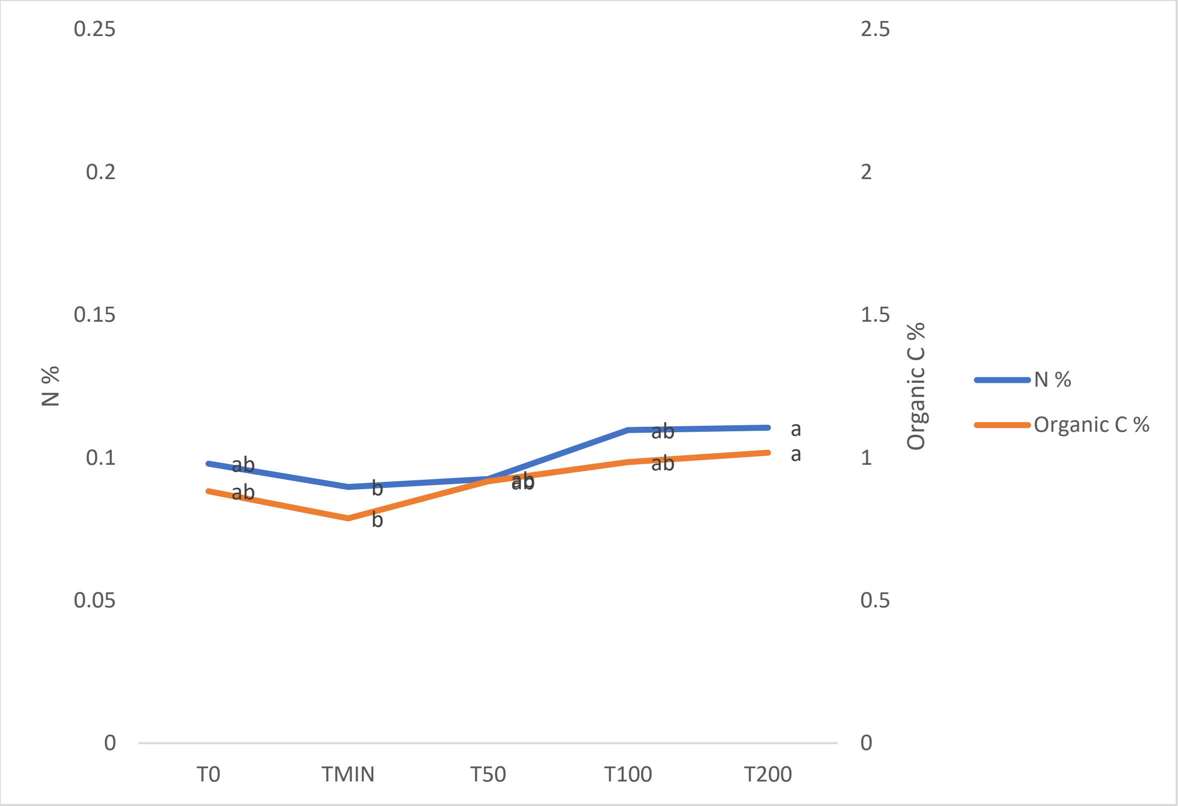


Figure 3.11. Nitrogen and organic carbon content at 0-20 cm soil depth for various fertilization treatments. The alphabets in the figure represent statistical significance for $p < 0.05$ when compared with Tukey's HSD test

CONCLUSION

Commercial yield values were statistically significant for the processing tomatoes, cabbage, and lettuce varieties. The yield values were the higher for TMIN, followed by T50, due to the immediate availability of nitrogen for plant uptake when mineral fertilizer was applied to fulfill the complete or partial crop N requirement. For other vegetables in succession, the differences in yield were not significant among the treatments, suggesting that the initial fertility of the soil, incorporation of the crop residues, and seasonal temperature variations could be some of the many factors that might have masked the true effect of applied fertilizer treatments, and further long-term study with similar crop succession might help to provide more concrete results. These factors also influence the uptake, distribution, and utilization of nitrogen taken up by plants among the marketable and non-marketable biomass within the plant. The total biomass yield was statistically significant for Caramba cabbage only, where for TMIN was significantly higher than T0, whereas other compost treatments had moderate values.

Agronomic efficiency was statistically significant for Chard and Chicory and the highest values were obtained for TMIN followed by T200, and T100 had the lowest values. The results show that the application of compost at a rate double the recommended, performed better for most vegetables in the succession, but T100 did not perform as expected except for the physiological efficiency of Lollo rosso lettuce. The apparent recovery efficiency of fertilizers was significant for Chard, Chicory and Delica pumpkin, indicating that the highest amount of N was able to be recovered when either mineral fertilizer was applied or when higher amount of compost was applied. Though the results varied considerably among different vegetables, treatments, and varieties of the same crop, it helped us to suggest that the total utilization efficiency of the vegetables follows the pattern of agronomic efficiency rather than physiological efficiency, hence, concluding that in vegetable crops, the crops are said to be more nitrogen efficient if the applied nitrogen is utilized in producing marketable yields.

A higher amount of nitrogen was removed from TMIN plots, understandably due to the higher availability of readily available nitrogen that gave higher yields in the vegetable crops. This justifies the lowest amount of soil N remaining at the end of the experiment for TMIN, though it was not significantly different from other treatment values. The N removal trend varied based on the N requirement of individual crops, however, the values for fertilized treatment were not significantly different from T0 in most cases. This result might indicate that apart from the applied fertilization, the inherent fertility of the soil may be enhanced by the incorporation of crop residues as a major part of the nitrogen absorbed by the vegetables was utilized to produce non-marketable biomass of the crop. Since the least amount of cumulative N was removed from the soil in T100, it also had the highest value for soil N at the end of the experiment.

The nitrogen and organic carbon distribution in the soil were significantly influenced by the depth of the soil as well as the treatments applied when analyzed at the end of the third experimental year. On the top 20 cm of soil, the amount of nitrogen and organic carbon stored was significantly influenced by the fertilization treatments, and the highest value was obtained for T200 plots. Overall, we can see a positive effect of compost fertilization over the three years of an experimental period on vegetable succession in terms of yield, N efficiencies, and stored soil N. Hence, we recommend the integrated application of organic and mineral fertilizers in the beginning years of transition followed by applying a higher than recommended dose of organic fertilizer to maintain yield of vegetable crop, N efficiencies of fertilizers, and N balance in soil.

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CHAPTER 4

CONCLUSIONS

With the increasing demand for sustainability in agricultural practices, a shift from conventional fertilization towards organic fertilization with a holistic adaptation approach is of prime importance. However, farmers usually have reservations about making the transition owing to the slow, variable, and insufficient supply of nutrients from the organic fertilizers, causing a reduction in the crop yield and quality. Various studies are being conducted to identify measures to make farmers' transition from mineral to organic fertilization more approachable. Our study aimed to identify the impacts of different rates of mineral and compost fertilizers on yield, quality, and nitrogen use efficiencies of the vegetable crops in succession. The results of which would be used to recommend the farmers the possibility of application of compost as a partial or a complete replacement to the mineral fertilizers.

The commercial and the total biomass yield of the vegetables in succession were the highest when mineral fertilizer was applied in the recommended dose (TMIN), especially in the early years of succession due to the immediate availability of N for plant uptake. These values were closely followed by T50, where the partial fulfilment of the crop requirement was from the mineral N. The yields were statistically significant among the fertilization treatments for the processing tomatoes, cabbage, and lettuce. For the rest of the vegetables, there were not treatment differences, suggesting that the initial soil fertility and incorporation of the crop residues could be the reason that masked the effect of the applied fertilizer treatments. The yield trend varied notably among the vegetables under study, making it difficult to derive a concrete conclusion, and further long-term study with similar crop succession might help to provide more strong recommendations. Most qualitative parameters were also not statistically significant among the fertilization treatments. Electrical conductivity was the highest in T200 for Verona and Chioggia varieties of radicchio and mini moscata variety of pumpkin. In lettuce, chlorophyll, flavonoid, and anthocyanin values of lettuce varieties were also the highest for T200; total soluble solids of the delica pumpkin were the highest for TMIN. Thus, we can conclude that the compost application improves, if not maintains the quality of vegetables.

The N use efficiency of the vegetables was measured based on the agronomic efficiency (AE), physiological efficiency (PE), apparent recovery efficiency (ARE), and utilization efficiency (EU). Significant results were obtained for chard, chicory, lollo rosso lettuce, and delica pumpkin. The AE and ARE of most vegetables were higher for TMIN, followed by T50, as the commercial yield was the highest for mineral fertilizer application. With partial or complete compost fertilizer, the crop's overall biomass was increased, improving the PE. However, when the compost was applied at the recommended rate (T100), the values of both AE and PE were not satisfactory compared to other treatments. The results suggest that the N absorbed from T100 was mostly utilized to produce non-commercial biomass. Based on our study, the total EU of vegetables depends on the AE, rather than PE, suggesting that N-efficient vegetable crops have better marketable yield compared to non-efficient vegetables. Along with this, we can also conclude that the integrated application of compost and mineral fertilizer (T50) and the higher application rate of compost fertilizer (T200) both are more N-efficient than the compost application at recommended dose (T100).

As the highest N amount was available for plant uptake in TMIN, it also had the lowest soil N at the end of the experiment, though not significantly different from other treatment values. T100 had the highest amount of soil N at the end of the experiment, suggesting that the organic N was slowly mineralized in T100 compared to other organic treatments. On the top 20 cm of soil, the N and organic C were significantly influenced by the fertilization treatments; the highest N and C values were obtained for T200.

We can conclude that to minimize the steep reduction in yield, quality, and N efficiencies, an integrated application of organic and mineral fertilization could be applied in the early years of transition from mineral fertilization to organic fertilization, gradually followed by the application of compost as a fertilizer as a complete replacement to the mineral fertilizer.