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EVALUATION OF NUTRIENT SOLUTIONS PRODUCED FROM AQUEOUS EXTRACTS AND DECOMPOSITION PRODUCTS OF ORGANIC WASTE MATERIALS ON THE PLANT GROWTH PERFORMANCE IN HYDROPONICS

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Under the Supervision of Dr. Elke Neumann

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Declaration of Original Work

I, Noura Said Al Nuaimi, the undersigned, a graduate student at the United Arab Emirates University (UAEU), and the author of this thesis entitled "*Evaluation of Nutrient Solutions Produced from Aqueous Extracts and Decomposition Products of Organic Waste Materials on the Plant Growth Performance in Hydroponics*", hereby, solemnly declare that this thesis is my own original research work that has been done and prepared by me under the supervision of Dr. Elke Neumann, in the College of Agriculture and Veterinary Medicine at UAEU. This work has not previously been presented or published or formed the basis for the award of any academic degree, diploma, or a similar title at this or any other university. Any materials borrowed from other sources (whether published or unpublished) and relied upon or included in my thesis have been properly cited and acknowledged in accordance with appropriate academic conventions. I further declare that there is no potential conflict of interest with respect to the research, data collection, authorship, presentation, and/or publication of this thesis.

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Abstract

Hydroponic plant production involves the cultivation of plants in absence of soil. In this system, the supply of the plant root with water and nutritional elements occurs via a nutrient solution made of inorganic salts. Hydroponic plant cultivation often achieves higher yields, water use efficiencies and quality of crops compared with soil production. In addition, it renders the farming system independent from soil properties. However, the currently available systems rely on steady input of non-renewable inorganic salts. Unlike soil-based systems, hydroponics, so far, do not offer feasible opportunities for recycling of nutritional elements from within crop residues or organic waste materials. The main aim of this thesis was thus to elucidate the potential of producing nutrient solutions suitable for hydroponic plant cultivation from locally produced vegetable crop residues, commercial compost, and biosolids. In a first experiment, the release of soluble nutritional elements from the organic test materials was investigated over time and for different substrate/water ratios. Dried and ground organic substrate samples were placed into nylon mesh bags and allowed to extract and mineralize in aerated water for up to 23 days. The release of nutritional elements was monitored at intervals of three days and revealed that the highest amounts of soluble nutrients were present in the extraction solution between 3 and 6 days after set-up of the trial. The use of one L of water for the extraction of six g of dry organic substrate resulted in the highest nutrient release. In a second experiment the ability of two different nutrient solutions produced from organic waste materials to support the growth and element uptake of corn and cucumber seedlings was investigated. Either dry and ground biosolids or cucumber crop residues were extracted and mineralized for five days in aerated water before the extraction solution was used as a growth medium for hydroponic plant seedlings. A control treatment was supplied with a standard nutrient solution prepared from mineral fertilizer salts. The results revealed that all tested solutions well supported the growth of the seedlings. The solution prepared from biosolids was superior over the one deriving from cucumber leaves. Cucumber plants growing on the biosolid solution grew even better than those on the standard mineral nutrient solution. Corn plants performed best on the standard nutrient solution and the least on the one prepared from cucumber leaves. The results of this study suggest that recycling of nutritional elements from organic waste materials into

hydroponic plant production systems is well possible, using a relatively simple and cheap extraction procedure that could easily be upscaled. Biosolids might be particularly suitable in this respect, and hydroponic plant production might be a feasible way of valorizing this material, which is currently largely dumped into landfills.

Keywords: Organic, aerobic fermentation, hydroponic, mineralization, compost, organic liquid fertilizer, nitrification, nutrient solution, biosolids.

Title and Abstract (in Arabic)

تقييم استخدام محاليل مغذية منتجة من مستخلصات مائية و نواتج تحلل المخلفات العضوية على نمو النباتات في نظام الزراعة المائية

الملخص

يشمل نظام الزراعة المائية زراعة النباتات في غياب التربة، في هذا النظام يتم إمداد جذورالنبات بالماء والعناصرالغذائية عن طريق محلول مغذي مكون من مركبات الأسمدة المصنعة، غالبًا ما تحقق النباتات في نظام الزراعة المائية انتاجية أعلى وكفاءة في استخدام المياه وجودة انتاج أفضل مقارنة بالزراعة في التربة. بالإضافة إلى ذلك، نظام الزراعة المائية مستقل عن خصائص التربة بشكل كلي. ومع ذلك، فإن الأنظمة المتاحة حاليًا تعتمد على المدخلات الزراعية من موارد غير متجددة مثل مركبات الأسمدة المصنعة، على عكس الزراعة في التربة نظام الزراعة المائية لا يوفر حتى الآن فرصًا مجدية لإعادة تدوير العناصر الغذائية من بقايا المحاصيل أو مواد المخلفات العضوية، إن الهدف الرئيسي من هذه الأطروحة هو البحث في إمكانية إنتاج محاليل مغذية مناسبة لنظام الزراعة المائية من بقايا المحاصيل النباتية المنتجة محليًا، والسماد العضوي المحلي، والمواد الصلبة الحيوية.

في بداية الدراسة، تم إجراء تجارب لفحص إطلاق العناصرالغذائية القابلة للذوبان من مواد الاختبارالعضوية بمرور الوقت ووفق تراكيز مختلفة، حيث تم وضع عينات من المواد العضوية المجففة والمطحونة في أكياس شبكية من النايلون وتركها في وسط مائي في ظروف هوائية لمدة تصل إلى 23 يومًا. تم كذلك مراقبة تحرر و تمعدن العناصر الغذائية على فترات مدتها ثلاثة أيام، ووجد أن أعلى كمية من العناصر الغذائية القابلة للذوبان كانت في مستخلص العينات بين 3 و 6 أيام بعد بدء التجربة، بناء على هذه التجربة يتبين أن أعلى كمية من العناصر المغذية يمكن استخلاصها باستخدام 6 جرام من المواد العضوية الجافة في لتر واحد من الماء.

في المرحلة الثانية من التجربة، تم دراسة قدرة محاليل مغذية مختلفة تم انتاجها من مخلفات عضوية لدعم نموشتلات الذرة والخيار وقدرتها على امتصاص العناصر من المحاليل المغذية، تم استخدام المواد الصلبة الحيوية و مخلفات محصول الخيار كمواد أولية لتحضير المحاليل العضوية، وقد تم الإستخلاص عن طريق إضافة المواد العضوية الجافة في الماء بتركيز 6 جرام/لترفي ظروف التهوية لمدة خمسة أيام قبل أن يتم البدء في استخدامها في نظام الزراعة

المائية، تم كذلك استخدام محلول مغذي قياسي محضر من أملاح الأسمدة المعدنية كشاهد في التجربة، أظهرت النتائج أن الشتلات نمت بشكل جيد في المحاليل المغذية العضوية، حيث أن المحلول المغذي العضوي من المواد الصلبة الحيوية أعطى نتائج أفضل مقارنة بالمحلول العضوي المحضر من مخلفات أوراق الخيار، بالنسبة لنبات الخيار، كان نموه أفضل في المحلول المغذي المحضر من المواد الصلبة الحيوية مقارنة بالمحلول المغذي القياسي، أما بالنسبة لنبات الذرة، فقد كان نموها أفضل في المحلول المغذي القياسي وأقل في المحلول المغذي المحضر من أوراق الخيار، تشير نتائج هذه الدراسة إلى أن إعادة استخدام العناصر المغذية للمخلفات العضوية في أنظمة انتاج الزراعة المائية هو أمر ممكن جدًا، وذلك عن طريق إجراء عملية استخلاص بسيطة نسبيًا ورخيصة الثمن يمكن التوسع فيها بسهولة، قد تكون المواد الصلبة الحيوية مناسبة بشكل خاص في هذا الصدد، وقد يكون انتاج نباتات الزراعة المائية طريقة مجدية لتثمين هذه المادة، والتي يتم حاليًا رميها إلى حد كبير في مكب النفايات.

مفاهيم البحث الرئيسية: عضوي، تخمير هوائي، زراعة مائية، تدوير، سماد عضوي، محلول مغذي، مخلفات زراعية.

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Dedication

To my Khalid & Wasayef

"My beloved twins"

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List of Abbreviations

ANOVA	Analysis of Variance
B	Boron
Ca	Calcium
Cu	Cupper
DW	Dry Weight
EC	Electrical Conductivity
Fe	Iron
ICP	Inductively Coupled Plasma Spectroscopy
K	Potassium
Mg	Magnesium
Mn	Manganese
Mo	Molybdenum
N	Nitrogen
NS	Nutrient Solution
P	Phosphorous
pH	Potential of Hydrogen
S	Sulfur
SD	Standard Deviation
Zn	Zinc

Chapter 1: Introduction

1.1 Overview

In face of increasing scarcity of natural resources and progressing environmental pollution, sustainable agricultural production concepts, such as organic farming, have gained attention in recent decades. Sustainable farming, including organic certification standards, are based on recirculation of water and nutritional elements rather than through-flow. Closing nutrient cycles on the farm as far as possible, minimizes adverse environmental impacts of agricultural food production. Nutritional elements often leave the farm within the marketable harvest products, while crop residues remain available for the return of nutrients to the soil, e.g., in form of compost, mulch or animal feed/manure. For most crops, the residues account for approximately 50% of the total plant biomass. Elements that have left the farm with harvest products will end up with the processing industry and consumers, and finally largely in waste materials that industries and households produce. While strategies for recycling of nutritional elements from some industrial organic waste materials have been developed, comprehensive recycling paths are lacking for waste leaving the end-users, e.g., in form of sewage or household waste. In the UAE more than 100.000 t of dry biosolids are produced every year, which are deposited into landfills rather than being returned to farming land. This ultimately leaves farming systems with a nutrient deficit that needs to be balanced. The nutrient deficit is particularly large for soilless plant production systems. Established methods for returning nutritional elements from within crop residues are based on the presence of soil and its ability to mineralize organic matter applied to it.

In hydroponic crop production plants are grown with their roots in a solution of water and inorganic nutrient salts in absence of soil (Bradley & Marulanda, 2000). Advantages of hydroponic systems include a higher production per unit area, higher water use efficiency, a better control of plant development, and independence from the quality of soil (Van Os, 1999). Different from soil, however, conventional hydroponic cultures do not allow for the addition of organic fertilizers or waste materials to the growth medium. Apart from technical difficulties of having solid constituents in the solution, this might cause the generation of potentially phytotoxic intermediate decomposition products that could cause damage to the roots of the plants. Therefore, only synthetic mineral fertilizers are used in conventional hydroponic nutrient solutions, and these systems do not offer opportunities for element recycling from waste. Mineral fertilizers are largely based on non-renewable resources, and their production consumes huge amounts of energy and has a high CO_2 footprint, which renders the whole system rather unsustainable.

Though hydroponic vegetable production systems have shown to use water and energy more efficiently than conventional soil-based cultivation, organic certification bodies usually exclude soilless production systems from certification. The absence of recycling opportunities for organic waste materials is a main reason for this.

Organic production methods require the use of organic waste materials as a source of plant nutritional elements. Ideally, residues are recycled within the community of organic farms, so that no intake of synthetic fertilizers into the system occurs. The resulting reduction of nutrient losses to the environment and lower need for non-renewable resources increase the environmental feasibility of organic farming (Cheng et al., 2004; Mazuela et al., 2005). Since neither compost nor animal manure or other solid organic materials can be added directly to a soilless production system, recycling of such materials into hydroponic plant cultivation would require an extraction or mineralization procedure that releases soluble, plant available nutritional elements. In soil culture, organic fertilizer is usually added directly during cultivation. The organic fertilizer incorporated into the soil is mineralized by soil microorganisms and becomes plant available over time.

Release of plant nutritional elements from solid organic materials into water can occur via diffusion of soluble components, and/or mineralization by microorganisms in the solution. The latter is encouraged by aeration of the solution and maintenance at an adequate temperature. In organic farming liquid extraction of compost or manure is sometimes practiced for the preparation of ‘compost tea’ or ‘dung water’. Using similar techniques, it might be possible to process organic fertilizers or waste materials into a nutrient solution for hydroponic plants (Shinohara et al., 2011). In a previous investigation, mineralizing microorganisms were successfully cultured in a liquid medium containing solid organic materials and microbial inoculum under moderate aeration (Shinohara et al., 2011). According to Shinohara et al. (2011), the resulting culture solution containing the microorganisms and soluble constituents was a suitable solution for hydroponic plants. In this study, solution was continuously produced by adding fresh organic fertilizer to the mineralization tank, as the organic nitrogen was mineralized into nitrate at an efficiency of 97.6% with no harmful effects on plant growth.

In conclusion, future food security requires the closure of agricultural element cycles and a further reduction in the use of non-renewable natural resources. Hydroponic systems have a high energy and water use efficiency under climatic conditions of the UAE, but to date their sustainability is limited by the absence of feasible technologies for the recycling of organic waste materials and the nutritional elements they contain. The overall aim of the present study was to lay the foundation for the development of such technologies and pave the way for hydroponic systems that qualify for organic certification.

1.2 Specific objectives

- Quantify the release of soluble nutritional elements from different organic waste materials submerged in aerated water over time.
- Identify the most suitable extraction time and water/substrate mixing ratio for three different organic waste materials.
- Identify the most suitable type of organic substrate for the preparation of aqueous extracts serving as nutrient solutions in hydroponic plant culture.
- Evaluate the ability of the extracts to serve as nutrient solutions for commercial hydroponic plants.

1.3 Hypothesis

The aqueous aerobic mineralization and extraction of organic waste materials can recycle at least 50% of nutritional elements that these materials contain into hydroponic production systems. The extracts can support plant growth in a similar way as conventional nutrient solutions based on mineral fertilizer salts do.

Chapter 2: Review of Literature

2.1 Agricultural sustainability

Nowadays, food security is a serious global concern because of ascending population growth. As a result, there is a considerable pressure on the agricultural sector to further increase productivity. Previous yield increments have been based on upscaling of the agricultural production processes and a high input of mineral fertilizers and pesticides. Concurrently, enormous water resource withdrawals as well as natural habitat clearings have taken place, imposing serious threats to the environment (Srivastava et al., 2016). Poor land management resulted in considerable agricultural ecosystem degradation, attributed to loss of soil organic matter, erosion and ultimately decreasing productivity. To sustain adequate yields on degraded soils, farmers often increase the mineral fertilizer application rates (Duong et al., 2013), mostly with a high risk of nutrient leaching, environmental pollution and natural resource depletion (Srivastava et al., 2016). To protect soils and reduce the use of non-renewable resources, the sustainable valorization of organic sources of plant nutritional elements, such as compost, plant residues, municipal solid waste, vermicompost and manure is imperative.

The number of farmers who want to adopt ecofriendly and sustainable cultivation practices is increasing steadily, encouraged by an increased environmental responsibility and eco-appreciation of consumers (Moncada et al., 2020). Organic certification has proven most efficient in supporting farmers to implement principles of recirculation and ecological processes to agro-ecosystems, even at the cost of maximum yield achievement. The International Federation of Organic Agriculture Movements (IFOAM, 2005) defined organic farming as (quot.): “a production system that sustains the health of soils, ecosystems and people. It relies on ecological processes, biodiversity and cycles adapted to local conditions, rather than the use of inputs with adverse effects. Organic Agriculture combines traditions, innovation and science to benefit the shared environment and promote fair relationships and a good quality of life for all involved".

2.2 Organic waste material recycling into agricultural systems

Potentially recyclable biomass involves any biodegradable, non-hazardous product, waste, or residue originating from an organic source such as agriculture, forestry, and related sectors, as well as municipal and industrial waste products (Alatzas et al., 2019). Pollution resulting from improper disposal of organic waste has become a serious issue worldwide. Based on a report done by the Center of Waste Management of Abu Dhabi and the Abu Dhabi National Oil Company (2018), proper waste management and treatment are taken seriously by the government of Abu Dhabi Emirate to minimize risks for public health and the environment. The total solid waste generated in the Emirate of Abu Dhabi was about 9.99 million tons in 2018. The agriculture sector accounted for 13% of non-hazardous waste generated in Abu Dhabi, which equaled 1.3 million tons in 2018. In the same year, municipal solid waste accounted for 1.8 million tons, accounting for 18% of total non-hazardous waste. The same report revealed that around 1.1% of the total waste was processed into compost. This material is likely to return to the agricultural sector.

According to Polprasert and Koottatep (2017), actions of waste recycling and reduction entails enormous economic values and environmental benefits. The authors point to three major benefits, i.e. (i) reducing the demand for scarce natural resources,

(ii) cutting down on transport and production energy costs, and (iii) using waste which otherwise be lost to landfill sites.

Waste recycling through composting is being considered in many parts of the world as a method to reduce waste destined for the landfill by returning biodegradable materials back into soils and reducing the organic matter content of waste streams. The latter can be up to 55% of the total waste volume.

2.3 Hydroponic plant production and its current dependency on mineral fertilizer inputs

Soilless plant cultivation or hydroponic systems involve the use of production technologies that make it unnecessary for plants to interact with soil (Mowa et al., 2018; Resh, 2012). The supply of mineral nutrients and water occurs through an aerated nutrient solution, with or without an inert growth medium such as rockwool, coconut fiber, peat, or perlite for mechanical support. According to Maucieri et al. (2019) and Bradley and Marulanda (2000), soilless cultivation systems have many advantages compared with soil-based plant production. One of these lies in the reduction of water use by as much as 70% - 95% through recirculation of the nutrient solution and the absence of evaporation losses. Hydroponic culture makes farmers independent from the soil type and contaminations with pathogens that it may contain. Moreover, the system provides better control of the nutrient supply, and often considerably increases the shoot/root ratio of crops. The absence of soil leaves harvest products clean and of high quality (Maucieri et al., 2019; Gilmour et al., 2019).

In conventional hydroponic cultures the addition of organic materials to the nutrient solution causes generation of harmful intermediate decomposition products which are phytotoxic and cause damage to the roots of the plants. To date, only chemical fertilizers are used for the preparation of hydroponic nutrient solutions, with the exception of aquaponic systems that recycle nutrients released by cultured fish. Hydroponic systems based on mineral fertilizer salts are relatively cheap and easy to adjust, but largely based on non-renewable resources. Synthetic ammonia production via the Haber-Bosch Process is extremely energy consuming and has a higher CO_2 output compared with most other chemical industrial processes (Boerner, 2019) This renders conventional hydroponics environmentally unsustainable, and despite their water and energy saving potential such systems do so far rarely qualify for organic certification.

2.4 Hydroponics and organic certification

In 2017, the National Organic Standards Board (NOSB), an advisory committee to the United States Department of Agriculture (USDA), voted not to prohibit hydroponic and aquaponic farms from being eligible for being USDA certified organic. Organic certification has become an important marketing opportunity for farmers investing into sustainable production systems. The market for organic food is growing in the UAE, providing attractive opportunities for local farmers. However, the environmental conditions of the country do not allow for year-round production of vegetables of high quality, encouraging farmers to invest into infrastructure to protect plants from heat, dust and drought. Yields of plants growing in such protected environments have to achieve high yields to pay off the investment costs. As the sandy desert soils of the country often do not support this, hydroponic plant production systems remain as the most economically feasible option. Whether or not hydroponic production systems might qualify as organic when nutrient solutions are based on recycled organic waste, remains speculative. It might be desirable, taking the environmental conditions of the Gulf Region into account. In the European Union, however, the standards are maintained that organic plant production should be based on nourishing the plants primarily through the soil ecosystem and production on and in living soil in connection with the subsoil and bedrock. Consequently, hydroponic production does not qualify as organic, and neither does the cultivation in containers, bags, or beds, where the roots are not in contact with the living soil (European Union, 2018).

2.5 Recycling of organic waste materials into agricultural systems

2.5.1 Crop residues

With the exception of some leafy vegetables, crop cultivation involves the production of relatively large amounts of non-edible crop residues. Relative quantities of such residues produced are reflected in the harvest index (HI, edible biomass / total aboveground plant biomass produced), which varies depending on the crop species, cultivar and yield level. For wheat, barley, rice and corn the harvest index is typically in a range of 0.50 – 0.65 (Evans, 1993; Kush, 1995; Hay & Porter, 2006). Harvest indices for soybean are mostly between 0.50 and 0.60 (Leffel et al., 1992; Bullock et al., 1998). Irish potatoes achieve HIs ranging from 0.70 to 0.80 (Geremew et al., 2007), and sweet potatoes from 0.50 to 0.60 (De Queiroga et al., 2007). Throughout the last decades plant breeding programs have achieved an increase in the HI for many crop species, but there are physiological limitations to the extent by which dry weight partitioning can be shifted towards the harvest products (Evans, 1993; Spiertz, 2014). Currently, in all parts of the world, crop residues constitute at least half of the agricultural plant biomass that is produced (Smil, 1999).

Crop residues normally remain in the farming system and are returned to the soil. In direct seeding and mulch based cropping systems the fresh plant material is chopped and directly returned to the field. When crop residues are palatable by farm animals, their use as animal feed and return in form of animal manure is also practised. In both cases the return of nutritional elements into crops is ultimately based on organic matter decomposition through soil heterotrophs.

The application of fresh or dried plant material or animal manure to field soil bears the risk of disease and weed transmission. Especially when animal waste is applied, not only plant diseases but also animal and human pathogens may play a role. To reduce such risks, raw organic materials are often processed into compost before being returned to the field soil.

2.5.2 Aerobic composting

Compost can be prepared from a wide range of organic waste materials. These are usually placed into a bin, drum or on a pile and left for aerobic decomposition until the degraded material is considered mature. In some cases, microorganisms or earthworms are added to the organic material to encourage the degradation process. Only rarely (e.g. in 'bokashi' compost) does composting involve anaerobic processes, as these often involve the production of phytotoxic compounds (Coker, 2014). During the process of composting and the high activity of the microorganisms involved, the inner part of a compost pile or heap heats up to around 60 – 65º C, which serves in the elimination of pathogens and weed seeds. Compost heaps or piles are turned over several times to make sure that all parts of the organic mixture have been exposed to the desired temperature, and to make sure that the process remains aerobic. Phytotoxicity is a common problem in compost that underwent anaerobic degradation processes. Immature compost involving manures can be rich in ammonia, which causes toxicity to the plant (Phibunwatthanawong & Riddech, 2019; William, 2000).

In addition, immature compost may not be thoroughly free from weeds, pests and pathogens.

Compost is a valuable organic fertilizer and soil amendment in agriculture. It is usually applied before crops are sown or planted and mixed with the upper 20 – 30 cm of the soil. As the organic material is further degraded by soil microorganisms, it releases plant nutritional elements and generates humic compounds. The latter provide a long-term carbon sequestration in the soil and improve its physical and chemical properties. On the other hand, low-quality compost that is immature or prepared from inappropriate ingredients can have elevated NH_4^+-N levels, contain toxic heavy metals or organic compounds that hamper plant growth (e.g. ethylene oxide, phenolic compounds) (Selim et al., 2011; Phibunwatthanawong & Riddech, 2019). It was found that the germination index of cress plants sown on compost of different maturity levels increased with decreasing in NH_4^+-N, and water extractable Zn and Cu content. Increasing NO_3^--N and water extractable P_2O_5 and K_2O content supported seed germination (Selim et al., 2011).

2.5.3 Biosolids

Biosolids are an output product of the municipal wastewater treatment process. There is increasing pressure to use biosolids for agricultural purposes due to the low economic and environmental feasibility of the disposal of these materials in landfills. The Emirate of Abu Dhabi produces more than 40.000 t of dry biosolids every year (Al Braiki, 2017). Biosolids contain organic matter and essential mineral nutrients for crop production (Sullivan et al., 2015). They usually contain macronutrients such as 3 - 8% N, 1.5 - 3.5% P, 0.1 - 0.6% K, 1 - 4% Ca, 0.4 - 0.8% Mg, and 0.6 - 1.3% S (Sullivan et al., 2015; Giusquiani et al., 1988). Recommendations for biosolid application to agricultural soils are usually based on rates intended to supply crops with adequate N. Other nutrients they contain also reduce fertilizer requirements (Sullivan et al., 2015; Binder et al., 2002). Biosolids contain organic nitrogen and ammonium-N. However, nitrate-N is absent in most biosolids (Sullivan et al., 2015; Binder et al., 2002). Depending on the sources of wastewater feeding into the concerned sewage treatment plant, biosolids can contain compounds that are of environmental concern or even impose a health threat, such as heavy metals, NaCl, polycyclic aromatic hydrocarbons, antimicrobial residues, and microplastics. According to Sullivan et al. (2015), the trace element concentration thresholds for biosolids are 7500 mg/kg Zn, 75 mg/kg Mo, and 4300 mg/kg Cu. In the Emirate of Abu Dhabi, the quality framework for the use of biosolids in agriculture is provided by the Regulation and Supervision Bureau for the Water, Wastewater and Electricity Sector in the Emirate of Abu Dhabi (RSB, 2018).

A study done by Angin et al. (2017) indicated that biosolids application is an effective way to improve vegetative growth and yield of crops. It can also improve soil and plant chemical properties and is thus economically feasible. On an alkaline soil biosolid application significantly reduced soil pH due to organic acid production during the mineralization process, which can have beneficial effects on nutrient availability to plants. Similarly, biosolids application significantly increased macro and micro-nutrients content of leaves (Angin et al., 2017). On the other hand, biosolids can contain harmful compounds such as industrial organic chemicals, heavy metals or antimicrobial residues. In order to minimize adverse effects of biosolids on agricultural systems and the environment, properties of biosolids need to be thoroughly analyzed and evaluated prior to their use. So far there are no strategies for the recycling of biosolids into soilless plant production systems. This, however, might be a particularly promising approach to valorize these materials in urban environments where they are produced. There is an increasing number of high-tech hydroponic and aeroponic vertical farms in urban areas of the UAE. These might increase their sustainability by recycling urban waste materials into soilless plant production systems.

2.5.4 Slurries and compost tea

Several methods have been proposed for the partial or entire conversion of solid organic waste materials, manures and composts into liquid fertilizers or slurries. Usually this is done to facilitate the application of such organic fertilizers to standing crops, or to provide them with highly available nutritional elements. So far there are only few studies that have investigated opportunities for the use of such liquid fertilizers as nutrient solutions for hydroponic plants. Guajardo-Rios et al. (2018) produced animal manure-based organic nutrient solutions and compared these with an inorganic reference solution for their ability to support soilless tomato growth. The results indicated that yield, plant height and fruit quality did not differ between plants of the organic and conventional solution. Organic fertilizers contain water soluble and insoluble compounds (Hirzel et al., 2012; Guajardo-Rios et al., 2018). The preparation of liquid fertilizers, or nutrient solutions from organic materials thus often involves a mineralization process. In this the total N released in plant available form is related to the mineralization capacity of the source, nutritional factors, and the microbial growth environment, e.g. the temperature, moisture, oxygen level, pH. Nutrient solutions deriving from manure can be a promising technique compared to solid manure application for organic nutrition of herbs in soilless culture. Aboutalebi (2013) prepared a stock solution by dissolving manure in a covered tank for 3 days before it was used in soilless plant cultivation. The author filtered and diluted the slurry to EC levels varying between 1.8 and 2.3 mS cm^{-1} and applied it to basil plants. Arancon et al. (2019) evaluated the suitability of vermicompost tea as an additive or substitute for mineral hydroponic nutrient solutions for lettuce and tomato. The authors found that vermicompost teas significantly increased lettuce yields when the nutrient solution concentration was reduced to 25% or 50% of the recommended rate. This suggests that nutrients from within compost tea were well available to plants. Compost tea is prepared by placing compost into a fabric ('tea') bag and submerging it in aerated water to which sugar or molasses has been added. The resulting microbial activity and aerobic decomposition of the compost in the liquid environment releases nutritional elements for plants. In addition, compost tea may provide growth stimulating hormones such as auxins, cytokinins, gibberellins and humic acids (Arancon et al., 2012, 2019).

A study by Mowa et al. (2018) found that the rate and quality of mineralization of manures in a liquid environment decreases with increasing amounts of organic material added. Small (0.25g/l) rather than large quantities of manure encouraged the establishment of a microbial community supporting mineralization of organic nitrogen compounds. Compost tea is usually left for a few days (i.e., less than a week) before it is applied to plants. However, even when longer decomposition periods are used, there seems to be little risk of phytotoxicity of the resulting solutions (William, 2000; Selim et al., 2011; Phibunwatthanawong & Riddech, 2019). The aerobic microbial decomposition process seems to play an important role in preventing phytotoxicity. For example, the use of wheat straw leachate as a nutrient solution in a static hydroponic system had an inhibitory effect on wheat growth. This negative effect could be alleviated by incubating the leachate with a microbial community before use (Garland & Mackowiak, 1990). A study by Mackowiak et al. (1996) investigated the growth of potato plants grown hydroponically in nutrient solution produced from inedible potato biomass. The authors found that it was possible to recycle approximately 50% of the total nutrients that the waste material contained.

2.6 Liquid organic fertilizers as a base for organic hydroponics

Liquid extracts or decomposition products of organic waste materials or composts might help to reduce the need of hydroponic plant cultivation for mineral fertilizer salts. This might pave the way for sustainable hydroponics and potentially even organic accreditations. In several studies, the organic liquid substrates were as efficient as conventional mineral nutrient solutions in supporting plant growth (Shinohara et al., 2014). A study done by Michitsch et al. (2007) compared the growth and mineral nutritional status of hydroponic nursery plants supplied with extracts of different organic materials. The authors found that plants raised in spent mushroom compost extract amended with mineral fertilizer salts grew as well as those in half-strength Hoagland's number 2 solution. Therefore, this study indicated that, with proper amendments of N, P, K, and other plant nutritive elements, organic waste extracts have the potential for use as supplemental nutrient sources for hydroponic plant production. Such a practice would, however, most likely not qualify for organic certification. The market opportunities for organic vegetables and fruits are growing in urban areas, and the production of certified organic vegetables is an attractive opportunity for urban vertical hydroponic or aeroponic farms in the UAE. Investment in such farming operations has recently strongly increased in the country. The identification of technologies for the production of nutrient solutions entirely based on the recycling of organic waste materials might provide opportunities for organic certification of such farms and their products.

Chapter 3: Material and Methods

3.1 Location of the research work

The experimental work was done at the United Arab Emirates University (UAEU) Aquaponic Research Station in Falaj Hazzaa, Al Ain, UAE (Figure 1). This research facility belongs to the UAEU College of Agriculture and Veterinary Medicine. It lies in the coordinate latitude and longitude of 24.1880°N and 55.7226°E. The chemical analyses were done in the UAEU Soil and Water Laboratory, as well as the laboratories of the Abu Dhabi Agriculture and Food Safety Authority.

Figure 1: Greenhouse in which the plant experiment was done

3.2 Choice of organic materials as substrates for the preparation of nutrient solutions

A locally produced compost and two different organic waste materials produced in Abu Dhabi were chosen as test substrates for this study. The compost sample was provided by the Emirates Bio Fertilizer Factory. The compost had been produced from organic garden and farm waste. A biosolid sample was obtained from the Al Khazna Wastewater Treatment Plant, and crop residues in form of cucumber leaves and stalks came from a commercial hydroponic farm in Abu Dhabi (Figure 2). The compost and biosolids were autoclaved before being used in the experiment to eliminate the risk of human pathogen exposure. All materials were oven-dried at 60°C for 48 hours using a drying oven, and ground into a coarse powder with a hammer mill prior to being used in the experiment.

Figure 2: Greenhouse from which the cucumber leaves with stalk (crop residues) were obtained.

3.3 Mineral element analysis of organic materials

Organic test substrates and plant material were analyzed for their element concentrations. Analyzed elements involved mineral nutrients essential for plants. The latter are required by plants to complete their life cycle, and constitute either macronutrients such as N, P, K, Ca and Mg, or micro-nutrients such as Fe, Cu, Mn, Zn, B and Mo. Between 0.2 and 0.5 g of dry, pulverized organic material was weighed into a Teflon tube and microwave digested in presence of 10 ml nitric acid (HNO_3 69%) and 2 ml hydrochloric acid (HCl 37%), for 35 minutes at 200ºC. After cooling, the digested solution was brought to a volume of to 50 ml with doubled distilled water. Concentrations of P, K, Ca, Mg, Na, Fe, Mn, Zn, Cu, B and Mo in the liquid samples were then measured using Inductively Coupled Plasma Mass Spectroscopy (ICPMS-9820; Figure 3). To measure N concentrations, dry pulverized subsamples of approximately 0.5 g of the organic materials were analyzed according to Kjeldahl using an auto analyzer (Figure 4). Three replicates of each sample were analyzed, and the results were averaged.

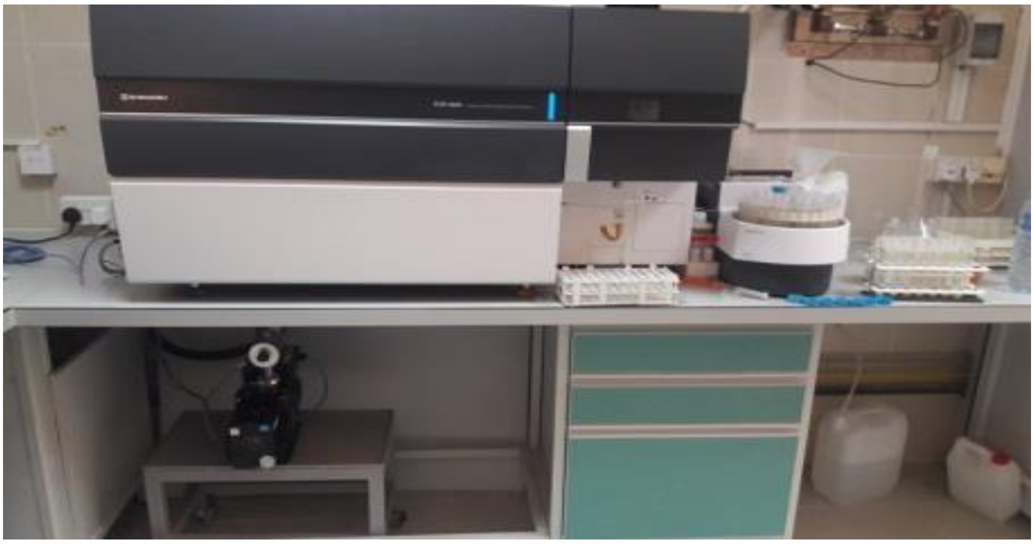

Figure 3: Nutrient analysis using inductively coupled plasma spectroscopy.

Figure 4: Nitrogen analysis using auto analyzer.

3.4 Estimation of water extractable nutritional elements in the organic substrates used for the preparation of the nutrient solution

To estimate amounts of water extractable nutrients in the organic substrates, respective subsamples were extracted with either hot or cold double-distilled water. Subsamples of 0.7 g dry weight were mixed with 50 ml of water in glass bottles. Heat-treated samples were put on a hot plate until the liquid started boiling. All the bottles were then shaken using a rotary shaker for 1 hour. Then the contents of the glass bottles were passed through Blue Ribbon filter paper and analyzed for P, K, Ca, Mg, Na, Fe, Zn, Cu, Mo and Mn using ICPMS. Four replicates were prepared of each extraction and analysis. The water extractable nutrient concentrations in mg per g dry weight were calculated, and the amounts of water extractable nutrients in percent of total were estimated using Equation 1.

Equation 1:

$$\textbf{percentage of nutrient extraction}\ (\%) = \frac{\text{Nutrient liquid extracted } (\frac{\text{mg}}{\text{g}})}{\text{Nutrient digest analysis of the material } \left(\frac{\text{mg}}{\text{g}}\right)} \text{x100}$$

3.5 Assessment of aerobic mineralization and element extraction from the organic substrates over time

The aerobic mineralization and extraction of elements from the organic test substrates was done in a closed room (Figure 5). The set-up included 30 plastic containers of 2 L with lid, each wrapped with aluminum foil to prevent algae growth and maintain the thermal stability of the solution. In each lid two openings were made, one to pass the aeration pipe through, and another for air release. A membrane pump was used to inject ambient air into the solution via a silicon tube caped with an air stone. The temperature and dissolved oxygen concentration of/in the fermentation liquid was recorded using a benchtop dissolved oxygen meter (DIOBASE, model PH-810).

Figure 5: Aerobic fermentation system setup.

The plastic containers were each filled with 1 L of deionized water. Samples of autoclaved (compost and biosolids), dried and ground organic substrates were weighed into nylon mesh bags. One bag was then placed into each plastic container and submerged in water. The bags contained either 3 g, 6 g or 9 g of dry organic material. Three replicates were prepared of each treatment. Subsamples of the extraction solutions were taken every 3rd day over a period of 23 days. These samples were passed through Blue Ribbon filter paper before element concentrations were measured using ICPMS and a N autoanalyzer (see Chapter 3.3). Whenever subsamples were taken, the oxygen meter was used to measure the percentage of dissolved oxygen and temperature. The electrical conductivity (EC) and pH of the solution was also recorded using a Hanna pH and EC meter. After each sampling, the solution remaining in each plastic container was weighed, and deionized water was added until the original weight at the time of experimental set-up was re-established. From the chemical analysis data, the concentration of each nutrient in the extractant over time was compared between the different treatments of the experiment. The amounts of nutritional elements extracted in percent of total element contents in the added organic materials were calculated.

3.6 Comparative evaluation of the ability of organic substrate extracts to support the growth and element uptake of hydroponic plants

A greenhouse experiment was conducted to compare growth and element uptake of young hydroponic cucumber and corn plants supplied either with a mineral nutrient solution, or organic substrate extracts.

3.6.1 Preparation of the standard mineral nutrient solution

The standard nutrient solution was prepared according to Neumann et al. (2010), with element concentrations and applied forms stated in Table 1. The solution was prepared by pipetting stock solutions for N, P, K, Mg and micronutrients into tap water. To supply the solution with Ca, $CaSO_4$was added in solid form.

Table 1: Element composition of the standard mineral nutrient solution

Element	**Concentration of element**	**Applied form**
N	5 mM	$Ca(NO_3)_2.4H_2O$
Ca	3.5 mM	$Ca(NO_3)_2.4H_2O$ and $CaSO_4.2H_2O$
S	1.5 mM	$CaSO_4.2H_2O$
P	0.5 mM	KH_2PO_4
K	1.5 mM	KH_2PO_4 and K_2SO_4
Mg	0.6 mM	$MgCl_2.6H_2O$
B	56 µM	H_3BO_3
Fe	40 µM	Fe-EDTA
Mn	3.6 µM	$MnSO_4$
Zn	1.5 µM	$ZnSO_4$
Cu	1.6 µM	$CuSO_4$

(Source: Neumann et al., 2010)

3.6.2 Organic substrate based nutrient solution preparation

Thirty L of organic substrate based nutrient solution was prepared from each, dried cucumber leaves and biosolids at the same time (Figure 6). Each type of organic nutrient solution was prepared in three buckets, each with lid and filled with 10 L of deionized water. The liquid was aerated with two air pumps (Regent 9500 240 L/h air pump). The air was distributed evenly across all buckets using a main silicon pipe and lateral smaller silicon pipes connected with syringe needles. A 60 g of organic material was added to each bucket in a nylon mesh bag that was hung into the water. To prevent anaerobic processes within a large bulk of organic material, the 60 g portions were divided into 6 sub-portions within the same mesh bag using cable binders (Figure 7). After four days of aerobic extraction and mineralization, the organic solutions were frozen at -20ºC until used in the experiment. Before freezing, a subsample of 50 ml was taken for element analysis. Before being used in the experiment, the organic extracts were brought to room temperature and $CaSO_4$ was added at the same rate as to the standard mineral solution.

Figure 6: Buckets and aeration system used for extraction.

Figure 7: Nylon bags filled with organic test materials.

3.6.3 Seedlings preparation

Two different plant species were tested for their performance in hydroponic culture based on either the standard mineral solution, or one of the two organic extracts. To establish the plants, 100 cucumber F1 seeds (*Cucumis sativus*. “Zeco”) representing a dicot species, and 100 super sweet corn F1 seeds (*Zea mays var. saccharate.* “Warwick”), representing a monocot, were sown. The seeds were germinated on paper tissues soaked with a saturated $CaSO_4$ solution under greenhouse conditions, where the average temperature was 25°C during the day, and the average relative humidity was 80%. The seeds were germinated on 20 cm long sheets of double aluminum foil wrapped around the wet paper towels. They were lined up horizontally along the upper rim of the foil as a temporary seed bed. The foil was folded vertically with width of 10-14 cm (Figure 8). The seeds start germinating after 3 days and were transplanted to the hydroponic system at day 6 (Figure 9)

Figure 8: Cucumber and super sweet corn seeds germination.

Figure 9: Cucumber and super sweet corn seedlings were transplanted to the hydroponic system.

3.6.4 Hydroponic plant culture

The plant experiment was set up as completely randomized. One replicate comprised of a 1 L plastic container wrapped with aluminum foil, which was filled with 900 ml of either the standard mineral nutrient solution, or an organic substrate extract, prepared either from cucumber leaves or biosolids. Each container was used to grow 4 seedlings of the same plant species, either cucumber or corn. A Styrofoam sheet wrapped with aluminum foil was placed as a lid on top of each solution container. It had four holes into which the seedlings were inserted. The hypocotyls of the plants were wrapped with a piece of kitchen sponge to hold them in place. Each treatment had four replicates, resulting in eight growing containers for each solution type (Figure 10). The solution was replaced once in four days.

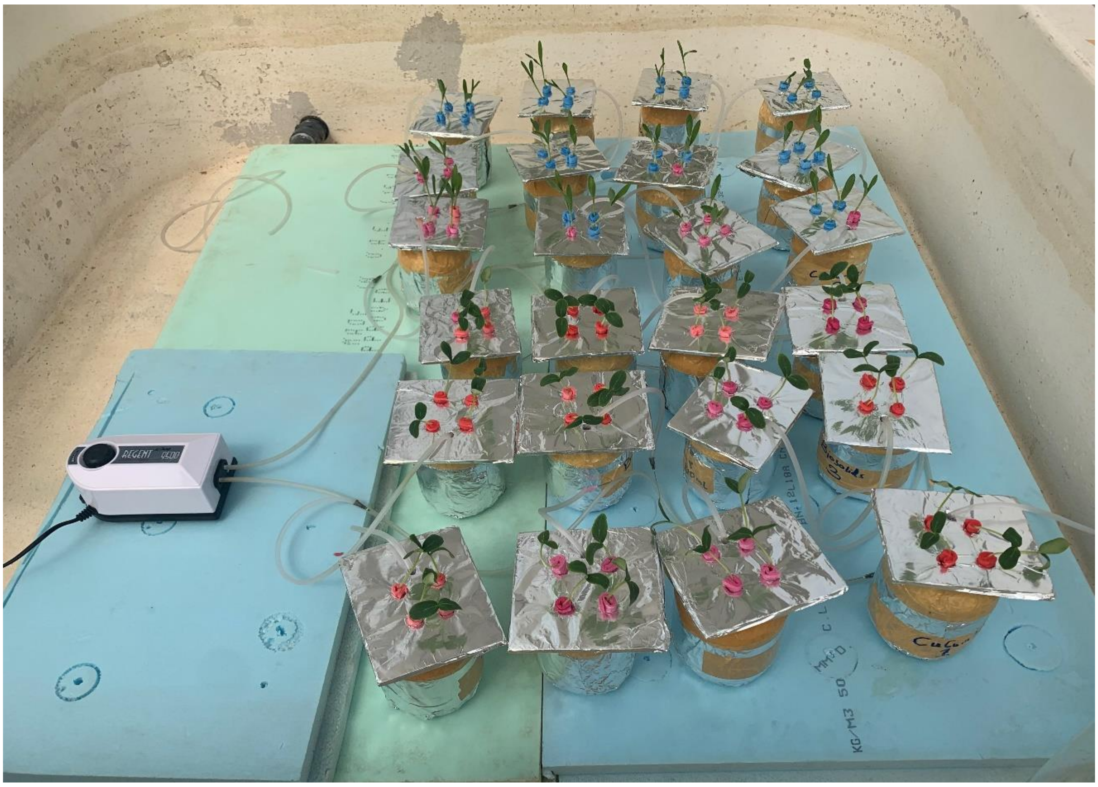

Figure 10: System setup of plant culture test of the different solutions.

3.6.5 Assessment of plant performance

Two randomly chosen plants of the four plants of each replicate were harvested twelve days after having been transferred to hydroponic culture. The plants were rinsed with deionized water, separated into their shoot and root tissues, and then dried at 60ºC in a drying oven. The plant dry weight was then estimated. Element concentrations in the dry plant material were then measured as described in Chapter 3.3.

3.7 Statistical Analysis

The results were presented as mean values and standard deviations. Data were tested using statistical analysis in IBM SPSS statistics 26 software. Means were compared using t-tests and One Way ANOVAs at significance level of $P < 0.05$. Differences between means of the treatments were compared by the Tukey's Multiple Comparison. A Two-Way ANOVA was performed on the data obtained for the experiment investigating the element release from organic materials into aerated water over time. The analysis revealed whether there was a significant effect of the duration of the extraction (factor 1), or the amounts of substrate used (factor 2), and whether there was a significant interaction between both factors. The significance level was $P < 0.05$.

Chapter 4: Results

To test the stated hypothesis, sequential experimental work was done. In a first step the original organic substrates were analyzed and water extracted. This was followed by an experiment assessing the release of plant nutritional elements from the organic test substrates into an aerated water over the course of 23 days. Based on the findings of first part of the study, a plant experiment was performed to study the ability of some organic extracts to serve as nutrient solutions for hydroponic cucumber and corn plants. The experimental plants were grown in the test solutions for twelve days before they were harvested, and their weight and tissue element concentrations were assessed.

4.1 Element concentrations in the organic test substrates used for the preparation of extracts

Nitrogen, P and S concentrations were highest in biosolids (Table 2), while K and Mg concentrations were highest in the cucumber leaves. However, Ca and Na concentrations were significantly higher in compost compared with the other materials (Table 3). Micronutrient concentrations in the different raw materials are shown in Table 4. Iron, Zn and B concentrations were highest in biosolids, while Mn concentrations were highest in the compost material. The Cu and Mo concentrations were higher in cucumber leaves compared with all other materials.

Table 2: Organic test materials nitrogen, phosphorous and potassium mean concentrations

	N	***P***	***K***
Cucumber leaves	32.57±0.38 B	4.95±0.13 A	21.14±0.34 C
Compost	21.03±0.45 A	9.16±0.33 B	12.19±0.29 B
Biosolids	35.00±1.06 C	26.98±0.50 C	1.57±0.003 A

Table 3: Organic test materials calcium, magnesium, sodium, and sulfur mean concentrations

	Ca	***Mg***	***Na***	***S***
Cucumber leaves	38.09±2.96 A	11.29±0.35 C	0.94±0.07 A	9.04±0.08 B
Compost	48.17±0.35 B	6.58±0.47 A	1.99±0.07 C	4.47±0.04 A
Biosolids	37.99±0.37 A	10.14±0.15 B	1.16±0.05 B	14.51±0.48 C

(P≤0.05)

Table 4: Organic test materials micronutrient mean concentrations

	Fe	***Cu***	***Mn***	***Zn***	***B***	***Mo***
Cucumber leaves	106.03±3.700 A	235.53±13.40 C	98.23±1.55 A	57.67±3.46 A	204.10±13.98 B	39.85±6.33 B
Compost	1601.2±208.91 B	34.37±0.67 A	272.8±9.95 C	186.03±10.42 B	59.17±7.23 A	2.5±1.05 A
Biosolid	9419.77±477.24 C	199.93±8.08 B	217.80±5.45 B	573.07±17.23 C	232.33±2.63 C	4.40±5.25 A

(P≤0.05)

4.2 Nutritional elements released from organic test substrates by extraction with hot or cold water

A liquid extraction of nutrients from the different organic materials was done using either cold or hot water. Hot water extraction of cucumber material increased Na, P, Zn, Mn, and Mo retrieval compared with the use of cold water. For compost, extraction with hot rather than cold water resulted in higher K, Mg, Fe, Cu, Zn, and Mo release. In biosolids hot water extraction led to higher release of all nutritional elements. extraction.

4.2.1 Water extractable sodium percentage

Mean water extractable Na was found to be the highest in biosolids followed by compost and lastly by cucumber (Figure 11). Using hot instead of cold water for extraction slightly increased amounts of retrieved Na across all materials. sodium extraction rates were relatively high, ranging from 81 to 99%.

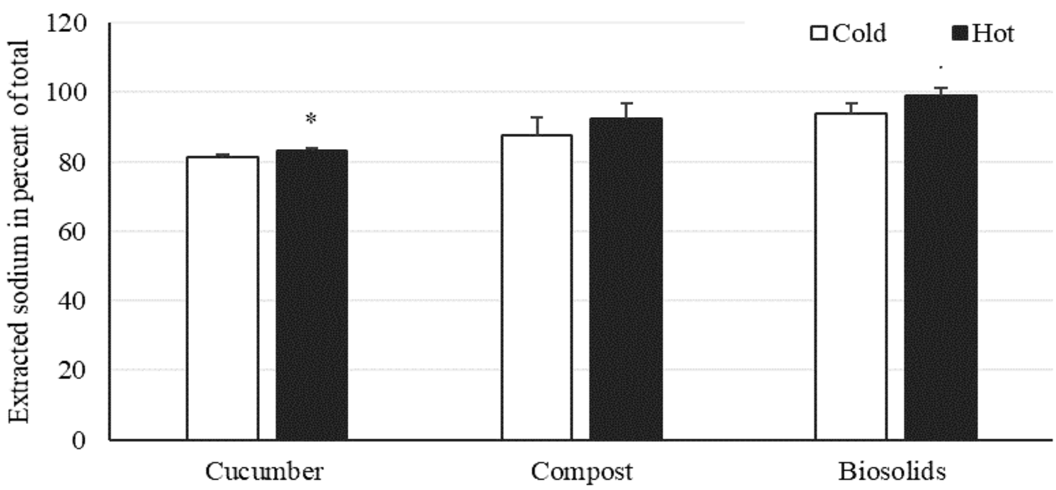

Figure 11: Cold and hot water extractable sodium in percent of total amounts measured in corresponding microwave digested materials.

4.2.2 Water extractable phosphorous percentage

The cold-water extractable P fraction was highest in biosolids, followed by compost and cucumber (Figure 12). Hot rather than cold water extraction increased P release from cucumber and biosolids, but not compost. Percentages of P extracted were far lower compared with those reported for Na, remaining below 20% of total P across all treatments.

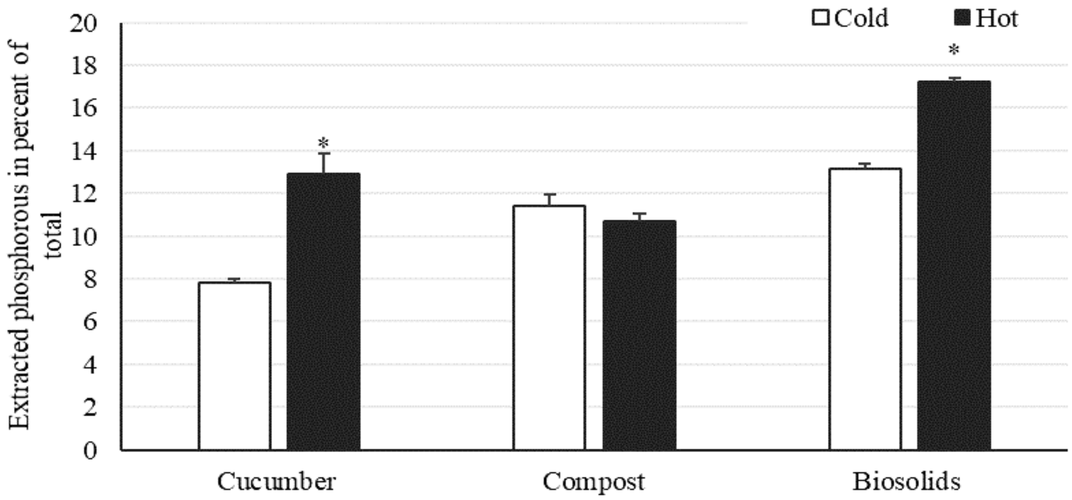

Figure 12: Cold and hot water extractable phosphorous in percent of total amounts measured in corresponding microwave digested materials.

4.2.3 Water extractable calcium percentage

The cucumber material released far greater proportions of Ca compared with compost and biosolids when water extracted (Figure 13). Using hot instead of cold water increased Ca extraction from biosolids but not from the other materials. Only around two percent of total Ca were extracted from biosolids, while cucumber leaves released around 40% of the calcium they contained.

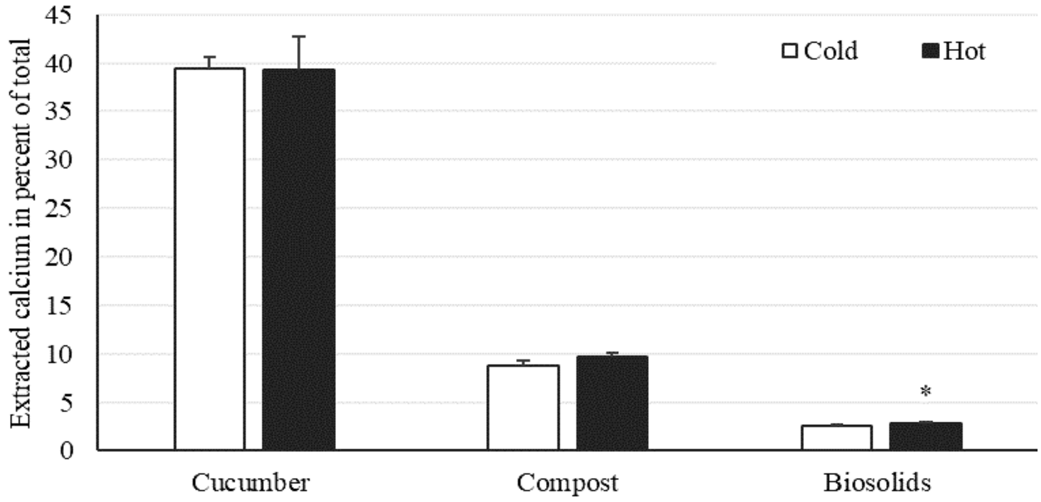

Figure 13: Cold and hot water extractable calcium in percent of total amounts measured in corresponding microwave digested materials.

4.2.4 Water extractable magnesium percentages

Similar with Ca, the percentages of total Mg released from cucumber material into the extraction water were far higher compared with corresponding values for compost and biosolids (Figure 14). Hot-water extraction increased Mg release compared with the use of cold water from biosolids and compost, but not cucumber leaves. The latter released almost the entire Mg they contained, irrespective of the water temperature.

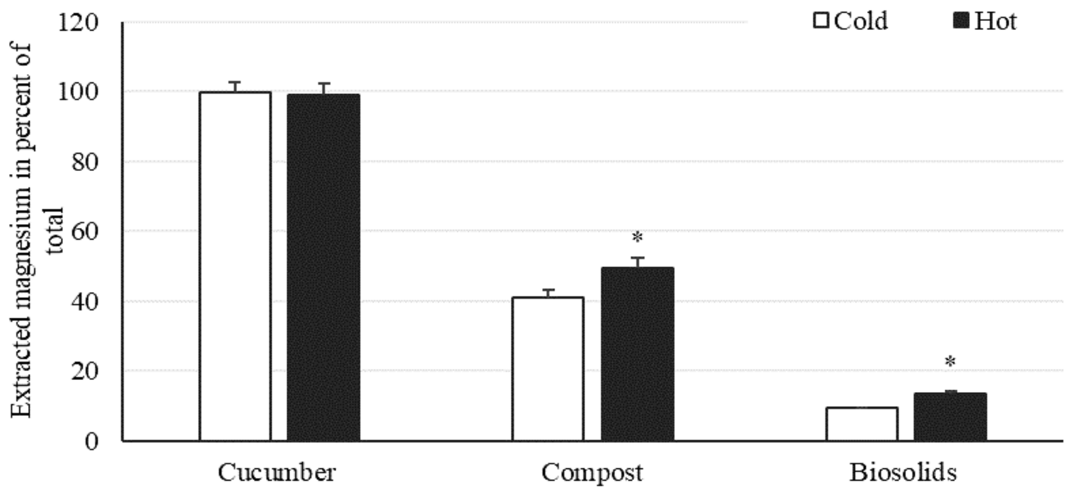

Figure 14: Cold and hot water extractable magnesium in percent of total amounts measured in corresponding microwave digested materials.

4.2.5 Water extractable sulfur percentages

Mean water extractable S percentages were highest in cucumber leaves, followed by biosolids and lastly by compost (Figure 15). Maximum percentages of S extracted from cucumber leaves were above 100%, suggesting an inaccuracy in the measurement. The extraction of S remained largely unaffected by the temperature of the water. Sulfur extraction from biosolids was slightly increased when hot rather than cold water was used.

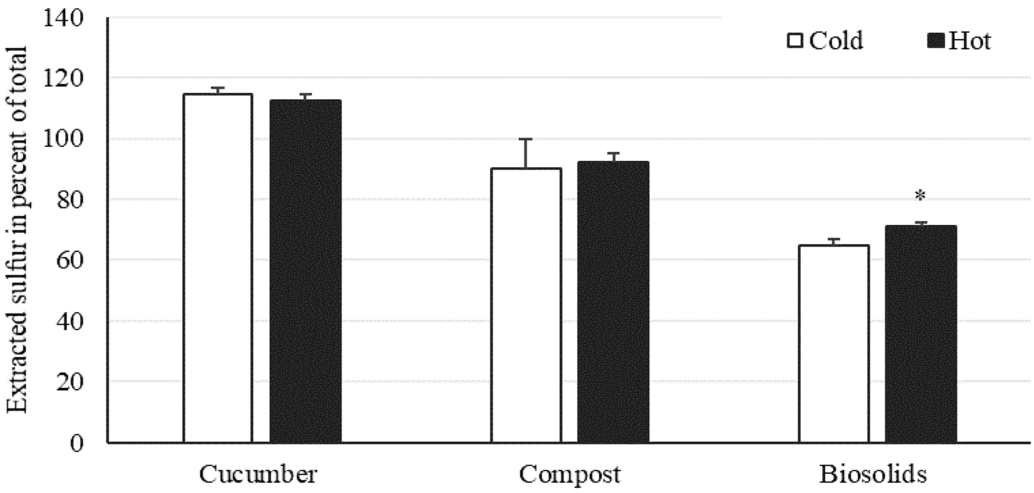

Figure 15: Cold and hot extractable sulfur in percent of total amounts measured in corresponding microwave digested materials.

4.2.6 Water extractable micronutrient percentages

Water extractable portions of micronutrients, except for Cu, were found to be the highest in cucumber, followed by compost and biosolids (Figures 16-20). The water extractable Cu percentages were highest for compost, followed by cucumber and biosolids. For Fe and Mn water extractable fractions were below 10% of total contents across all tested materials, while extractable Zn and Cu percentages remained largely below 25%. Particularly low percentages of Zn, Cu, Mn and Fe were water-extracted from the biosolids. Compared with these metals, water extractable portions of Mo were higher across all treatments and reached around 100 percent in cucumber. Water-extractable Mo was strongly increased from all tested materials when the extraction water was hot rather than cold. For compost and biosolids the water extracted amounts of Fe, Cu and Zn were increased by high water temperature, while increasing temperature was not able to increase Fe, Cu, Zn or Mn from cucumber leaves.

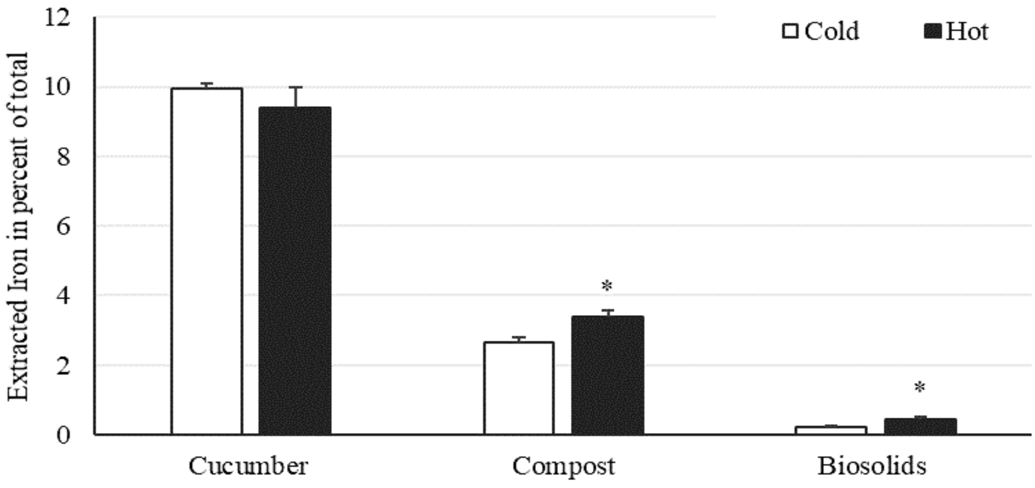

Figure 16: Water extractable Iron in percent of total amounts measured in corresponding microwave digested materials.

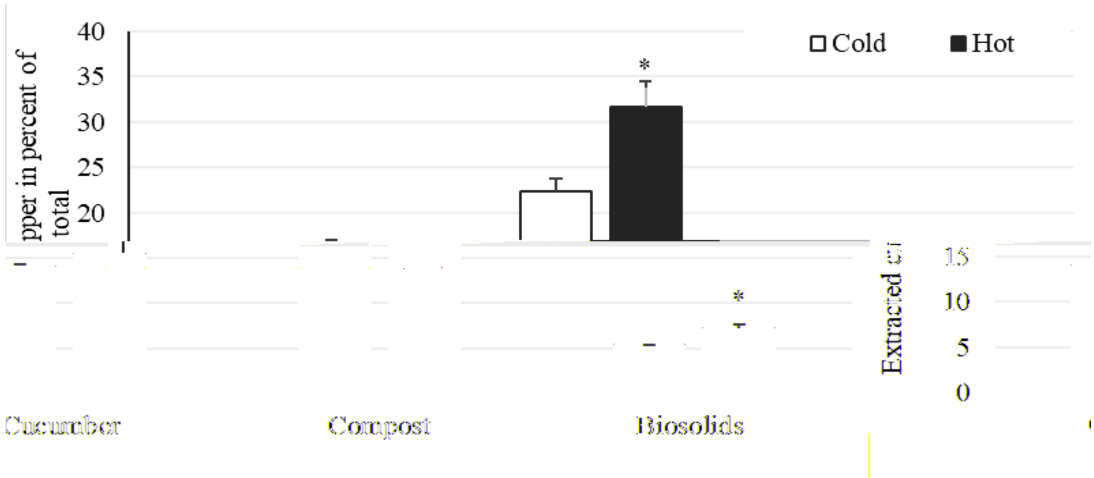

Figure 17: Water extractable Cupper in percent of total amounts measured in corresponding microwave digested materials.

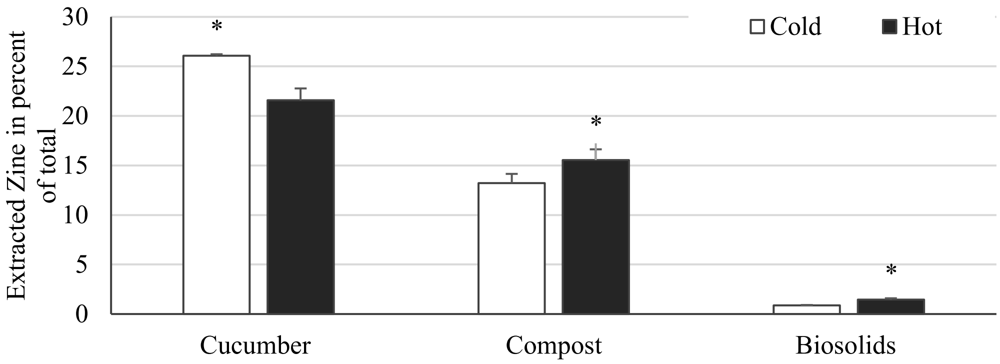

Figure 18: Water extractable Zinc in percent of total amounts measured in corresponding microwave digested materials.

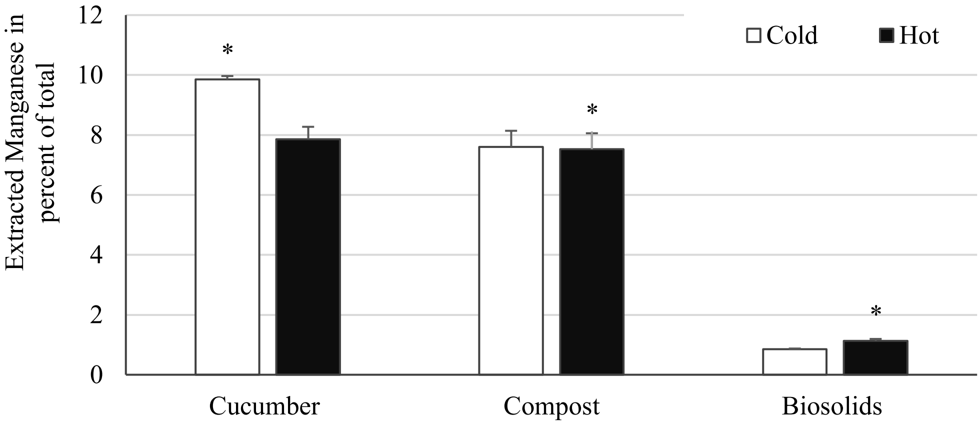

Figure 19: Water extractable Manganese in percent of total amounts measured in corresponding microwave digested materials.

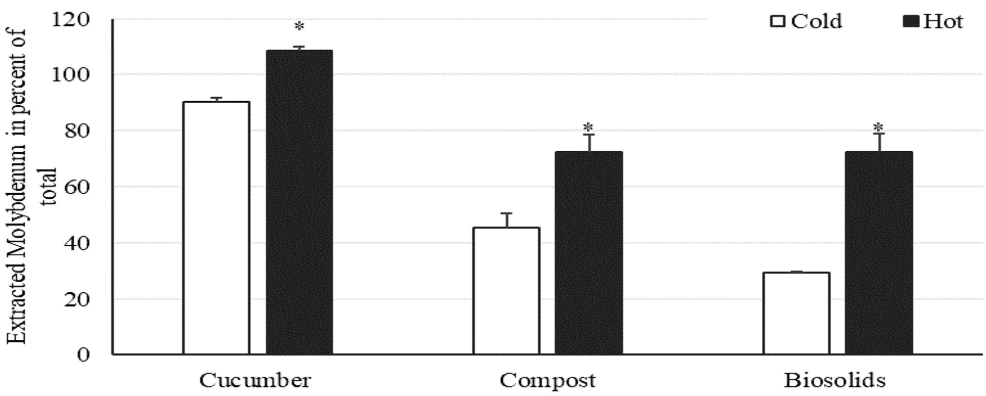

Figure 20: Water extractable Molybdenum in percent of total amounts measured in corresponding microwave digested materials.

4.3 Nutrient concentrations in the aerated solution surrounding nylon bags filled with organic test substrates over time

4.3.1 Concentration of nitrogen in the extraction and mineralization solution over time

The average N concentration in the solution prepared from cucumber leaves cucumber extractant was highest during the first 3 – 5 days after set-up of the experiment (Figure 21). Thereafter the concentrations remained between approximately constant between 50 and 100 mg per L, which is within the range of the N concentration of mineral hydroponic solutions commonly used for vegetables. After the first three days the N concentration in the cucumber solution was higher when higher amounts of organic matter had been put into the water, but there was no such difference at later sampling dates. The amounts of N found in the compost extract did show a clear trend over time, and remained approximately in the same range across all three application rates throughout the entire experiment. During the first 15 days the N concentrations were higher for treatments that had received higher amounts of material, but such differences were absent thereafter. The N concentrations in the biosolid constantly increased over time across all application rates, from approximately 50 to 100 mg per L. In the biosolid solution the N concentration remained higher for the higher application rate treatments throughout the entire test period. In none of the tested materials did the doubling or tripling of the amount of organic matter applied per L lead to a corresponding effect on N concentrations. Across all materials the N release per unit of dry material decreased with increasing application rate of organic material to the aerated water.

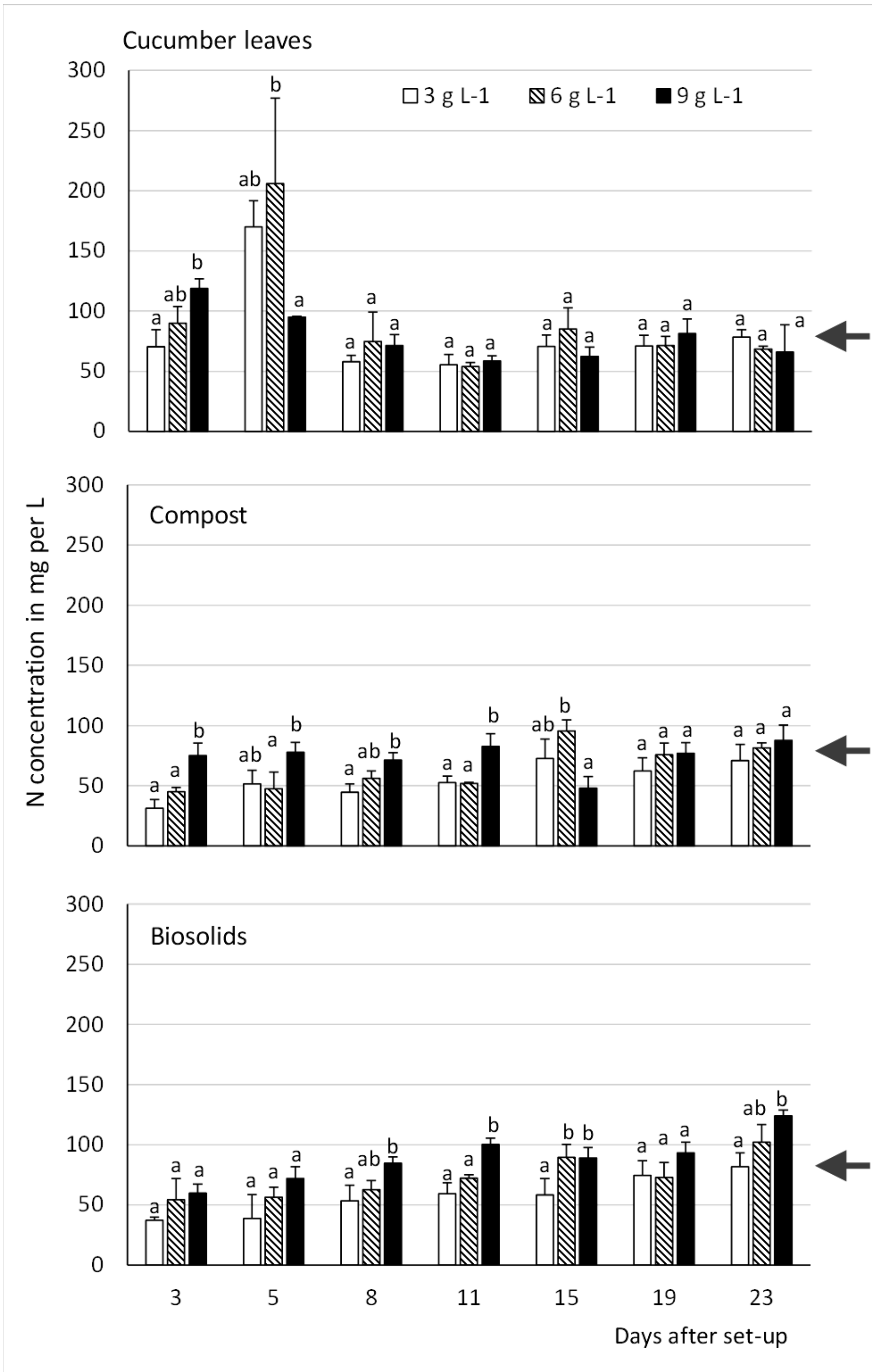

Figure 21: Concentrations of nitrogen in aerated solution

4.3.2 Concentration of phosphorus in the extract solution over time

The concentrations of P in the solutions prepared from cucumber leaves and compost were far below those usually found in mineral nutrient solutions for hydroponic plants (Figure 22). For both materials, the P concentrations were highest by 3 days after set-up, and then either slightly declined (cucumber leaves) or remained approximately constant (compost) over the remaining time of the trial. The net P release into the solution by both materials was largely unaffected by the quantities of material that had been filled into the nylon bags. This suggests that the P release per g of dry material declined with increasing amounts of cucumber leaves or compost added per L of aerated water.

Different from the cucumber and compost material, biosolid extraction and mineralization established a solution that contained P in concentrations comparable with those found in horticultural mineral nutrient solutions. The P concentrations in the biosolid solution remained approximately constant throughout the first 15 days after set-up, and then declined. Increasing amounts of biosolid added to each L of water led to corresponding increase in the P concentration of the solution, irrespective of the sampling time.

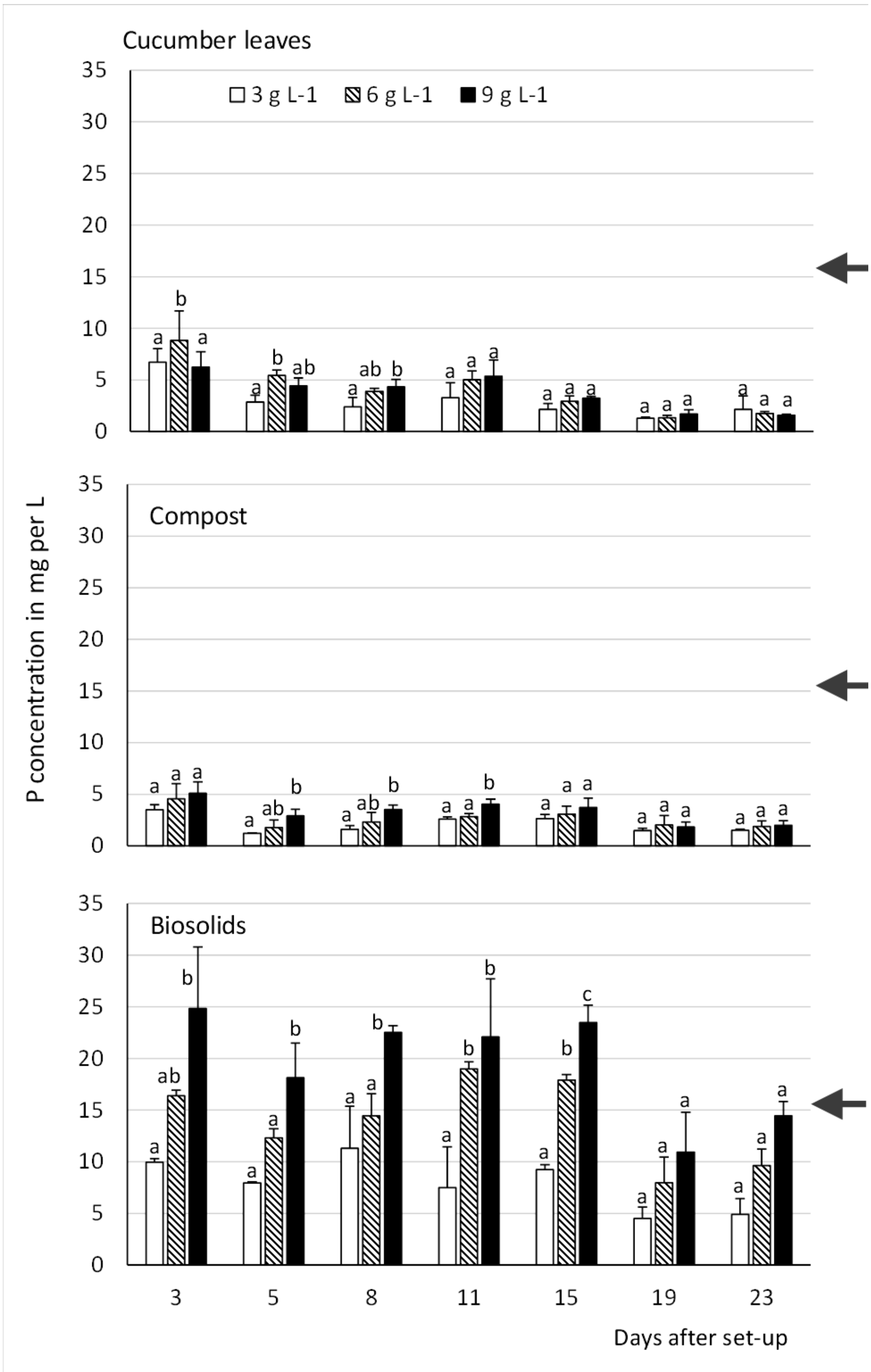

Figure 22: Concentrations of phosphorous in aerated solution

4.3.3 Concentration of basic cations in the extract solutions over time

While nutrient solutions prepared from biosolids had much higher P concentrations compared with those extracted from cucumber leaves and compost, the opposite was the case for concentrations of K (Figure 23). The latter remained far below levels usually found in hydroponic solutions and varied only little depending on the quantities of material that had been added to the aerated water. The concentrations of K in the cucumber and compost solution were in the same range as those in commercial solutions (compost), or even higher that that (cucumber). They were in the highest range by 3 days after set-up, and then remained approximately constant at a slightly lower level until 15 days after set-up. Across all materials the K concentrations were lower by 19 and 23 days after set-up. In both, cucumber and compost, the solution K concentration increased proportionally with increasing amounts of material applied to the water. The K concentrations in the cucumber solutions were approximately twice as high as those in corresponding compost solutions.

Similar with K, the concentrations of the divalent cations Ca (Figure 24) and Mg (Figure 25) were highest in solutions prepared from cucumber leaves, making the cucumber solution the one with the highest concentrations of basic cations. However, while Mg concentrations were in approximately the same range as commercial mineral nutrient solutions for hydroponic plants, the Ca concentrations remained far below these across all treatments. The lowest amounts of basic cations were released by biosolids. calcium and Mg in the biosolid solution neither changed much over time, nor was there an effect of the amounts of material that had been applied. The Ca and Mg concentrations in the compost solution remained approximately constant between

3 and 15 days after set-up, and then declined. They increased slightly with increasing amounts of material applied.

The cucumber solution showed the highest Ca and Mg concentrations by 3 and 11 days after set-up. The lowest concentrations were observed by 19 and 23 days. The Mg but not the Ca concentrations in the cucumber solution increased with increasing amounts of material applied to the aerated water.

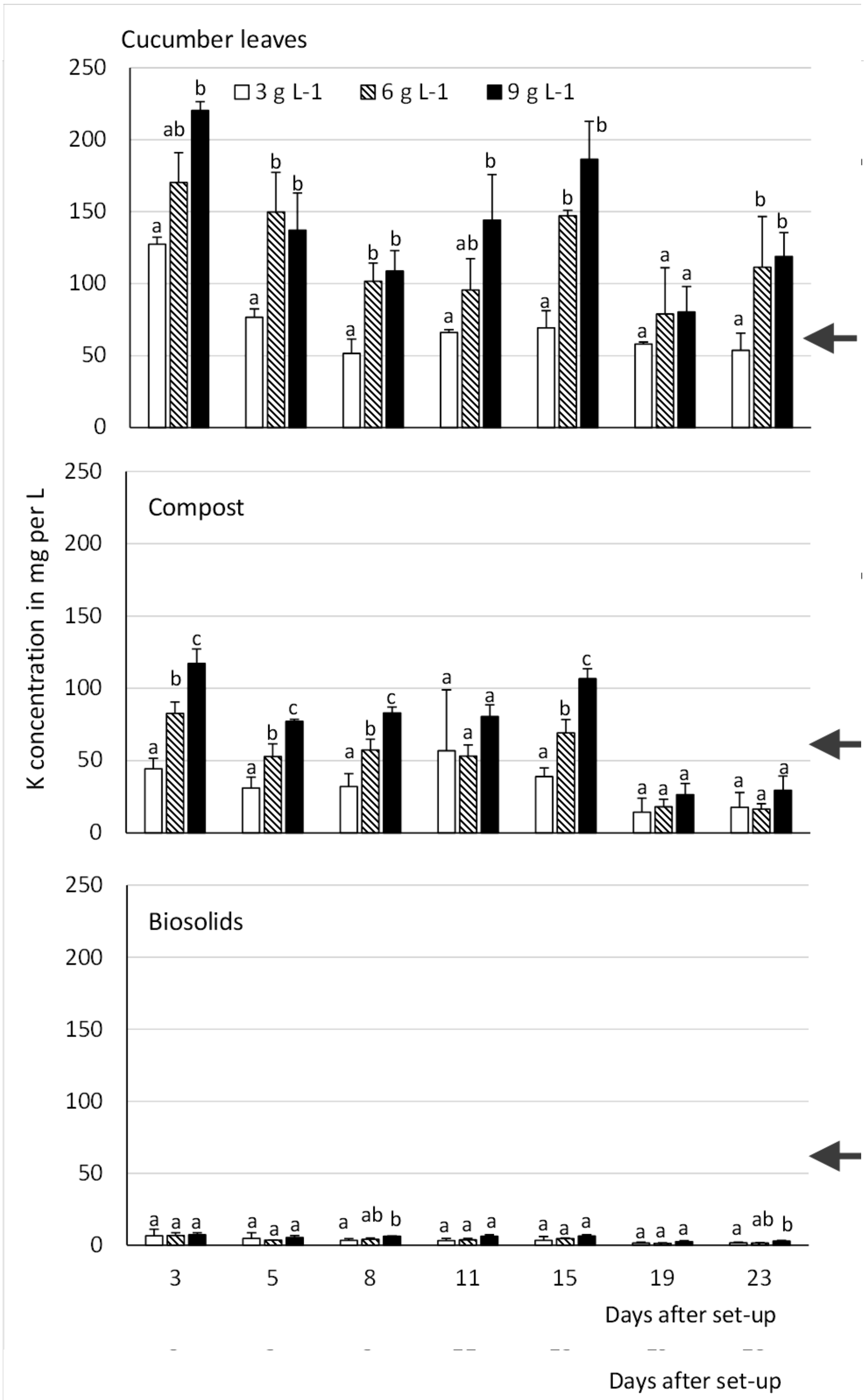

Figure 23: Concentrations of potassium in aerated solution.

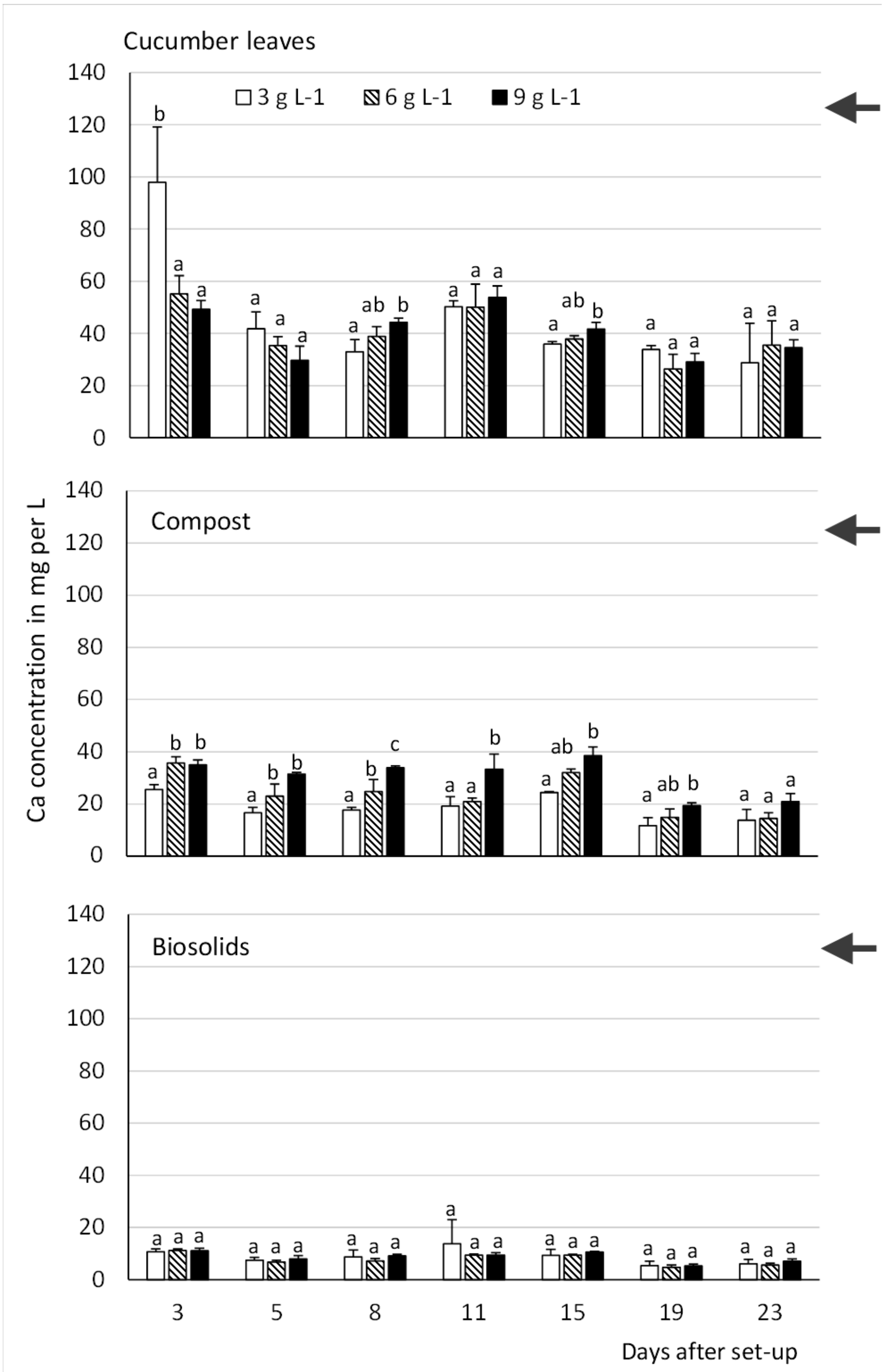

Figure 24: Concentrations of calcium in aerated solution.

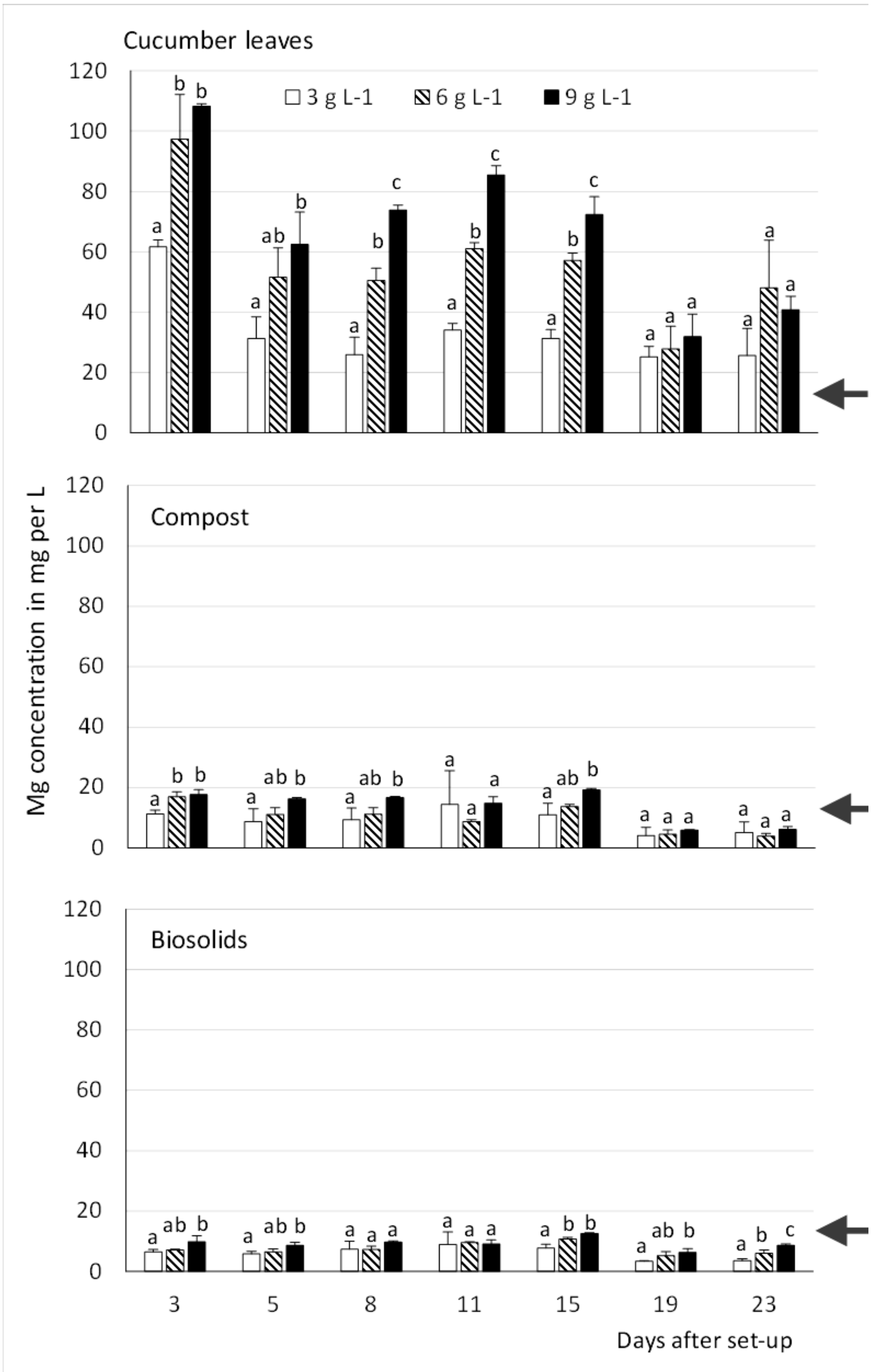

Figure 25: Concentrations of Magnesium in aerated solution.

4.3.4 Micronutrient concentrations in the extract solutions over time

The Fe concentrations in all solutions prepared from organic materials remained far below those in standard nutrient solutions for hydroponic plants (Figure 26). The highest Fe concentrations were found in compost solutions, while amounts released from biosolids and cucumber leaves were approximately in the same range. When compost material was extracted, increasing quantities of material added led to a corresponding increase in the amounts of Fe released. A positive effect of increasing amounts of material on the Fe concentrations in the solution could also be observed in the cucumber and biosolid solutions, even though relative differences were smaller and less consistent. Across all treatments the highest Fe concentrations were found by 3 days and 11 days after set-up. By 19 and 23 days the Fe concentrations were lower compared with the earlier sampling dates, irrespective of the extracted organic material.

Similar with Fe, the highest concentrations of Mn were observed in the compost solutions, especially by 3 days after set-up (Figure 27). However, all solutions prepared from organic materials had Mn concentrations below what is recommended for mineral nutrient solutions. Particularly low concentrations were observed in the biosolid solution, with no difference depending on the time of sampling or the amount of material applied. In the compost solution there was a positive effect of increasing amounts of material applied on Mn concentrations in the solution during the first 11 days after set-up. Thereafter all compost solutions had similar Mn concentrations that were below those observed during the first 11 days. Similar with the compost solution, the highest Mn levels in the cucumber solution were observed by 3 days after set-up.

There was, however, no effect of the applied amount of cucumber material on Mn concentrations in the solution.

While concentrations of Fe and Mn in all solutions prepared from organic materials were below values recommended for mineral hydroponic cultures, the levels of Zn and Cu were mostly in an adequate range. The Cu concentrations in compost and biosolid solution were in a similar range and remained largely constant during the first 15 days after set-up before declining (Figure 28). There was a positive effect of increasing quantities of material applied on the Cu concentrations in the biosolid solution, but this effect was less consistent for the compost treatments. Similarly, there was no consistent effect of the application rate on Cu concentrations in the cucumber solution. The Cu concentrations in the cucumber solution were several times higher than those observed in the other solutions and peaked by 3 days after set-up. Between 5 and 11 days after set-up the concentrations remained approximately constant at a lower level, before declining again during the last two sampling dates.

The concentrations of Zn in the cucumber and biosolid solution were in the same range, while those in the compost solutions were higher (Figure 29). In the cucumber and compost solution increasing amounts of material applied led to increased amounts of Zn in the solution, but no such effect could be observed for the biosolids. Across all treatments the highest Zn concentrations were observed by 3 and 11 days after set-up of the experiment, and the lowest levels were recorded for the last two sampling dates.

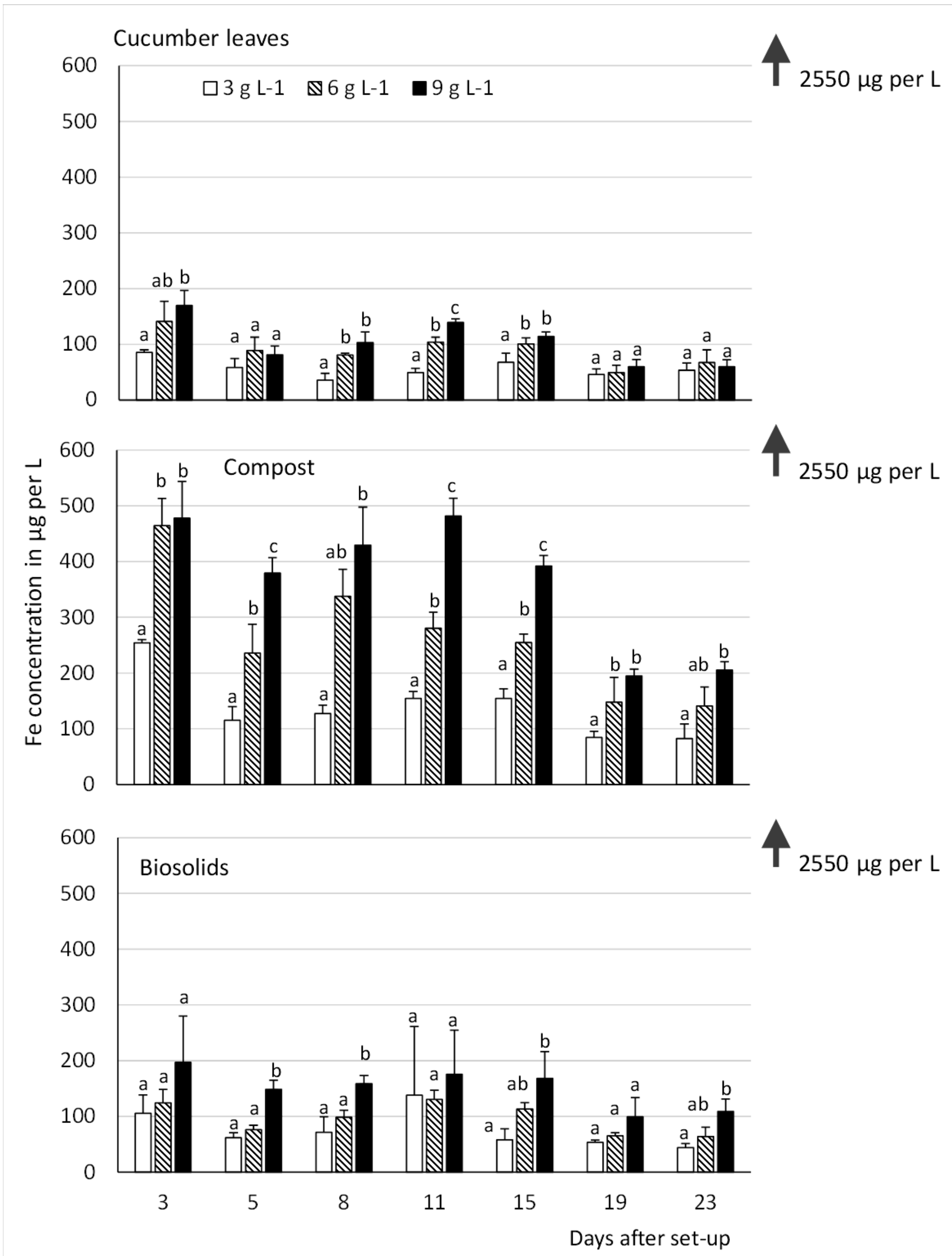

Figure 26: Concentrations of Iron in aerated solution.

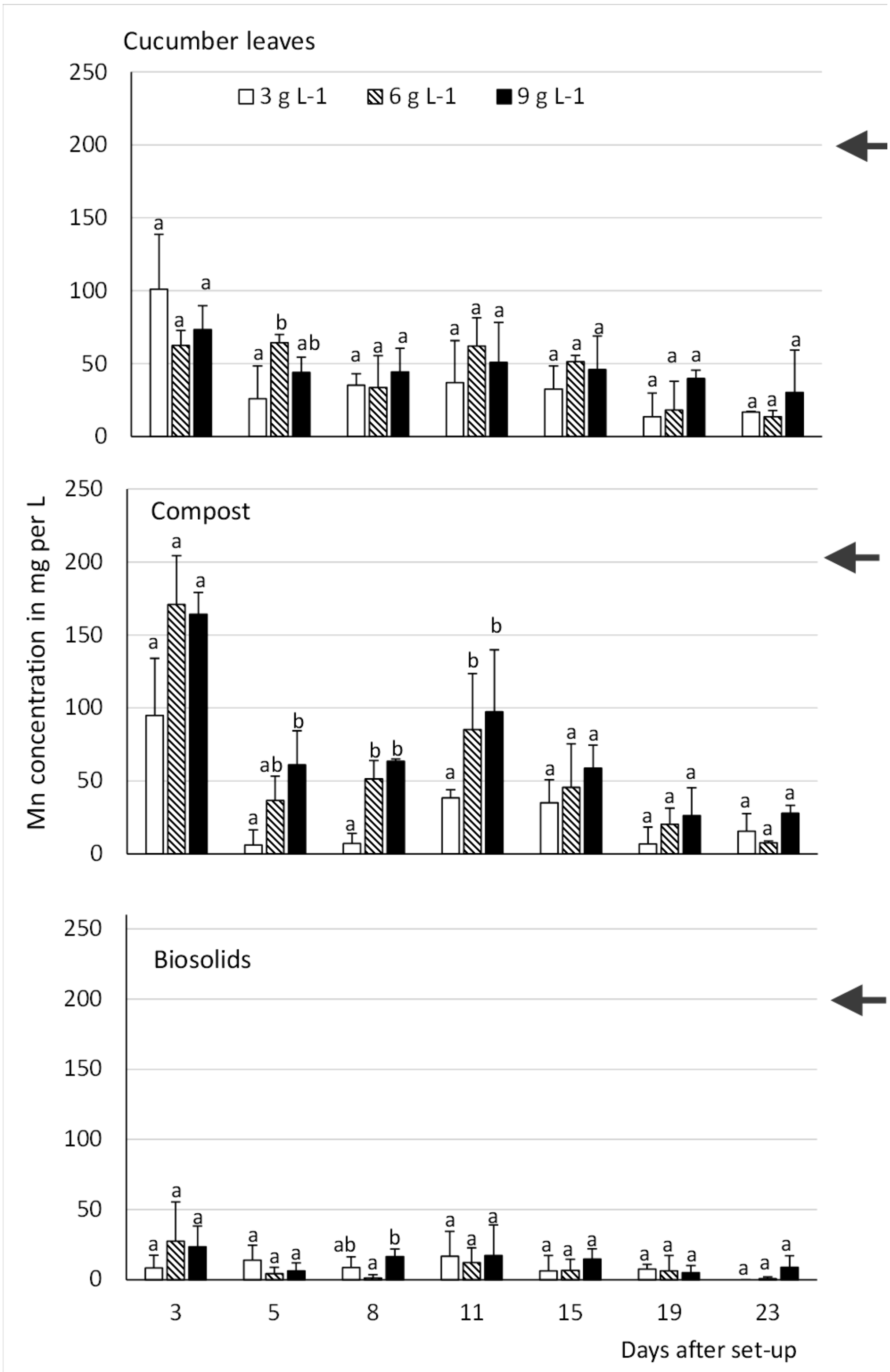

Figure 27: Concentrations of Manganese in aerated solution.

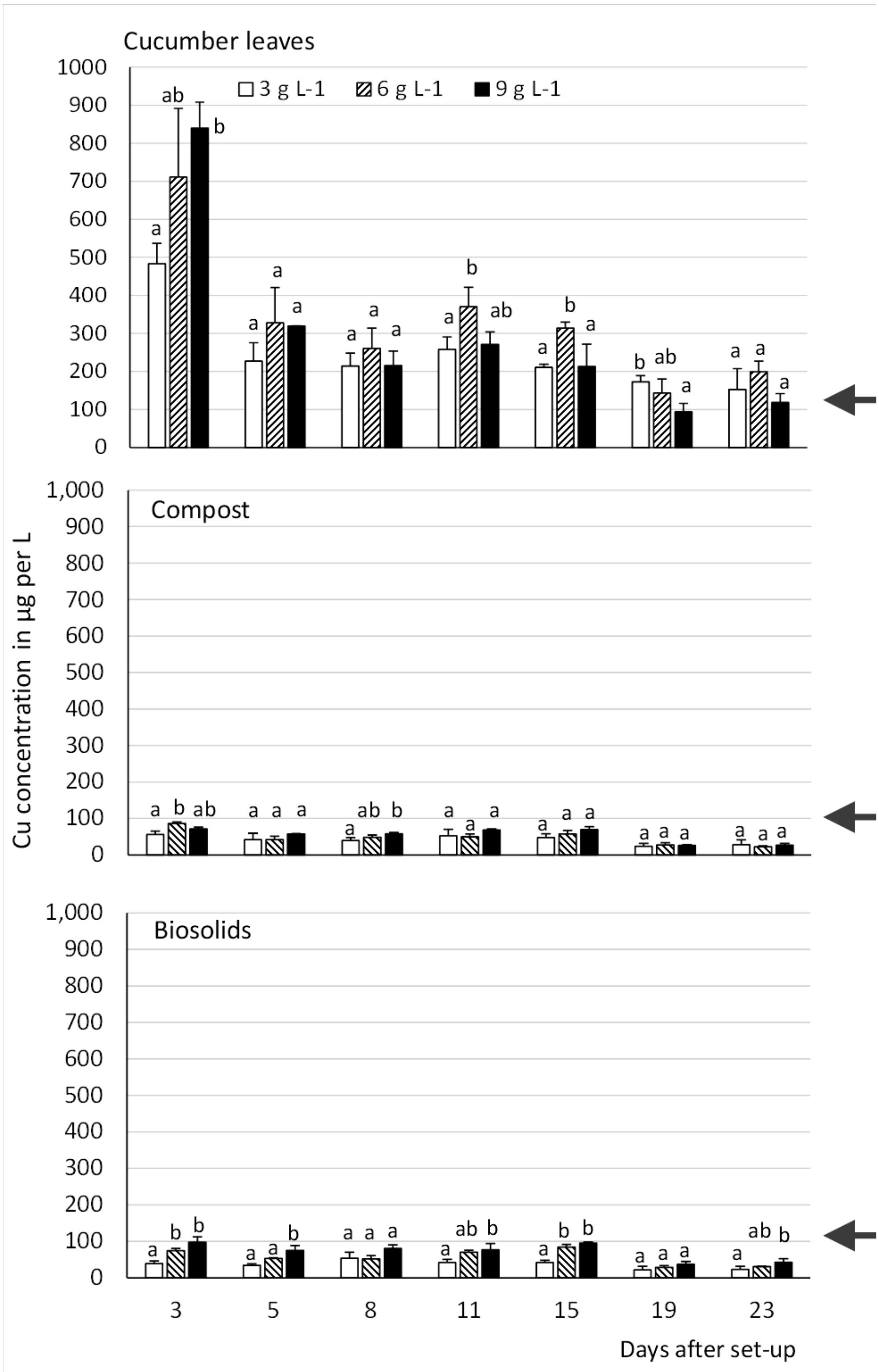

Figure 28: Concentrations of Cupper in aerated solution.

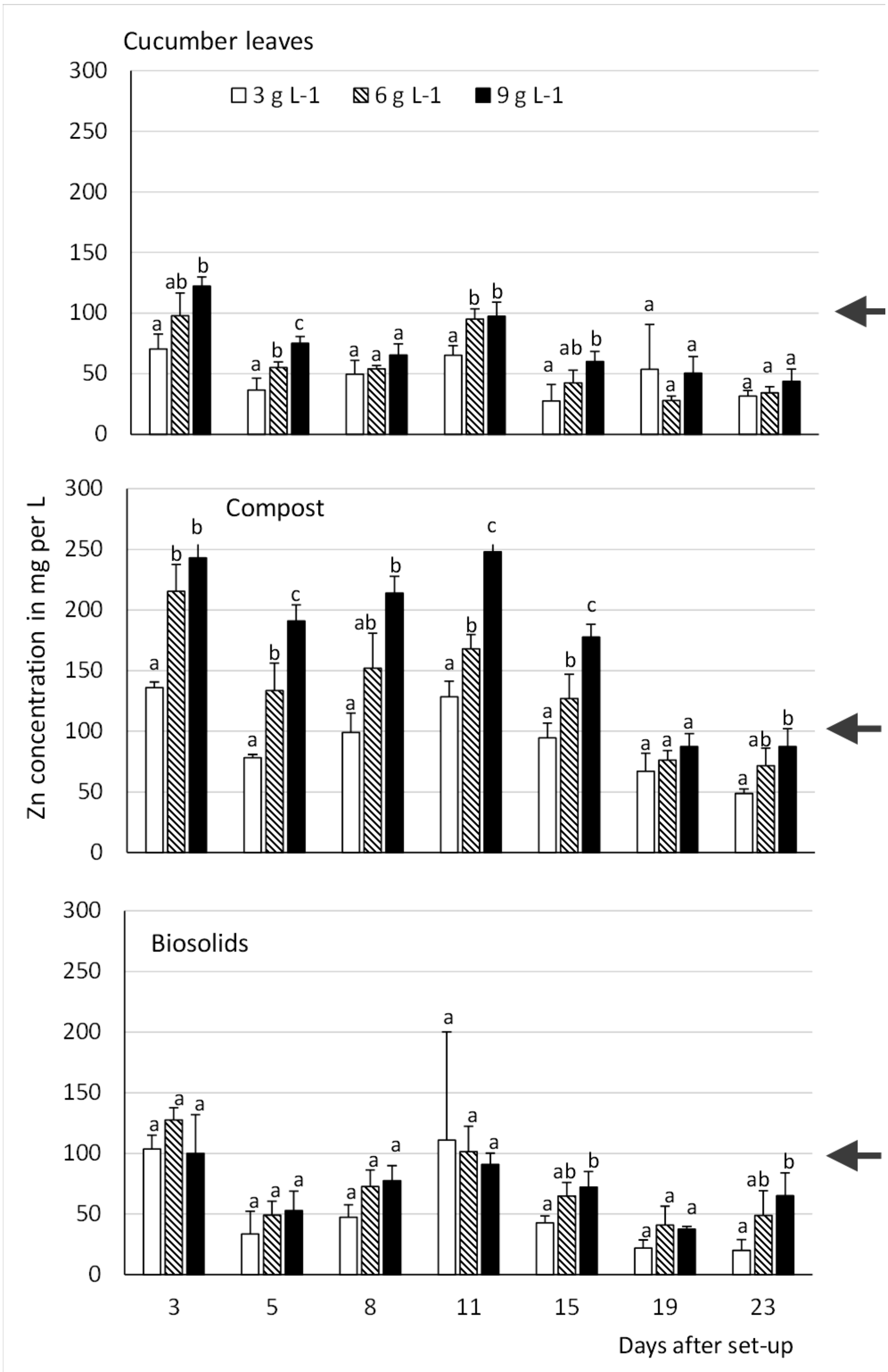

Figure 29: Concentrations of Zinc in aerated solution.

4.4 Organic nutrient solution plant test

The ability of two different nutrient solutions prepared from organic materials to support plant growth was studied in a greenhouse experiment. Biosolids and cucumber leaves were extracted in aerated water for five days, before the solutions were used to grow hydroponic corn or cucumber seedlings. A reference treatment based on a mineral nutrient solution was established. The element concentrations in the shoot tissues, and the dry weights of the plants were measured.

4.4.1 Dry weights of the corn seedlings grown on different nutrient solutions

The total plant dry weight at the time of harvest was lower for plants that had grown on cucumber solution compared with those of the mineral control treatment (Table 5), but there was no difference between the control and the biosolid treatment. As shown in (Figure 30) corn plants that had grown in biosolid solution showed 4.84 times increase in total weight compared to the weight before planting. The cucumber solution plants showed 3.03 times increase in total weight compared with their original weight.

Table 5: Corn mean dry weight (mg) ± SD grown in different hydroponic solutions.

	Shoot dry weight	Root dry weight	Total dry weight
Pre- test seedling	22.00	10.50	32.50
Biosolids	121.87 ± 28.59 AB	68.00 ± 11.29 AB	189.88 ± 36.67 AB
Cucumber	95.5 ± 32.81 A	35.50 ± 14.19 A	131.00 ± 46.78 A
Standard	221 ± 78.03 B	75.38 ± 22.34 B	296.38 ± 92.05 B

($P \leq 0.05$)

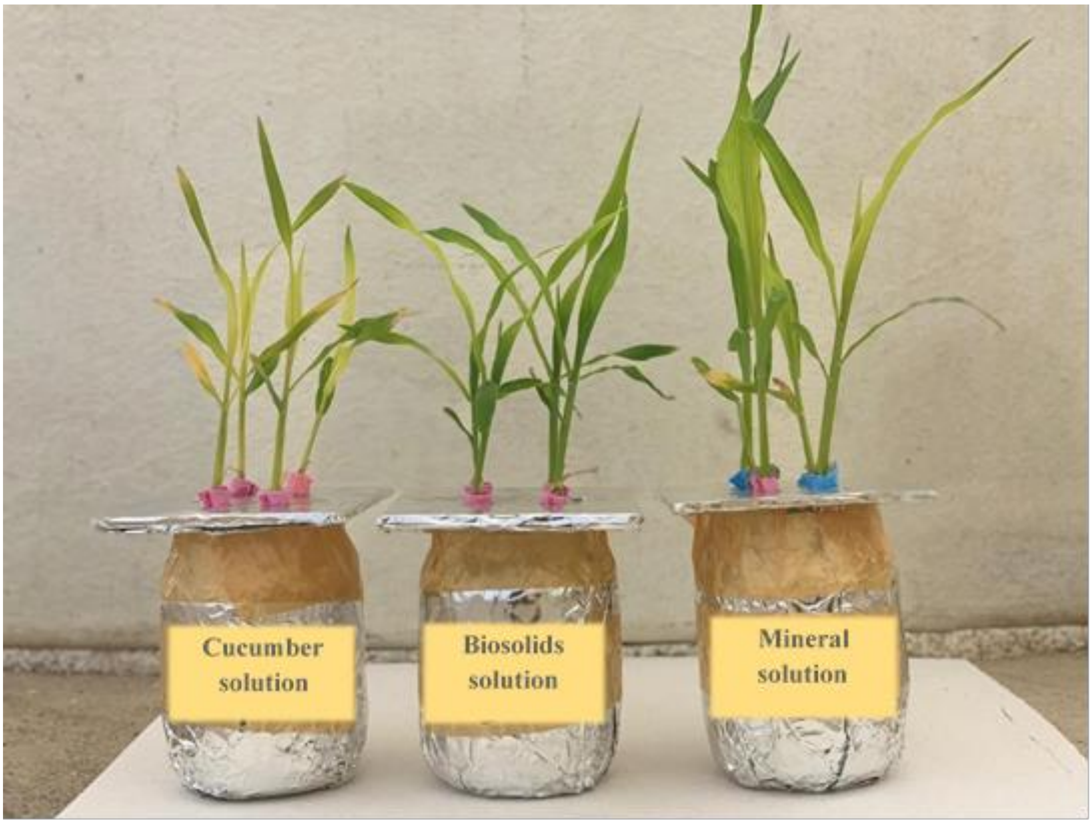

Figure 30: Corn seedlings grown in the different nutrient solutions.

4.4.2 Cucumber seedlings mean dry weight

Cucumber plants that had grown on the biosolid solution showed a higher dry weight compared with the other treatments (Table 6). There was no difference in total plant dry weight between the cucumber and the mineral solution. As shown in (Figure 31) cucumber plants grown in biosolid solution showed a 8.72 times increase in total dry weight compared with the day of planting. Plants grown on cucumber and mineral nutrient solution showed 5.29 and 4.43 times increase in total dry weight compared to their original weight, respectively.

Table 6: Cucumber mean dry weight (mg) ± SD grown in different hydroponic solutions.

	Shoot dry weight	Root dry weight	Total dry weight
Pre- test seedling	21.20	4.30	25.50
Biosolids	211.25 ± 8.59 B	36.5 ± 3.34 B	247.75 ± 11.44 B
Cucumber	128 ± 5.76 A	32.63 ± 1.89 B	160.63 ± 7.54 A
Standard	144.87 ± 25.44 A	18.63 ± 2.81 A	138.50 ± 28.09 A

(P≤0.05)

Figure 31: Cucumber seedlings grown in the different nutrient solutions.

4.4.3 Nutrient composition of corn shoot tissue

Corn plants grown in different nutrient solutions were analyzed to evaluate the effect of the type of solution on the element concentrations in shoot tissues (Tables 7-9). The plants that had grown on the biosolid solution had higher S and lower Mn concentrations compared with those exposed to the mineral solution. When grown on the cucumber solution, corn plants had lower micronutrient concentrations compared with the biosolid and the mineral solution, while the macronutrient concentrations did not differ. Plants grown on either biosolid or cucumber solution had much lower shoot Mn concentrations than plant obtained from mineral solution culture.

4.4.4 Nutrient composition of cucumber shoot tissue

Cucumber plants grown in different nutrient solutions were analyzed to evaluate the effect of the type of solution on the element concentrations in shoot tissues (Tables 10-12). The N levels in cucumber plants were in a similar range across all treatments, while plants that had grown on cucumber solution had much lower P concentrations compared with the other two solutions. The plants that had grown on cucumber solution had lower concentrations of Ca, S, Fe, Mn and Zn compared with the mineral controls. Cucumber plants grown on biosolid solution had lower concentrations of K, Ca, Mg, Cu and Mn compared with those of the mineral control treatment. The tissue concentrations of P, S, Fe and Zn were lower for plants of the cucumber compared with the biosolid treatment, while plants of the cucumber treatment had higher Mg concentrations.

Table 7: Corn shoot tissue concentrations of nitrogen, phosphorous and potassium.

	N*	P	K
Biosolids	5.56	10.50±2.05 B	15.80±4.07 A
Cucumber	4.02	2.25±1.40 A	14.60±8.77 A
Standard	3.74	8.05±3.10 B	27.35±9.46 A

*not mean value

Table 8: Corn shoot tissue concentrations of calcium, magnesium, sodium, and sulfur.

	Ca	Mg	Na	S
Biosolids	5.06±1.14 A	5.39±1.66 A	0.16±0.05 A	6.09±1.05 B
Cucumber	2.47±1.56 A	4.31±2.55 A	0.17±0.16 A	1.69±1.03 A
Standard	5.05±1.60 A	4.54±2.26 A	0.19±0.12 A	3.52±0.98 A

Table 9: Corn shoot tissue concentrations of micronutrients.

	Fe	Cu	Mn	Zn
Biosolids	67.23±26.87 B	24.80±3.49 B	9.85±1.11 A	239.53±80.86 B
Cucumber	26.63±17.19 A	7.88±4.60 A	6.43±3.96 A	47.29±28.35 A
Standard	40.08±7.62 AB	20.38±2.77 B	96.10±30.32 B	143.45±89.71 AB

Table 10: Cucumber shoot tissue concentrations of nitrogen, phosphorous and potassium.

	N*	P	K
Biosolids	5.03	9.48±0.5 B	9.50±1.25 A
Cucumber	4.36	2.15±0.73 A	14.65±4.25 A
Standard	4.74	10.05±1.30 B	26.50±2.28 B

*not mean value

Table 11: Cucumber shoot tissue concentrations of calcium, magnesium, sodium, and sulfur.

	Ca	Mg	Na	S
Biosolids	17.45±3.11 A	4.16±1.07 A	0.16±0.05 A	6.61±1.37 B
Cucumber	17.73±2.36 A	9.06±1.27 B	0.17±0.16 A	3.37±0.47 A
Standard	28.10±3.81 B	5.55±0.56 A	0.19±0.12 B	5.04±0.51 AB

Table 12: Cucumber shoot tissue concentrations of micronutrients.

	Fe	Cu	Mn	Zn
Biosolids	142.60±35.36 B	14.55±3.08 A	15.18±3.00 A	84.53±11.00 B
Cucumber	39.53±5.81 A	13.73±2.72A	10.10±1.72 A	56.23±9.80 A
Standard	118.43±36.88 B	17.10±0.53 A	271.68±79.29 B	87.00±9.04 B

Chapter 5: Discussion

Previous studies testing the performance of hydroponic plants supplied with nutrient solutions deriving from organic materials are rare. Direct addition of organic matter to hydroponic systems may be rather unfeasible, suggesting the use of a mineralization or fermentation process off the hydroponic system. Organic extracts might then be added from there to the system (Shinohara et al., 2011).

The present study involved several laboratory experiments prior to the plant test, allowing for a better understanding of the ability of different organic waste materials to release soluble nutritional elements into an aqueous solution. The results of this study indicate that aqueous extracts of organic waste materials can recycle a considerable amount of plant nutritional elements and are ultimately able to support the growth and nutrient uptake of young plants in a similar way as conventional mineral nutrient solutions. The biosolid solution was superior to the cucumber solution in supporting plant performance.

The chemical analysis of raw materials used in this study indicated that all organic materials contained considerable amounts of nutrients. Cucumber leaves and biosolids were rich in N, Ca and Mg. The cucumber leaves contained considerable amounts of K, while the biosolids were rich in P and micronutrients. These materials are thus a potentially rich source of nutritional elements.

The element concentrations in biosolids were within the range reported in studies of Sullivan et al. (2015) and Giusquiani et al. (1988), where Biosolids usually contain macronutrients ranging between 3 – 8% N, 1.5 - 3.5% P, 0.1 - 0.6% K, 1 – 4% Ca, 0.4 - 0.8% Mg, 0.6 - 1.3% S.

The results of the water extraction (over one hour on a rotary shaker) imply that organic materials respond differently to a heat treatment during extraction. Hot extraction of cucumber material significantly increased the retrieval of Na, P, Zn, Mn, and Mo. For compost, extraction under hot conditions significantly increased Mg, Fe, Cu, Zn, and Mo compared with room temperature. In biosolids hot extraction significantly increased the retrieval of all nutritional elements. High percentages of Mg, S and K could be extracted from the tested organic materials only with water, suggesting that no sophisticated techniques might be needed to recycle considerable amounts of these elements from waste materials.

The results indicate that hot water extraction of organic material is effective in increasing the retrieval of various nutritional elements from biosolids, but not necessarily cucumber residue and compost. This suggests that appropriate extraction technologies have to be identified for each organic material in question. Results obtained by Nuapia et al. (2020) revealed that the extraction of micronutrients from *Moringa oleifera* leaves was increased by increasing the extraction temperature. In the same study the extraction of macro-nutrients was enhanced by increasing the extraction time rather than the temperature.

The results of the long-term mineralization and extraction experiment where organic test substrates were placed in nylon bags and submerged in aerated water for up to 23 days, support the conclusion that the optimum extraction times and mixing ratios vary depending on the organic materials that are used, and the nutritional elements in question. For example, soluble N release from cucumber leaves was highest during the first 3-5 days after set-up of the trial, while the release of N from biosolids increased gradually over time. Such differences might be due to the form and quantity of nitrogen present in the original organic material. In relation to N concentration in original material, cucumber residue had the highest nitrogen concentrations, and it is well possible that some of this was stored in the cytoplasm in form of nitrate which was easily released into the aerated water during the first days of the test period. Thereafter microbial growth in the nylon bags or the surrounding solution might have fixed the nitrogen, and/or a part might have been lost from the solution in form of NH3.

More complex forms of organic nitrogen might be present in the biosolids, which would require microbial activity to be released. The microflora added with the organic materials might certainly also play a role in this context. In the present study the biosolids and compost had been autoclaved and the cucumber material dried at a relatively high temperature. Both treatments have likely reduced the microbial inoculum. The inoculum quantity can influence the composition and population of microbial species and supported mineralization processes (Scheuerell & Mahaffee, 2002; Tikasz et al., 2019). Shinohara et al. (2011) suggested that 5 g/L of bark compost inoculum is needed to mineralize organic fertilizer into nitrate. Mowa et al. (2018) found that at the initial mineralization stage, small quantities of manure (0.25 g/L) encourage the establishment of the microbial ecosystem required for subsequent mineralization of organic nitrogen compounds. High amounts of manure hampered the release of mineral N, and in the present experiment the amounts of N released per unit of dry substrate were also lower when high amounts of substrate were used.

The average P concentration in biosolids and cucumber extracts was significantly higher compared to compost. However, the P concentration in original compost material was higher compared with cucumber residues. Reasons for a poor release of P from compost might lie in a lower phosphate mobility in the compost compared to cucumber residues. According to Koimiyama et al. (2010) the amount of soluble P in animal manure compost is positively related to Mg concentration and negatively to Ca concentration. For compost of this study, the Mg concentration was lower compared with other materials, which indicates that compost might have had lower amounts of soluble magnesium-phosphate and larger amounts of insoluble compounds. Phosphate exists in various chemical forms, including inorganic and organic forms, which differ widely in their mobility in different materials (Fuentes et al., 2006; Chen et al., 2003; De Brouwere et al., 2003). Regarding the P extraction from organic substrates, quantities of 6 g/L of cucumber and compost material submerged into aerated water for three days gave the best results. The best P extraction from biosolids required a higher quantity of material, 9 g/L for the same extraction period.

The average K, Ca and Mg concentration in cucumber extract was significantly higher compared to other materials. While K, Ca and Mg concentration in biosolid extracts were the lowest. The biosolids were particularly poor in K. Similar finding indicated by Sullivan et al. (2015) that potassium is the major nutrient not provided in significant quantities by biosolids. Which might be due the way biosolids have been treated or stabilized. Based on previous results, the maximum K, Ca, and Mg concentration was reached after three days of system set up for all materials. Using higher quantities did not significantly increase the concentrations of materials extracts. Therefore, the best K, Ca, and Mg extraction could be achieved by using 6 g/L of organic material for 3 days of extraction and mineralization in aerated water.

The concentrations of Fe, Zn, and Mn were particularly high in compost solution, while Cu was highest in solution based on cucumber material. Cucumber leaves used in the extraction experiment had particularly high concentrations of Cu. However, high concentrations in the original material may not guarantee that the extract solution also contains high amounts of Fe and Zn. For example, biosolids contained high amounts of micronutrients, but only small quantities of these were released into the solution used for extraction and mineralization. Similar findings were obtained by Garland and Mackowiak (1990), who reported that the recovery of micronutrients from organic materials was generally low by aqueous extraction techniques. The role of micronutrient as constituents in membrane bound enzymes and insoluble protein complexes may be the cause of low recovery in water extracts. Based on the obtained results, the optimum micronutrient release from all materials was achieved after three days of exposure to aerated water. Using quantities higher than 6 g/L did not lead to correspondingly higher release of micronutrients. Therefore, the best micronutrient extraction could be achieved by exposing 6 g dry organic material to one L of aerated water for three days.

Regarding the influence of different nutrient solutions on plant culture, plant performance was evaluated using extracts of biosolids and cucumber as organic nutrient solutions for hydroponic culture and compared with a standard inorganic nutrient solution. For corn plants the growth was higher in standard inorganic nutrient solution compared with the cucumber solution, but there was no difference in growth between plants on biosolid and mineral solution. This suggests that biosolids might be a particularly suitable material for the production of nutrient solutions for plants. In the cucumber plants, dry weights were even higher for the biosolid compared with the control treatment. However, the nutrient solution obtained from the extraction of cucumber leaves was also able to support plant growth and element uptake.

The effects of the two different nutrient solutions obtained from organic materials on plant element uptake was also investigated. Across all treatments and plants, the element concentrations were indicative of sufficient supply, suggesting that both, the cucumber and the biosolid solution were able to provide plants with sufficient quantities of all nutritional elements during early stages of growth. The biosolid material provided particularly high amounts of plant available N, S and P, while the cucumber solution was high in Mg and K. Supply with Mn and Fe might not be sufficient in nutrient solutions based entirely on the mineralization and extraction of organic waste materials. The amendment with mineral fertilizers might be envisaged here. It might also be considered to mix different solutions to better match the plant demand.

Chapter 6: Conclusion

This thesis investigated opportunities to produce nutrient solutions for hydroponic plant cultivation from aqueous extracts and decomposition products of organic waste materials. The process of mineralization was based on aerobic processes involving microorganisms in the liquid organic solutions. Based on analysis been done, it can be concluded that aqueous extracts of aerobically extracted and mineralized organic waste materials can recycle a considerable amount of plant essential nutrients, and support plant growth and element uptake in the same way as conventional mineral nutrient solutions do. The use of biosolids for the production of hydroponic nutrient solutions might be particularly promising.

Based on the obtained data, the best extraction and mineralization results can be achieved by applying 6 g/L of organic material to 1 L of aerated water for a period of three days. Strategies for chemical adjustment of the obtained solutions might be tested in future experiments, as well as opportunities for mixing the solutions to achieve an improved nutritional balance.

This study laid the foundation for the development of hydroponic plant production systems based on recycling nutritional elements from organic materials such as biosolids and crop residues. To better understand the implications of these results, future studies could also address the chemical properties of the solutions, such as their pH and EC value, as well as biological parameters related to the microbial composition and activity. Further research is needed to determine the effects of the organic nutrient solutions on later stages of crop growth, and in different hydroponic production systems.

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