ORGANIC GREENHOUSE ADVANCES: ROOT ENVIRONMENT AND WASTEWATER MANAGEMENT

Organic farming in Canada continues to grow at a phenomenal rate, with the domestic market valued at $6.38 billion in 2017, and an average annual growth rate of 8.7% since 2012 . From 2014 to 2018, greenhouse vegetable sales increased by 5% each year. Recent statistics for Canada are scarce, but in Quebec the proportion of organic greenhouse vegetables has risen to 22%. Organic farming has come a long way!

Faced with high consumer demand for healthier and more environmentally friendly products, what was once a fledgling cottage industry has reinvented itself, moving from a production mode based on empirical knowledge to a more intensive approach supported by scientific research. Backed by Agriculture and Agri-Food Canada's two Organic Science Clusters (OSC) (2008-2013 and 2013-2018), Dr. Martine Dorais and her team have played a leading role in boosting the efficiency of organic greenhouse production to a level equivalent to or surpassing that of hydroponics, while continuing their efforts to reduce its environmental footprint. Organic farming could do more, and better, and has done exactly that.

Dr. and Professor Martine Dorais at Université Laval and her team of three researchers, four research associates, and eight graduate students have contributed greatly to the advancement of knowledge in the field of organic greenhouse production.

Proper plant nourishment begins with proper soil nourishment

For Dr. Dorais, achieving these goals was contingent on improving the productivity and sustainability of organic systems by:

a. Improving soil nutrition to better nourish plants by better managing the root environment (i.e., substrate, irrigation, fertilization);
b. Optimizing water use and nutrients, and recycling drainage water;
c. Improving the yield potential of organic crops to a level comparable to or higher than that of hydroponics in high-technology greenhouses (i.e., winter production with supplemental lighting).

In the eyes of consumers, organic farming has always benefitted from a positive environmental image. Nonetheless, European studies reveal that some aspects are far from positive, in particular with regard to nitrogen and phosphorus use, which represents a potential source of groundwater pollution. The relevance of intensive organic greenhouse production in northern climates has also been called into question by some communities around the world. The industry's reliance on fossil fuels challenges the public's perception that "if it's organic, it's good." In intensive systems, such as tunnel farming, it is important to make a distinction: if it's organic, it's good – if it's done right. Organic farming thus needs to become as sustainable as possible to comply not only with certification standards but with the very foundations of agro-ecological systems. Dr. Dorais' team was therefore interested in examining the weaknesses of the different organic systems in use, to propose strategies aimed at enhancing their sustainability.

This article presents advances pertaining to the root environment and greenhouse effluent management.

MANAGING THE ROOT ENVIRONMENT

Growing media

A number of scientific reviews have reported a 20% productivity gap between organic crops and conventional crops, and that gap varies widely for fruit and vegetable crops. The difference is generally attributable to suboptimal management of nitrogen Fertilization, which creates a disparity between nutrient availability and crop requirements. This is particularly true for greenhouse crops, where the annual yield per unit area cultivated is 10 times that of field crops. Relative to hydroponic culture, organic crop production has long been coping with a number of limiting factors, such as variable physico-chemical soil properties and the difficulty of accurately managing soil nutrient availability in relation to solar radiation and time of day.

To evaluate tomato performance on different soil types, Gravel et al. compared productivity in four organic soils from commercial farms (sand, sandy loam, loam, and muck soil), a reconstituted organic soil with 40% air porosity, and a peat-based growing medium amended with sawdust (Fig. 1). Irrigation was controlled independently by tensiometry, with a set point of -3kPa. Fruit yield and number followed the same trends across soil types, and were lowest in the reconstituted organic soil and the peat soil amended with sawdust and highest in the muck soil. The differences diminished over time, however, in response to changes in soil properties.

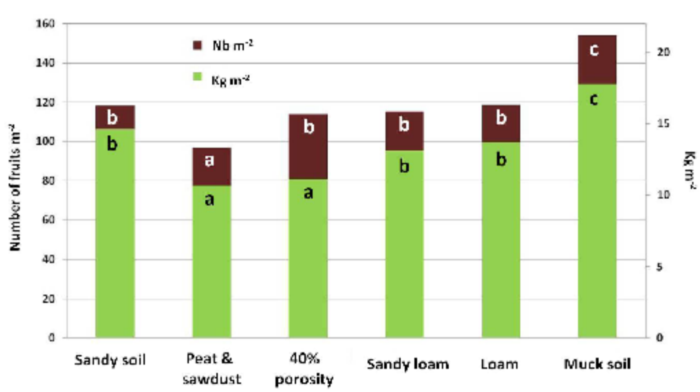

Figure 1: Tomato yield and number of fruits on six organically managed soils. Columns with the same letter are not statistically different.

These results underscore the importance of optimizing the initial properties of organic soils to maximize yield potential. Contrary to hydroponic substrates, which essentially provide support, oxygen and precise water and nutrient supply management, organic soils are characterized by significant water retention and cation exchange (CEC) capacities. The latter promote complex exchanges between soil particles, roots, microflora, microfauna and macrofauna, making it more difficult to accurately regulate nutrient supply.

Subsequent work by the team also validated the importance of:

a. Minimizing long-term salt accumulation;
b. Ensuring oxygenation in the root zone, essential to water and nutrient absorption and crop health;
c. Providing balanced Fertilization in raised-bed container systems, taking into account plant requirements, ratios between the nutrients in the rhizosphere, and losses to the environment;
d. Using the same growing medium for at least two years to develop biological activity and nutrient cycling ;
e. Adapting irrigation management (frequency and quantity) for different soil types to stimulate biological activity in the soil while ensuring an adequate water supply for the plant.

These concepts are already well established in hydroponics and have been integrated into these production systems across the industry. Organic production thus needed to master its own cornerstone – the root environment – and learn how to adapt it for different soil types.

In a context of commercial rasied-bed container production, Gravel et al. showed that an organic peat-based growing medium (Certified organic Agro-Mix, Fafard et Frères Ltd., Saint-Bonaventure, Qc, Canada) used for a second year under organic management was just as productive as a coco fibre growing medium (Biogrow, Montescot) under conventional management (the producer's standard management practices) (Table 1). Lower yields in the first year reflect that the fresh organic growing medium lacked the available nutrient reserves needed to meet immediate crop requirements and that microbial activity in the new substrate had yet to be established.

Treatment	*Total yield*	
	(fruits/m²)	*(kg/m²)*
Organic medium		
First year	332a	44.61a
Second year	351ab	53.54b
Conventional	370b	52.64b
P value	0.0176	0.0031

Table 1. Tomato-on-the-vine yield in organic and conventional growing media. In each column, values followed by the same letter are not significantly different according to Tukey's test (P≤0.05). Values represent the mean of three replicates.

Over the years, genomic and isotope techniques have been applied to learn more about soil microbial communities present in the crop production systems currently in use, species cultivated, fertilizer sources, and potential organic nitrogen absorption by plants. This in turn has increased our understanding of the crop root environment. The research has advanced the development of organic, raised-bed container production with prepared growing mediums and has brought spectacular progress in irrigation and soil fertility management.

Irrigation management

Irrigation management should provide the root environment with an adequate supply of water while ensuring that the root zone and soil are sufficiently oxygenated. The availability of nutrients for crops is determined by the mineralization of soil amendments by microorganisms which in turn require proper aeration. In hydroponic systems, irrigation frequency is generally based on the cumulative amount of light received; the irrigation threshold is determined by taking into account the estimated speed of water uptake per unit of light (potential evapotranspiration, PET), the readily available water (RAW) in the growing medium, and the risk of root asphyxiation. The sun is thus considered as the main factor affecting water uptake. So the higher the available water content, the longer the period between irrigations and the higher the volume of water applied at each irrigation.

There are, however, a number of other factors that influence water uptake: air drying capacity (moisture deficit in the air, vapour pressure deficit), air velocity, soil electrical conductivity, and crop stress (e.g., excessively high temperatures, telluric diseases). When properly installed and calibrated, tensiometers generally provide an accurate picture of the effect of all the factors that influence water uptake. So when irrigation set points are well defined for a specific soil type, irrigation management by tensiometry can be used to optimize water and air availability in the root environment. Applying irrigation strategies based on water tension in organic container growing media, Dorais et al. and Lemay et al. recorded higher yields than in rockwool or coco fibre in which the irrigation threshold was based on the cumulative amount of light received. Lemay et al. found that the photosynthetic efficiency of the crop responded differently in the peat-sawdust mixture than in rock wool. The optimum photosynthetic efficiency was near -0.5 kPa matric potential for rockwool and considerably drier at -0.9 kPa for a peat-sawdust mixture. At its peak, photosynthetic efficiency for the peat-sawdust mixture was 10 to 20% higher higher than rockwool. The photosynthetic efficiency of the tomatoes was also maintained over a wider range of water content in the peat-sawdust mixture, and was improved when the growing medium went through intermittent irrigation (as opposed to being watered constantly). As a result, irrigation setpoints were determined to be -1.5 kPa in tensiometer-based controlled irrigation. These characteristics related to the ability of the different substrates to hold water, and provide air to roots.

Authors	*Growing medium*	*Yield (kg/m²)*
Dorais et al. (2012b)	Coconut fibre	22.69
	Organic peat-based mixture	25.18
Lemay et al. (2012)	Rockwool	29.81
	Peat-sawdust mixture	32.06

Table 2. Comparative yields of conventional and organic crops (Adapted from Dorais et al. (2012b) and Lemay et al. (2012))

DID YOU KNOW?

Properly managed, organic farming can match the yields of hydroponics. Well managed, it can also reduce its environmental footprint.

FERTILIZATION MANAGEMENT: CROP RESPONSE AND ENVIRONMENTAL FOOTPRINT

Fertilization is probably the most important parameter that has yet to be mastered in organic greenhouse production. First because it requires a complex holistic approach that takes into account physical, chemical and biological properties, and second because of the intensive nature of the growing systems. Nonetheless, it has been shown that it is possible to obtain yields in organic systems similar to or higher than those obtained in hydroponic systems, which suggests that there are no apparent limiting conditions. So we're on the right track! But there are a few issues that still need addressing – crop protection and ability to respond to nutrients, and groundwater pollution due to nutrient applications that are excessive or mismatched to the plants' needs.

Groundwater pollution due to nutrient runoff from organic greenhouse operations is a major issue, not only in Canada but in the European Community as well. A better understanding of organic fertilizer sources and their mineralization rates is needed to enable the industry to better manage nutrient inputs and maintain high environmental performance. Organic fertilizers can be a significant source of greenhouse gas (GHG) emissions (carbon dioxide, nitrous oxide, methane). Nutrient leaching and the volatilization of a major portion of the nitrogen input have been observed in both soil-based and container-based organic growing media production systems. In addition to reducing mineral use efficiency, such losses increase the environmental footprint of organic production. Over the past 20 years, the hydroponic sector has stepped up its efforts to reduce fertilizer runoff. Why not do the same in the organic sector? A number of different strategies can be implemented in an effort to reduce emissions and runoff.

Organic fertilizer	*Mineral content*	*% N mineralization after (days)*			
	$N\text{-}P_2O_5\text{-}K_2O$	*Mineral soil*		*Peat-based growing medium*	
Blood meal	11-0.73-0.77	1	60	1	60
Feather meal	13-1.27-0.20	5	50.9	4.82	88
Alfalfa meal	2.59-0.5-3.23	3.35	50.98	0.9	79.75
Shrimp meal	5.69-10.80-0.12	-6.39	40.73	-4.86	57.5
Pelleted poultry manure	5.19-3.01-2.76	8.76	47.93	4.93	68.37
		20.14	21.09	33.4	29.85

Table 3: Mineralization rate of five organic fertilizers in a mineral soil and a peat-based growing medium

Reduce runoff

Careful irrigation management is the simplest approach to reducing water and nutrient losses through leaching. This means accurately estimating crop water requirements, thus evapotranspiration, and adapting inputs to soil type to prevent unnecessary leaching and nutrient losses in runoff, particularly nitrates, which are easily leached into the environment. Nitrous oxide emissions can be reduced by maintaining soil water content below 70% soil porosity. The use of tensiometers, with a set point adjusted to optimize soil water and air availability, is an effective and accessible method for producers looking for ways to reduce GHG emissions and limit unnecessary runoff.

Synchronize nutrient availability with specific crop requirements

To learn more about the mineralization rates of the main sources of organic fertilizer, Dion et al. measured the rate of nitrogen release from five organic fertilizers (Table 3) over a 364-day period, in a mineral soil (a sandy clay loam long used for organic greenhouse production) and a peat-based organic growing medium (previously used for one previous crop). Weekly readings showed that mineralization in the organic amendments was almost complete after only 60 days of incubation, with levels varying from 21% for poultry manure in the mineral soil to 88% for blood meal in the peat-based growing medium. The difference in the mineralization rate between the soil and the peat-based medium is mainly attributable to their different cropping histories and carbon contents of the amendments.

Fertilizers with higher C/N ratios (alfalfa meal, shrimp meal and poultry manure) had lower mineralization rates despite greater microbial activity in relation to feather meal and blood meal. Pelleted poultry manure released half of its nitrogen at the onset of incubation, reaching a plateau immediately thereafter, making it a good fertilizer for quick adjustments. However, an overdose of pelleted poultry manure can cause considerable damage to plants due to NH3 (ammonia) emissions. Blood meal and feather meal also showed rapid rates of mineralization, but with greater efficiency than pelleted poultry manure. In contrast, alfalfa meal was found to immobilize nitrogen during the first week of incubation, releasing it slowly thereafter. Alfalfa meal also emitted more carbon dioxide and nitrous oxide, since it increased soluble organic carbon in the soil, which in turn increased microbial biodiversity, bacterial biomass and the activity of nitrifying and denitrifying bacteria. Heightened bacterial activity is generally considered favourable to soil health and fertility. Blood and feather meal, on the other hand, were found to reduce soil biodiversity.

The study also showed that organic fertilizers promote the growth of diverse bacterial communities, which are closely linked to soil properties such as mineral nitrogen concentration, pH, and soluble carbon content. Besides the impact on microflora, the study underlined how important the presence of labile carbon from root exudates is to heterotrophic nitrifying bacteria, increasing the efficiency of organic fertilizers. In the field, for example, nitrogen use efficiency for poultry manure is estimated to be about 70-80%.

Increase the nutrient retention capacity of the soil

Clay is well known for its capacity to retain minerals at its surface. Due to its very fine texture and very high water retention capacity, however, adequate irrigation and leaching management is difficult to achieve without risking asphyxiation. Moreover, the high density of clay limits its use in off-ground production systems. Biochar, a product similar to charcoal, but produced through the process of biomass pyrolysis, is comparable to clay in terms of its mineral and water holding capacity but has a density nearly 14 times lower, as well as very high air porosity. The use of biochar as a soil conditioner dates back to the Pre-Columbian era, when Indigenous populations created Amazonian Dark Earths or Terra Preta. Dorais et al. amended six soil types, presented in Fig. 2, with 10% biochar (v/v) [balsam fir + black and white spruce, 750°C] for two years, and then with 15% (v/v) during the third year of production.

Soil microbial activity and nutrient retention improved significantly and nitrate leaching was reduced by 30 to 50% without affecting growth or yield parameters. In addition to reducing the environmental footprint of organic Fertilization, the use of biochar also improves soil fertility.

The physico-chemical characteristics of biochars vary depending on the raw material used and the conditions during pyrolysis (e.g., speed of temperature increase and oxygen level). Particle size also influences the effect of biochars in the soil. The main physico-chemical characteristics of the five biochars studied in Vicky Lévesque's doctoral research are presented in Table 4.

Parameter	***M400***	***M550***	***M700***	***P700***	***W400***
Raw material	*Sugar maple bark*			*Pine chips*	*Willow chips*
Pyrolysis temperature	400°C	500°C	700°C	700°C	400°C
pH (H_2O)	10.1	11.3	11.1	7.4	8.2
EC[1] (mS/cm)	0.6	1.4	1.1	0.1	0.4
% Base saturation	100	100	100	32.7	100
Dry matter	96.5	95.8	96.6	93.2	95.7
Ash content (%)	15.8	23.6	20.1	4.8	7.5
Volatile material (%)	36.6	29.4	33.7	15.8	17.7
C/N ratio	57.99	58.68	85.78	61.36	95.51
Bulk density (g/cm^3)	0.42	0.42	0.39	0.17	0.26
Total porosity (cm^3/cm^3)	0.75	0.76	0.77	0.9	0.83
Water content at -1kPa (%)	47	62	48	78	69

Table 4. Physico-chemical characteristics of biochars (Adapted from Lévesque et al. (2018))

1- EC: electrical conductivity *2- CEC: cation exchange capacity*

Three sources of biomass (sugar maple bark [M], pine chips [P], and willow chips [W]) and three pyrolysis temperatures (400, 550 and 700oC) were compared. The results showed that biochars do not all have the same characteristics. For a same biomass (sugar maple bark), the parameters most affected by the pyrolysis temperature were the electrical conductivity (EC) (0.6 to 1.4) and the C/N ratio (57.99 to 85.78). Incubation trials in a peat-based growing medium showed that nitrogen was partially immobilized by M400, and that the smaller particle size of willow biochar could reduce aeration in the substrate. These two biochars were thus considered unsuitable for production trials in peat-based growing media.

Lévesque et al. studied the agronomic effects of the M550, M700 and P700 biochars incorporated into a peat-based growing medium in proportions of 0, 5, 10 and 15% (v/v) used for greenhouse tomato (micro-Tom) and pepper (field cultivars) production, with 50 and 100% of the recommended nitrogen fertilization rate. The addition of biochar reduced leaching of nutrients such as N-P-Mg and Ca and improved water and nutrient use efficiency. This effect is attributable to more extensive root growth within the growing medium, which increases the release of exudates, a source of carbon necessary for microbial activity. The best combination for tomato was the 5% P700 biochar; peppers, however, benefitted most from the sugar maple biochars, regardless of the pyrolysis temperature. With biochar added to the growing medium, peppers even responded positively to the 50% fertilization treatment. Adding 5 to 15% biochar to peat-based growing media thus appears to be a promising approach for increased sustainability in organic production systems. Tests with more demanding crops (indeterminate greenhouse crops) will need to be conducted. The quality of the biochar used for soil amendment is also very important, and certain standards must be met to avoid the adverse effects of phytotoxic compounds. If it leaves your hands black, it's not a good sign!

DID YOU KNOW?
Biochars are not all equal; if it leaves your hands black, it's not a good sign!

Disease management with silica

Crop protection remains an important issue for producers. In hydroponic systems, silicate, in the form of sodium or potassium silicate, is used to control powdery mildew in greenhouse cucumbers. However, these silicate compounds are not permitted in organic farming. Looking for an alternative of comparative efficacy for use in organic production, Dr. Dorais' team found that adding 8 g/L of wollastonite (calc-silicate rock) to a peat-based growing medium resulted in a leaf silicate content equivalent to that observed with hydroponic products and improved growth by 6.5%. Thus far, however, powdery mildew has not been a problem in the test facilities so control efficacy has not been confirmed. Note that both wollastonite and the conventional form of Si are alkaline in nature.

MANAGING GREENHOUSE EFFLUENT

Biofiltration

Greenhouse effluent management strategies are primarily aimed at reducing the pollutant load of wastewater (particularly nitrates, phosphates and sulfates), and, in cases where the solution is reused for crop irrigation, eliminating pathogens and potentially phytotoxic molecules. Most of the research on effluent management has focused on constructed wetland technologies, due mainly to their low cost and their capacity to reduce pathogen levels.

Biofiltration is a procedure comprising a precise sequence of reactions that involve physical, chemical and biological processes. A series of distinct ecological niches (low and high pH, aerobic and anaerobic zones, presence of labile carbon) must be set up in a precise order to support the activity of the microorganisms involved. These microorganisms will then be able to carry out the reaction chains required to transform nitric and ammonia nitrogen into nitrogen gas (N2) and reduce sulfates to hydrogen sulfides and then reoxidize them to form insoluble compounds. When incomplete, these reaction chains can generate nitrous oxide and methane, potent greenhouse gases, or hydrogen sulfide, which is toxic to microflora, crops and humans when artificial wetlands or bioreactors are placed in an enclosed environment.

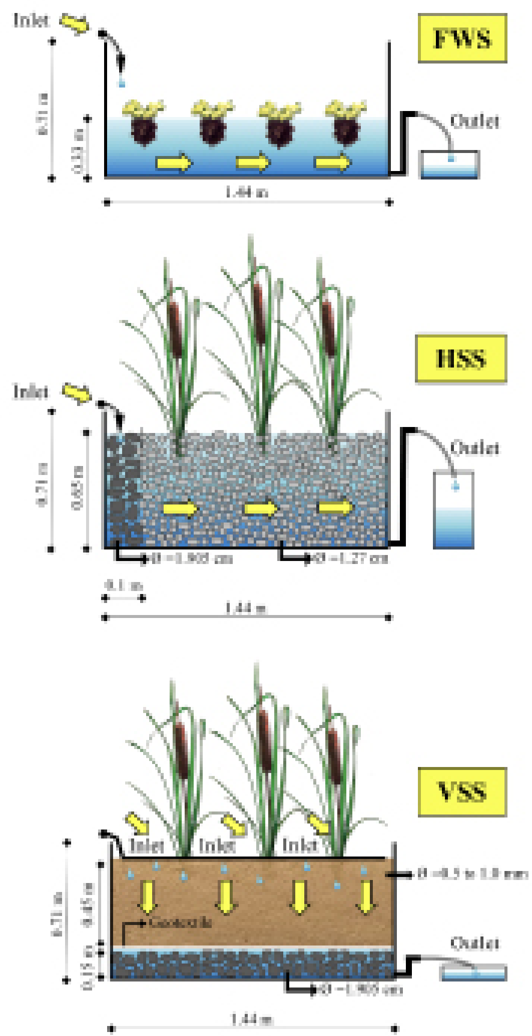

Figure 2: Three types of constructed wetlands

Three types of constructed wetlands (CW) were studied (Fig. 2):

Free water surface flow (FWS) CW: Effluent enters the basin at one extremity, flows horizontally beneath the aquatic flora (water hyacinth or other macrophytes), and then exits at the other extremity through an outlet pipe adjusted to maintain a specific retention time and water level in the constructed wetland. This design is similar to a wastewater pond.

Horizontal-subsurface flow (HSS) CW: Effluent enters the basin at one extremity at an inlet filled with coarse gravel (1.905 cm particle diameter), which ensures uniform distribution of the water flowing horizontally through a bed of sand, gravel or other filtering material (pozzolana), on which microbial films form. Macrophytes, such as cattail, colonize the substrate, and their roots provide the carbon and oxygen needed by the microorganisms responsible for denitrification and sulfate reduction. Treated wastewater flows out of the basin through an outlet pipe adjusted to maintain a specific retention time and water level in the constructed wetland.

Vertical subsurface flow (VSS) CW: Effluent is applied over the surface of the wetland and then percolates downward through a layer of sand, gravel or other filtering materials (pozzolana) measuring up to 1 m in depth, and then through an underlying 15-cm-deep gravel bed (particle diameter 1.905 cm) before being evacuated from the basin through an outlet pipe adjusted to maintain a specific retention time and water level in the constructed wetland.

For greenhouse effluent with excessive nitrate and sulfate levels, an additional carbon source is needed to maintain a sufficiently high level of microbial activity and prevent nutritional competition among nitrate- and sulfate-reducing organisms. With the addition of labile carbon, the HSS system is the most effective at reducing nitrates while limiting N20 emissions. The VSS is the least effective as it allows for greater oxygen exchange, thus limiting the activity of nitrate-reducing microorganisms. While the FWS system is the most effective at removing nitrates from wastewater, this type of wetland releases seven times more N_2O and twice as much CO_2 as the HSS system. In a commercial trial conducted in Quebec, a series of three VSS wetlands proved effective at treating effluent with a high fertilizer load, reducing nitrates by 86%, sulfates by 63%, and retaining 100% of the phosphorus by adsorption.

Other materials could be used to replace part of the gravel bed in CWs to increase their purification capacity. Gruyer et al. reported complete reduction of nitrates and sulfates in greenhouse effluent when pozzolana was used as a filtering medium. This highly porous material provides a greater surface area for the formation of biofilms. However, the cost of importing pozzolana is prohibitive. Dr. Dorais' team carried out additional research to demonstrate the benefits of adding biochar to filtering materials. Ouertani demonstrated that the addition of biochar favourably affected the expression levels of a number of key genes in the bacterial species involved in the CW filtering process, including those that control the release of greenhouse gases. Biochar also helps protect the microbial population from pesticides that may be present in wastewater. According to Dr. Dorais, the HSS system with a bed of gravel containing sufficient labile carbon is the one that best meets environmental criteria by significantly reducing phosphate, sulfate and nitrate levels in effluent and greatly reducing N2O emissions. An extremely high NO3 (500ppm) load and/or risk of phytotoxicity can be countered by adding biochar to gravel. Moreover, only 10% of the greenhouse surface area is required to purify heavy summer runoff, making this system a practicable and economical option.

CONCLUSION

Developing an organic industry suitable for ecosystems and humans will require meeting increasingly complex ecological and societal challenges in order to avoid the industrial excesses seen in other sectors since the 1960s. The organic industry will thus need to adopt production methods that – beyond yield and profitability – contribute significantly to enhancing the sustainability of greenhouse production systems. Effective tools for sustainable water and soil fertility management are now available for intensive organic greenhouse production, making it possible to attain high, good-quality yields while reducing the environmental footprint of this type of production. Limiting effluent discharge and greenhouse gas emissions will require more research, but the foundations are in place to ensure success. The organic greenhouse vegetable industry is heading toward a bright future: doing more, doing better!

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