דו"ח סופי לתוכנית מחקר מספר 301-693-161

**ביו-פחם: דרך המלך להפחתת גזי החממה באטמוספרה ולהסתגלות החקלאות לשינויי האקלים באמצעות פירוליזה של פסולות אורגניות**

**"The Biochar Vision" for Adaptation and Mitigation of Climate Change - Waste Treatment, Carbon Sink, Energy Source and Soil Conditioner**

מוגש ל קרן המדען הראשי, משרד החקלאות ופיתוח הכפר
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## Abstract

Introduction to the problem: The objectives of this research were: (i) characterize physical and chemical attributes of biochars produced from different biomass feedstocks; (ii) study content and release of nutrients from biochars made from different feedstocks at different temperatures as a function of pH; (iii) evaluate impact of biochar to soil water retention characteristics; (iv) determine the impact of biochar additions on crop yield, fruit quality, disease severity, and changes in soil microbial community in pot trials; (v) determine effect of biochar on sweet pepper yield, resistance to disease, and post-harvest fruit quality in a field trial; (vi) examine effect of microbial community changes due to biochar addition on plant health; and (vii) make a preliminary economic evaluation of the viability of the pyrolysis/biochar platform for Israel.

Methods: Biochars were produced from various feedstocks at a variety of temperature using in-house pyrolysis units, and physical and chemical characterizations were carried out in the laboratory. Pot trials where plant growth, disease severity, yield, soil microbiology, and fruit quality was tested were conducted under greenhouse conditions and also under field conditions in a net house.

Results: Biochar was prepared from 5 different feedstocks at temperatures ranging from 350 to 800$^{o}$C; biochar amount and exchangeable cation content decreased with increasing temperature of production (highest treatment temperature; HTT), while pH increased in increasing HTT. Many biochars were redox active, and were able to reduce organic compounds and release soil Fe and Mn to solution. Biochar increased soil water holding capacity, mainly at high suctions. High HTT biochars made from wood can have high specific surface areas (SSA) and hence high adsorption capacities; they may interfere with efficacy of soil-applied pest control products when applied at doses exceeding 2 tons per dunam. Biochars made from other feedstocks have notably lower SSAs at all HTTs, and are not expected to be problematic in this regard. Doses of various biochars of about 1 weight % (~ 2 tons/ha) improved growth and health of a variety of crops in pot trials: basil, tomato, pepper, wheat, and strawberry. Both SAR and ISR defense pathways were activated by biochar in strawberry against various foliar diseases, and in tomato, the JA pathway was primed by the presence of biochar. Biochar in the root zone induced changes in the rhizosphere microbial community and increased microbial diversity. In a field trial with peppers and several types of biochar, biochar addition of 2 tons/dunam was found to improve yield by about 15% per year and reduce incidence of powdery mildew. Fruit quality was unaffected by biochar treatments, yet pepper fruit from the biochar plots were more resistant to post-harvest mold infection. A preliminary economic evaluation shows that the pyrolysis/biochar platform has great promise is Israel, particularly as it presents a solution to problematic agricultural wastes. This evaluation needs to be deepened as more results from future research become available.

Conclusions and recommendations: In multiple systems we observed that biochar added to the soil medium enhanced crop productivity and improved plant resistance to disease. These findings were also seen in a field trial with pepper. Biochar has a tendency to increase soil water retention, and can increase soil CEC in organic matter poor soils. A preliminary economic analysis shows that the pyrolysis/biochar platform for wastes holds a great deal of promise for Israel. This analysis is supported by a similar conclusion by the Ministry of the Environment in a recent report. Despite the large amount of work done in this project, it is the first of its kind in Israel. In the rest of the world, biochar is also a very new technology and little is known. Thus,

many open questions remain. The results obtained here justify considerable additional research into answering these questions, such as: What is the longevity of the Biochar Effect? Does aging of biochar in the soil environment change its effect? What are the optimal doses of biochar? Should it be added in small doses on a yearly basis or in a single large dose? Can biochar efficacy be improved by creating biochar/fertilizer mixtures? Can biochar addition replace some standard pest control activities? Can biochar replace some fertilizer? Is there a difference in biochar performance if the biochar is produced from manure wastes as compared with plant biomass wastes? What are the possible negative impacts of biochar in the soil? How does biochar aging in the soil change its adsorption ability? Is it possible to isolate microbes having biocontrol and plant stimulation features which have been enhanced under biochar additions? Are there chemicals that are added with biochar that contribute to its impact in soil? Can they be isolated and characterized? Does biochar have a role to play in organic agriculture, where acceptable plant protection agents are few? Are there contaminants in biochar that may prove problematic when added to the soil? Is biochar protective against diseases caused by pathogens that are not fungi? Does addition of biochar to the growing medium result in alterations in plant metabolites, hormones, secondary metabolites? Which crop systems can most benefit from biochar additions? Which soils are best candidates for biochar amendment?

**תקציר**

<u>הצגת הבעיה</u>: ביו-פחם הינו תוצר פירוליזה של ביומסה. מטרות המחקר היו: (א') אפיון התכונות של ביו-פחם ממקורות ביומסה שונים; (ב') בחינת התכולה והשחרור של יסודות הזנה מסוגי ביו-פחם שונים;( ג') בדיקת השפעת ביו-פחם בקרקע על תכונותיה ההידראוליות; (ד') הערכת ההשפעה של ביו-פחם על כמות ואיכות יבול, מחלות צמחים ואוכלוסייה מיקרוביאלית בניסויי עציצים; (ה') קביעת ההשפעה של ביו-פחם בתנאי שדה על רגישות צמחים למחלות ותכונות לאחר קטיף; (ו') השפעה של שינויים במבנה אוכלוסיות מיקרוביאליות על הנבת הצמחים; ו-(ז') הערכה כלכלית של פוטנציאל השימוש בפירוליזה וביו-פחם בישראל.

<u>שיטות</u>: נוצרו סוגי ביו-פחם שונים ונערכו ניסויים במעבדות, כימיה, מיקרוביולוגיה, פיטופתולוגיה ובחממות במרכז וולקני וניסויים בתנאי שדה בחממות ניסויים לבדיקת תכונות סוגי הביו-פחם והשפעתם בהתאם למטרות שלעיל.

<u>תוצאות</u>: ביו-פחם נוצר מחמישה מקורות ביומסה בטמפרטורות בין 350 ו- 800 מ"צ. יבול הביו-פחם ותכולת קטיונים חליפיים (CEC) פחתו עם עליית טמפרטורת הייצור ועלו עם ה- pH, דבר המצביע על חשיבות המטענים השליליים הקשורים ב- pH בקביעת ה CEC, תכונה התורמת לתפוצת יסודות מזון וזמינותם בקרקע. ביו-פחם רבים הינם פעילי חמצון-חיזור, תכונה המשפיעה על תנועת אלקטרונים בקרקע ויכולה להביא לזמינות ברזל ומנגן. עם עלית טמפ' היצור עלה פני השטח הייחודי (SSA) של הביו-פחם. לביו-פחם יכולת ספיחה של חומרים אורגנים, כולל פסטיצידים, העולה עם ה- SSA. מינון נמוך יחסית של 1% מהביו-פחם השונים הגדילו בניסויי עציצים גידול ובריאות של צמחי בזיל, חיטה, עגבנייה ופלפל. ביו-פחם במצע גידול השרה מנגנוני הגנה מסוג SAR (חומצה סליצילית) וISR (חומצה ז'סמונית ואתילן) כנגד מחלות נוף בתות שדה ומנגנון הביוסינטזה של ח' ז'סמונית בעגבנייה. בנוכחות ביו-פחם, עלה המגוון המקרוביאלי בריזוספרה של עגבניות ופלפל וישנן עדויות שעלתה השכיחות היחסית של חיידקים המזוהים כמדבירים ביולוגים. בתנאי שדה 2 טון לדונם ביו-פחם עודד גידול צמחי פלפל, יבול ובריאות שלהם בתנאי שדה תוך השפעה מינימלית על התכונות ההדראוליות של הקרקע. בחינה כלכלית ראשונית מראה פוטנציאל משמעותי של ביו-פחם לשימוש בר קיימא על ידי חקלאים, אך הנושא דורש מחקר רחב.

<u>מסקנות והמלצות</u>: התקבלו תוצאות רבות במערכות השונות אשר מראות שתוספת ביו-פחם לקרקע יכולה לעודד צימוח ולהשרות עמידות מערכתית למחלות צמחים. תוצאות דומות התקבלו הן בניסויי עציצים והן בניסויי שדה בפלפל. בקרקע עם תוספת ביו-פחם יש עליה בתאחיזת מים ובקיבול קטיונים חליפים. הערכה ראשונית של כלכליות פירוליזה וביו-פחם בארץ מראה כי הרווח עולים על העלות. מסקנה זו מתאימה למסקנה של דו"ח משרד להגנת הסביבה (2014) שממליץ להשקיע במחקרים בתחום יצירת ביו-פחם מפסולות חקלאיות ועירוניות וכי הטכנולוגיה תהיה ישימה בטווח הבינוני של עד 5 שנים. כיוון שמחקר זה על שימוש בביו-פחם בארץ הינו חלוצי, ומכיוון שנושא פירוליזה/ביו-פחם הינו חדש בעולם, ישנן שאלות רבות אשר נותרו פתוחות ואשר נפתחו בעקבות המחקר הנוכחי, כגון: מה משך פעילות הביו-פחם; האם נוכחות ממושכת בקרקע משנה את פעילותו; מה המינון המיטבי; איזה גידולים וקרקעות מתאימים ביותר ליישום ביו-פחם ואיך אפשר לשפר את פעילותו; מה ההשפעות השליליות של ביו-פחם; האם יצור ביו-פחם הוא הפתרון המיטבי למחזור פסולות ובכללן חקלאיות; מה השיקולים הכלכליים לשימוש בו ועוד.

# Executive Summary

- Biochars were produced from five different feedstocks (eucalyptus wood chips, green house wastes (pepper plants), date palm frond, olive pomace, and yardwaste) at up to 4 highest treatment temperatures (HTT) between 350 to 800$^{o}$C. Biochar yields decreases as HTT increases.
- The cation exchange capacity (CEC) of biochars decreases as HTT increases. For a given biochar, the CEC increases as a function of pH. This points to the important role of pH-dependent negative charges at biochar surfaces in determining the CEC, a characteristic which contributes to nutrient distribution and availability in soil.
- Many biochars are redox active, a feature which can impact electron shuttling in the soil and may lead to increased bioavailability of Fe and Mn.
- The higher the biochar production temperature (HTT), the higher the specific surface area (SSA) of biochar.
- Mainly wood-derived biochars have high SSAs; biochars produced from other agricultural wastes such as pepper plants, olive pomace, and palm fronds have relatively low SSAs, even when produced at high HTT.
- Biochars have good adsorption capacities for organic compounds, including pesticides. Capacity increases with increasing SSA (and hence increasing HTT). If a biochar with a very high adsorption capacity is used, such as from wood, it may therefore compromise the efficacy of soil-applied pest control products. This is particularly true at high HTT biochars made from wood applied at rates greater than 2 tons/dunam. It is not yet known how adsorption changes over time in the soil.
- Water retention increases in soils amended with biochar, while changes in hydraulic conductivity are negligible. The significant change in water retention is apparent only in the dry range of the water retention curve. The significance of this finding is that in intensively irrigated agriculture there is probably neither benefit nor damage from the addition of biochar from a physical point of view, however, in non-irrigated agriculture, it will probably be much more significant as the slight addition to the moisture content from addition of biochar may make the difference between a wheat field that survives dry periods between rainfall episodes and a wheat field that does not.
- Plant-based biochars produced from crop residues may contain relatively high contents of nutrients, but their release is occurs early, and thus may not be well-timed with plant needs, particularly for intensive high input crops. Therefore, fertilizers or compost are needed in addition to biochar.
- Pot experiments testing the impact of various biochars on growth and health of basil, wheat, pepper and tomato, demonstrated that, by-and-large, irrespective of biochar type or crop system, relatively low doses of biochar (about 1% by weight, or 2 tons/dunam) tend to promote plant growth and health.
- Biochar additions to the growing media elicit plant system-wide defenses against foliar fungal pathogens in tomato, strawberry, wheat, and basil.
- Up-regulation of defense regulated genes in strawberry plants grown in biochar-amended media occurs along both SAR (salicylic acid) and ISR (jasmonic acid and ethylene) pathways.
- In tomato, biochar-elicited induced resistance occurs along the jasmonic acid pathway.
- Microbial community structure and diversity are both promoted in the rhizosphere of plants growing in biochar-amended soils, which in turn improves plant performance.

- Under commercial growing conditions in the Arava, a one-time dose of 2 ton biochar/dunam promotes pepper plant growth, improves yield, and positively influences its health.
- The preliminary economic analysis of the pyrolysis/biochar platform shows that this technology holds promise for waste handling in Israel:
  - Biochar life cycle: The life cycle of biochar begins and ends with vegetation. Plant residues are the feedstock for making biochar; biochar is added to soil where it improves primary production and creates its own future feedstock.
  - Supply side: There are abundant agricultural feedstocks that can be used for pyrolysis and biochar in Israel. Initial supplies of biochar from these different feedstock sources are estimated at 46,000 ton/yr from agricultural wastes, 15,000 ton/yr from JNF forests, and 55,000 ton/yr from municipal yard waste, all together, 120,000 ton/yr.
  - Demand side: There are many possible uses for biochar: (i) amending soils to improve crop productivity and plant health; (ii) replacing the highly polluting and primitive method of making charcoal used in Israel and the area with modern, non-polluting pyrolysis units; (iii) additive to sludges and manures for stabilization and odor reduction; (iv) *in situ* remediation of contaminated soils; (v) precursor to activated carbon; (vi) low cost filters.
  - Market price: Unblended biochar and biochar products blended with other materials are sold in many countries at a wide range of retail prices ranging from $0.08 to $13.48 per kilogram (300 NIS/ton to 50,000 NIS/ton). The average price reported was $2.48 per kilogram (918 NIS/ton).
  - Biochar production costs: The price of pyrolysis units ranges between 10,000 to 1,400,000 NIS, depending on the size and capacity of the unit. Production costs per ton range from 700 to 1120 NIS/ton biochar, not including income from co-produced energy.
  - Energy generation: Some pyrolysis units generate heat that can be used to heat nearby greenhouses. The energy generated is sufficient to return the investment on the unit within 3 to 5 years.
  - Cost-benefit comparison: The main benefits from the use of biochar are (i) increased yields, ranging from 230 to 1770 NIS/dunam, depending on the crop; (ii) carbon sequestration at 755 NIS per dunam; (iii) soil remediation at 909 NIS/dunam; and (iv) odor abatement at 104 NIS/dunam, with total benefits reaching between 2078 to 3618 NIS/ dunam. On the cost side, the main damages are the risks of reducing pesticide efficacy (300 NIS/dunam) and unknown long term soil damages at 49 NIS per dunam. Total damages could reach 362 NIS/ dunam. The net benefit can range from 1716 to 3256 NIS/dunam. Even without accounting for the potential of biochar use for contaminated lands, and taking into consideration only agricultural benefits and costs, there would still be a net benefit of 807 to 2,347 NIS/dunam.
  - Further development of efficient and inexpensive pyrolysis technologies, as well as development of use protocols, is needed.
- This first research program into biochar use in Israel has provided many insights and opened new research directions. Because the biochar/pyrolysis platform is so young, there are yet many scientific questions and applicative questions still remaining to be addressed in future research. These include:
  1. What is the longevity of the Biochar Effect?
  2. Does aging of biochar in the soil environment change its effect?

3. What are the optimal doses of biochar? Should it be added in small doses on a yearly basis or in a single large dose?
4. Can biochar efficacy be improved by creating biochar/fertilizer mixtures?
5. Can biochar addition replace some standard pest control activities?
6. Can biochar replace some fertilizer?
7. Is there a difference in biochar performance if the biochar is produced from manure wastes as compared with plant biomass wastes?
8. What are the possible negative impacts of biochar in the soil?
9. How does biochar aging in the soil change its adsorption ability?
10. Does biochar CEC change over time as biochar ages in the soil?
11. Can biochar be produced economically from agricultural wastes?
12. Is biochar production a good use of wastes?
13. Can biochar be an economically feasible agricultural tool?
14. Is it possible to isolate microbes having biocontrol and plant stimulation features which have been enhanced under biochar additions?
15. Are there chemicals that are added with biochar that contribute to its impact in soil? Can they be isolated and characterized?
16. Does biochar have a role to play in organic agriculture, where acceptable plant protection agents are few?
17. Are there contaminants in biochar that may prove problematic when added to the soil?
18. Is biochar protective against diseases caused by pathogens that are not fungi?
19. Does addition of biochar to the growing medium result in alterations in plant metabolites, hormones, secondary metabolites?
20. Which crop systems can most benefit from biochar additions?
21. Which soils are best candidates for biochar amendment?

## Introduction

This final report represents the culmination of a four-year (three years with funding, extended to fourth year without added budget) integrated research effort aimed at evaluating the possibility of using biochar additions to soil to improve Israeli agricultural efforts and simultaneously, help to offset greenhouse gas emissions by pyrolyzing waste biomass. It represents the first research of its kind in Israel.

Biochar is a type of charcoal (technically, charcoal is made from wood) made by pyrolyzing various types of organic feedstocks (agricultural wastes, forestry wastes, wood, manures, etc.) with the purpose of using the solid biochar product for non-energy applications. Pyrolysis consists of the thermal decomposition of organic matter under oxygen limited conditions, and has been used for millennia by humans to produce charcoal. The first evidence of humans' deliberate use of charcoal shows it was utilized as a fuel at least 5500 years ago in Southern Europe and the Middle East. By the commencement of the Bronze Age in Britain around 4000 years ago, the use of charcoal as a metallurgical fuel was commonplace. Yet, fuel was not the only ancient use for charcoal. There is considerable evidence that pre-Columbian natives of the Amazon Basin used charcoal as a soil additive together with manures, bones and pottery shards, turning otherwise unproductive soils into rich and fertile ones [1]. One of the major reasons these "Terra Preta" soils, abandoned between 500 to 2500 years ago, are fertile even today has been attributed to the nutrient-holding capacity of the added charcoal [2]. Similar scattered pockets of ancient, fertile, charcoal-containing anthrosols amidst native low fertility soils have since been found in parts of Ecuador, Peru, Western Africa, South Africa, Australia, and Asia. An example of charcoal use in Asian agriculture more than 300 years ago has been preserved in a textbook entitled 'Nogyo Zensho' (Encyclopedia of Agriculture) written by Yasusada Miyzaki in 1697, and translated thusly by Ogawa and Okimori [3]: "After charring all waste, concentrated excretions should be mixed with it and stocked for a while. When you apply this manure to the fields, it is efficient for yielding any crop."

As evidenced in 19$^{th}$ and early 20$^{th}$ century agronomy literature, charcoal also enjoyed widespread use in North American and European agriculture and horticulture. Some of the uses of charcoal were described in *A Brief Compend of American Agriculture* by R.L. Allen [4]:

> *Charcoal dust [drilled in with the seed] has been found to increase the early growth from four to ten-fold (p. 150).*
> *Scattered over the ground … [charcoal] absorbs and condenses the nutritive gases within its pores, to the amount of from 20 to over 80 times its own bulk. … Charcoal … often checks rust in wheat, and mildew in other crops; and in all cases mitigates their ravages, where it does not wholly prevent them (p. 45).*
> *A dressing of charcoal has in many instances, been found an adequate preventative [of rust]; and so beneficial has it proved in France, that it has been extensively introduced there for the wheat crop (p. 109).*

The use of charcoal in agriculture waned considerably in the 20$^{th}$ century, presumably due to its increased value as fuel and with the development of modern chemical fertilizers and pest control products. However, since the opening years of the 21$^{st}$ century, there has been a remarkable resurgence of interest worldwide in the agricultural utilization of charcoal for at least four inter-related reasons:

(i) Pyrolysis, the means by which charcoal is produced, generates renewable energy products. It is thought that pyrolysis may become part of an arsenal of affordable renewable energy technologies aimed at reducing net greenhouse gas emissions from the burning of fossil fuels and at diversifying energy supplies.

(ii) Many organic wastes can be treated and converted into energy via pyrolysis. As a result, pyrolysis is more versatile than technologies that produce biodiesel and ethanol from crops, and does not compete for resources with food production. Many different urban, agricultural and forestry biomass wastes and residues can be treated by pyrolysis.

(iii) When used as a soil conditioner together with organic and inorganic fertilizers, charcoal appears to significantly improve soil tilth, productivity, nutrient retention and availability to plants, improved water holding capacity, and soil aggregate stability [5]. Because it aids in soil retention of nutrients and agrochemicals for plant and crop utilization [6, 7], charcoal amendment may help fight against soil degradation, and can be a tool in the creation of sustainable food and fuel production in areas with severely depleted soils, scarce organic resources, and inadequate water and chemical fertilizer supplies.

(iv) The half-life of biochar in soil has been estimated to be hundreds to tens of thousands of years depending on feedstock and pyrolysis conditions [8]. This leads to carbon storage in the soil and its removal from the atmosphere [9]. In addition, modest additions of biochar to soil have been found to reduce emissions of greenhouse gases from cultivated soils, for example, reducing $N_2O$ emissions by up to 80% and completely suppressing methane emissions [10-12]. When contemplated as a part of this 4-part “Charcoal Vision” involving renewable energy generation, waste treatment, soil fertility improvement, and carbon sequestration [13], charcoal has earned a new moniker: BIOCHAR.

Currently, biochar is hardly utilized in modern agriculture, and its agronomic value in terms of crop response and soil health benefits has yet to be quantified. Impediments to the adoption of biochar use in modern agriculture are many, and include the great variability in biochar characteristics as a function of feedstock and pyrolysis conditions, particularly pyrolysis highest treatment temperature (HTT). Biochars produced at relatively low temperatures (below about 500$^{o}$C) have substantially different characteristics than those produced at high temperatures (above about 600$^{o}$C). Compared with high HTT biochars, low HTT biochars have lower pH values (neutral to mildly alkaline), lower ash contents, lower specific surface areas (SSA), and higher cation exchange capacities (CEC) per unit surface area. These characteristics can influence biochar suitability as a soil amendment in yet unknown ways, as well as its stability in the environment, which can affect its utility as a long term carbon sink.

## Research Objectives

There were a number of specific objectives in this research: (i) characterizing the physical and chemical characteristics of biochars made from different waste feedstocks; (ii) examining the content and release of nutrient minerals from different biochars; (iii) examining the impact of biochar additions on soil hydraulic characteristics; (iv) evaluating the impact of biochar additions on crop yield and quality, disease resistance, and microbial populations in pot experiments; (v) determining the impact of biochar on plant sensitivity to disease during the growing season and to post-harvest fruit in a field trial; (vi) examining changes in soil microbial community structure as a result of biochar addition and understanding the connection between these changes and biochar impacts on plant productivity; and (vii) providing a first analysis of the economic potential of pyrolysis/biochar use in Israel.

## Major results of the research

Results are arranged according to the objectives. In cases where the results have been published, only a summary is given, and the reader is referred to the publication.

## Producing biochars from different feedstocks and characterizing their physical and chemical characteristics

### Biochar Production

Two different pyrolysis systems were used to produce biochar at different temperatures. The first and main pyrolysis system was purchased from PowerLabs in USA, the BEK (Fig. 1) and modified in for agricultural waste treatment. The BEK is a continuous system where the feed flows downwards in the pyrolysis chamber (labeled (a) in Fig. 1), heating up during the movement until it becomes biochar. The heat is produced externally in a combustor (b) using butane gas, and it flows in the pyrolysis chamber double wall. Temperature is measured at different heights in the pyrolysis chamber and in the combustor. The temperature in the combustor is kept around 20 °C above the desire highest treatment temperature (HTT), and as soon as the biochar at the bottle of the pyrolysis chamber reaches the desired HTT, it is removed to the biochar hopper (c). In the biochar hopper, the biochar is cooled down through water spray.

Figure 1. BEK, PowerLabs pyrolysis system modified in the Volcani Center for agricultural wastes

During the pyrolysis process, the feedstock is converted to biochar and different gases. The gases flow upward in the pyrolysis chamber and are air-cooled in the vortex chamber (d). In the vortex chamber part of the gases become liquid (tar and wood vinegar) and part remains as gas (syngas). The syngas is burned in the combustor reducing the use of butane. The liquid is collected.

The BEK was used to produce biochar from different feedstocks: eucalyptus wood chips (EUC), greenhouse wastes, mainly pepper plants from the Arava (GHW), olive pomace (OP) and date palm fronds (Palm) at different temperatures (350, 450, 600 and 800 °C).

The reactor operation time depended on the feed stock and HTT, whereas the HTT was the most important factor to determine the operation time. For HTT up to 500 °C, biochar started to be produced after 45-60 minutes of operation. However, for higher temperatures, an increase in operation time was needed, because of the time required to reach this higher temperature. The longest time was 180 minutes at 800 °C. As observed by others, pyrolysis is an exothermic process up to 400-500 °C; however, above this temperature, it becomes an endothermic process, requiring more heat input to increase a single Celsius degree.

Greenhouse waste (GHW) was the only feed produced at all HTTs and the biochar yield (kg biochar/kg feed) was around 43, 37, 34 and 31% at 350, 450, 600 and 800 °C, respectively (Table 1). Decreases in biochar yield with increasing temperature has been observed by others, however, generally with lower yield values [14]. The explanation can be the difference in the systems used in the experiments. EUC and Palm biochar yields were similar to those of GHW at the temperatures tested (350 and 600 °C). Olive pomace (OP) biochars had lower yields at 600 °C (the only temperature tested), around 27%.

Table 1. Biochar yield (kg biochar/100 kg feed) from different feedstocks at different temperatures produced in the BEK system (number of replicate batches in parenthesis)

| **Feed Stock** | **Temperature (° C)** | | | |
|---|---|---|---|---|
| | **350** | **450** | **600** | **800** |
| Eucalyptus (EUC) | 43 ± 4.1 (7) | ND | 36 ± 4.1 (5) | ND |
| Greenhouse Waste (GHW) | 43 ± 4.7 (6) | 37 ± 4.9 (5) | 34 ± 5.9 (7) | 31 ± 6.0 (4) |
| Olive Pomace (OP) | ND | ND | 27 ± 6.5 (3) | ND |
| Date Palm Fronds (Palm) | 41 ± 13.1(2) | ND | 33 ± 7.4 (2) | ND |

ND – biochar yield not determined

The second pyrolysis system used was modified after a system developed in Udine University in Italy to be used in developing countries, the Udine system (Fig. 2). The Udine system is simpler to operate and does not require an external heat source, however, it is operated at batch mode only and the HTT cannot be controlled. The system was also modified to treat agricultural wastes (EUC, Palm, and yard waste (YW)). In the first step, the system is filled with the feedstock and fire is lit on the upper part of the feedstock. Air flows from the bottom part of the system upwards through the biomass keeping the fire going; however, it flows at a low rate preventing the bulk of the biomass from igniting. Only the gases produced during the process are burned, always in the upper part of the system. The heat front moves downward heating all the biomass. When the heating front reaches the lower part of the system, the fire is naturally extinguished, and the biochar is then wetted to eliminate smoke production.

Figure 2. Udine pyrolysis system modified in the Volcani Center to treat agricultural wastes

The Udine reactor HTT is dependent on the feedstock, since each feedstock naturally reaches an HTT in the exothermic field, i.e., it reaches the temperature when the process stops being exothermic and starts to be endothermic. For this reactor system, operation time is not an issue, since the HTT is always on the exothermic temperature field. The different feedstocks used in the tests gave similar HTTs, 625 and 585 °C, for Palm and EUC respectively. The biochar yield of the different feedstocks were also similar, 33 and 31% were observed for Palm and EUC, respectively.

## Biochar Physical and Chemical Characteristics

### *General*

Specific surface area ($m^2$/g), elemental composition, and ash content and composition of the produced biochars are tabulated in Table 2. There it is seen that the different feedstocks and production temperatures result in biochars with different chemical and physical characteristics. In the main, increasing HTT results in increased SSA. Other trends with HTT in the characteristics summarized in Table 2 are not observed.

Other chemical parameters are listed in Table 3, including dissolved organic carbon (DOC) content, pH, electrical conductivity (EC), total phenols, and redox potential. pH of the EUC biochar/water suspensions increases as a function of HTT, while the pH of other biochars suspensions is not so depended on HTT; these are generally alkaline. In general, feedstocks with high ash contents will result in high pH biochars due to the formation of alkaline minerals during pyrolysis, even at relatively low temperatures. GHW and OP biochars had a high soluble salt content (high EC) due their high original mineral content. The GHW biochars were produced from pepper plants grown in the Arava on saline water, hence their high salt content.

Table 2. Physical and chemical characteristics of produced biochars. Results published in [15].

| **Feedstock** | **Eucalyptus (EUC)** | | | | **Olive Pomace (OP)** | | | **Greenhouse Waste (GHW)** | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **HTT[a] /°C** | 350 | 450 | 600 | 800 | 350 | 450 | 600 | 350 | 450 | 600 |
| **SSA[b] /$m^2$ $g^{-1}$** | 13 | 108 | 133 | 217 | 0.2* | 0.2* | 3* | 2.7* | 4.0* | 19* |
| **C[c] /wt %** | 69.3±3.46 | 72.6±4.36 | 76.7±3.07 | 76.3±4.58 | 36.8±2.15 | 66.5±1.2 | 54.7±1.59 | 40.2±1.5 | 51.5±0.3 | 13.2±1.6 |
| **H /wt %** | 3.1±0.12 | 2.2±0.11 | 1.9±0.06 | 1.30±0.065 | 1.80±0.097 | 2.50±0.037 | 1.50±0.069 | 1.90±0.1 | 4.80±0.6 | 0.30±0.034 |
| **N /wt %** | 1.3±0.19 | 1.5±0.25 | 1.0±0.20 | 1.60±0.21 | 1.60±0.29 | 2.50±0.11 | 1.00±0.19 | 1.30±0.04 | 3.10±0.1 | 0.50±0.06 |
| **O /wt %** | 17.7±0.88 | 9.4±0.28 | 7.10±0.35 | 9.20±0.37 | 59.80±3.2 | 28.6±2.14 | 42.7±2.55 | 5.50±1.6 | 14.10±0.8 | 8.00±1.7 |
| **O/C** | 0.19±0.01 | 0.10±0.01 | 0.07±0.004 | 0.09±0.01 | 1.22 ±0.10 | 0.32±0.02 | 0.59±0.04 | 0.10±0.03 | 0.21±0.01 | 0.45±0.11 |
| **H/C** | 0.54±0.03 | 0.36±0.03 | 0.30±0.01 | 0.20±0.02 | 0.59±0.05 | 0.45±0.01 | 0.33±0.02 | 0.57±0.04 | 1.12±0.14 | 0.27±0.05 |
| **C/N** | 62.9±9.83 | 56.5±10.18 | 89.5±18.25 | 55.6.±7.97 | 26.8±5.11 | 31.03±1.48 | 63.8±12.27 | 36.08±1.74 | 19.38±0.64 | 30.8±5.25 |
| **H/O** | 2.80±0.18 | 3.74±0.22 | 4.28±0.25 | 2.26±0.14 | 0.48±0.04 | 1.40±0.11 | 0.56±0.04 | 5.53±1.63 | 5.45±0.75 | 0.60±0.14 |
| **Ash[d] /wt %** | 8.4±0.33 | 13.9±0.39 | 12.9±0.28 | 11.60±0.80 | 4.40±0.686 | 8.9±0.79 | 28.8±0.698 | 51.4±1.34 | 35.1±1.01 | 78.0±1.29 |
| **Ca /wt %** | 1.93±0.06 | 2.51±0.08 | 2.95±0.02 | n.a.[e] | 0.51±0.04 | 1.20±0.05 | 2.94±0.05 | 3.91±0.08 | 3.66±0.04 | 6.14±0.09 |
| **Mg /wt %** | 0.19±0.02 | 0.29±0.01 | 0.31±0.01 | n.a. | 0.08±0.01 | 0.18±0.02 | 0.42±0.00 | 0.72±0.03 | 1.23±0.01 | 1.27±0.06 |
| **K /wt %** | 0.46±0.01 | 0.60±0.002 | 0.56±0.01 | n.a.. | 1.24±0.09 | 2.33±0.09 | 4.45±0.10 | 1.06±0.02 | 0.94±0.03 | 1.17±0.01 |
| **Na /wt %** | 0.09±0.005 | 0.12±0.002 | 0.11±0.004 | n.a. | 0.13±0.01 | 0.14±0.001 | 0.48±0.003 | 0.14±0.003 | 0.59±0.002 | 0.25±0.009 |
| **S /wt %** | 0.06±0.006 | 0.08±0.003 | 0.07±0.001 | n.a. | 0.05±0.003 | 0.05±0.001 | 0.20±0.01 | 0.21±0.002 | 0.16±0.007 | 0.21±0.009 |
| **P /wt %** | 0.07±0.001 | 0.1±0.0004 | 0.10±0.001 | n.a. | 0.06±0.01 | 0.18±0.01 | 0.42±0.0003 | 0.36±0.007 | 0.31±0.001 | 0.50±0.009 |
| **Fe /wt %** | 0.39±0.001 | 0.29±0.001 | 0.31±0.018 | n.a. | 0.21±0.04 | 0.17±0.02 | 1.39±0.03 | 0.69±0.028 | 0.22±0.009 | 0.76±0.025 |
| **Zn /wt %** | 0.01±0.001 | 0.02±0.001 | 0.02±0.001 | n.a. | 0.00±0.002 | 0.01±0.0001 | 0.06±0.001 | 0.02±0.001 | 0.02±0.003 | 0.01±0.001 |
| **Mn /wt %** | 0±0.00026 | 0.01±0.00004 | 0.01±0.0002 | n.a. | 0.01±0.0001 | 0.01±0.00 | 0.02±0.0002 | 0.02±0.0006 | 0.01±0.0003 | 0.02±0.0001 |
| **Al /wt %** | 0.03±0.003 | 0.04±0.002 | 0.03±0.0009 | n.a. | 0.04±0.017 | 0.04±0.002 | 0.16±0.003 | 0.29±0.006 | 0.18±0.006 | 0.44±0.004 |

[a]HTT- pyrolysis highest treatment temperature; [b]SSA – specific surface area. Average of two replicates is given, with the exception of those designated by *, where only one replicate was measured; [c] – C, H, N, O and their ratios - results are average and standard error of 3 samples; [d] – Ash and elements – results are average and standard error of 6 replicates; [e] n.a. – not analyzed

Table 3. Chemical characteristics of biochar aqueous extracts. Results published in [15].

| Biochar | DOC[a] (mg/l) | Redox Potential[b] ($E_h$) (mV) | pH | EC[c] (mS/cm) | Total Phenols (μmol GAE[d]/l) | Total Phenols (μmol GAE/mg DOC) |
|---|---|---|---|---|---|---|
| EUC[e]-350 | 74 | 119 | 6.9 | 0.81 | 17.5 | 0.236 |
| EUC-450 | 44 | 90 | 8.8 | 1.01 | 8.2 | 0.186 |
| EUC-600 | 28 | 132 | 9.7 | 0.77 | <MDL[f] | <MDL |
| EUC-800 | 24 | -17 | 10.6 | 1.15 | <MDL | <MDL |
| OP[g]-350 | 371 | 23 | 9.4 | 3.22 | 126 | 0.338 |
| OP-450 | 404 | 27 | 9.7 | 3.94 | 149 | 0.368 |
| OP-600 | 85 | 32 | 10.1 | 5.86 | 10.8 | 0.127 |
| GHW[h]-350 | 248 | 13 | 9.9 | 7.31 | 133 | 0.537 |
| GHW-450 | 427 | 5 | 9.7 | 8.51 | 204 | 0.478 |
| GHW-600 | 42 | -29 | 10.7 | 7.71 | 6.2 | 0.148 |
| Water | 2 | 443 | 4.7 | 0.001 | <MDL | <MDL |

Notes: For biochar extracts, properties were measured in 1:20 weight:volume biochar:deionized water mixed for 24 hours and filtered with a 0.22 μm filter

[a]DOC - Dissolved Organic Carbon. Reproducibility of DOC analysis is better than 7%.

[b]Redox Potential (Eh) – Reproducibility is better than 10%.

[c]EC - Electrical Conductivity

[d]GAE - Gallic Acid Equivalents

[e]EUC – Biochar made from Eucalyptus wood chips at highest treatment temperature (HTT) in $^{o}$C as specified by number following EUC-

[f]MDL - Method Detection Limit. The MDL for total phenols is 3 μmol GAE $l^{-1}$, and the reproducibility (3 replicate analyses) for a given sample is better than 5%.

[g]OP - Biochar made from Olive Pomace at highest treatment temperature (HTT) in $^{o}$C as specified by number following OP-

[h]GHW - Biochar made from Greenhouse Waste at highest treatment temperature (HTT) in $^{o}$C as specified by number following GHW-

[j]n.a. – not applicable

### *Reducing potential*

As shown in Table 3, we found that aqueous extracts of various biochars are frequently reducing in nature (published in [15]). Biochar, being produced in an oxygen-restricted environment, is chemically more reduced than the original feedstock. Consequently, we hypothesized that reduced biochar components could participate in redox-mediated reactions in the soil. This hypothesis was tested by measuring the reducing capacities of aqueous extracts of biochars and the reduction and solubilization of soil Mn and Fe oxides by the extracts. The reduction capacity of extracts from biochars produced from three feedstocks (eucalyptus wood, EUC; olive pomace, OP; and greenhouse waste, GHW) at different highest pyrolysis treatment temperatures (HTT; 350, 450, 600 and 800oC) was less for the EUC feedstock than the others, and was greater for biochars produced at lower HTTs. The organic fraction of the extracts was responsible for the major part of the reducing capacity. Extracts of lower-HTT biochars, having greater dissolved organic carbon (DOC) contents, had greater reducing capacities than extracts of higher-HTT biochars from the same feedstock. Extracts of two GHW biochars (GHW-450 and GHW-600) solubilized Mn and Fe from soils at pH values below 8 (shown for Mn in Fig. 3.). The extract with the greater reducing capacity (GHW-450) solubilized both metals to a significantly greater extent. Lower-HTT biochars produced from agricultural wastes, having a greater variety and concentration of soluble reducing agents, are expected to have more impact on soil redox reactions than higher-HTT biochars. By participating in chemical and biological redox-mediated reactions in the soil, biochar could influence microbial electron shuttling, nutrient cycling, pollutant degradation, contaminant mobilization, and abiotic formation of humic structures. This work is published in [15].

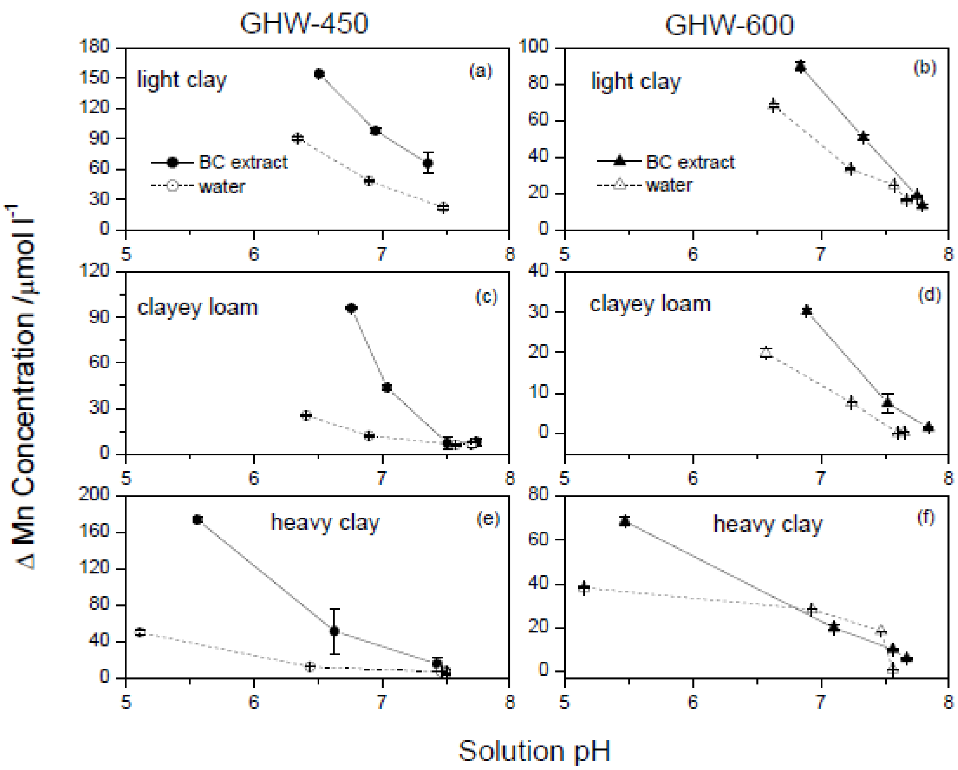


Fig. 3. Release of soil Mn from 3 different soils into aqueous extract of two biochars as a function of solution pH.

***GC/MS***

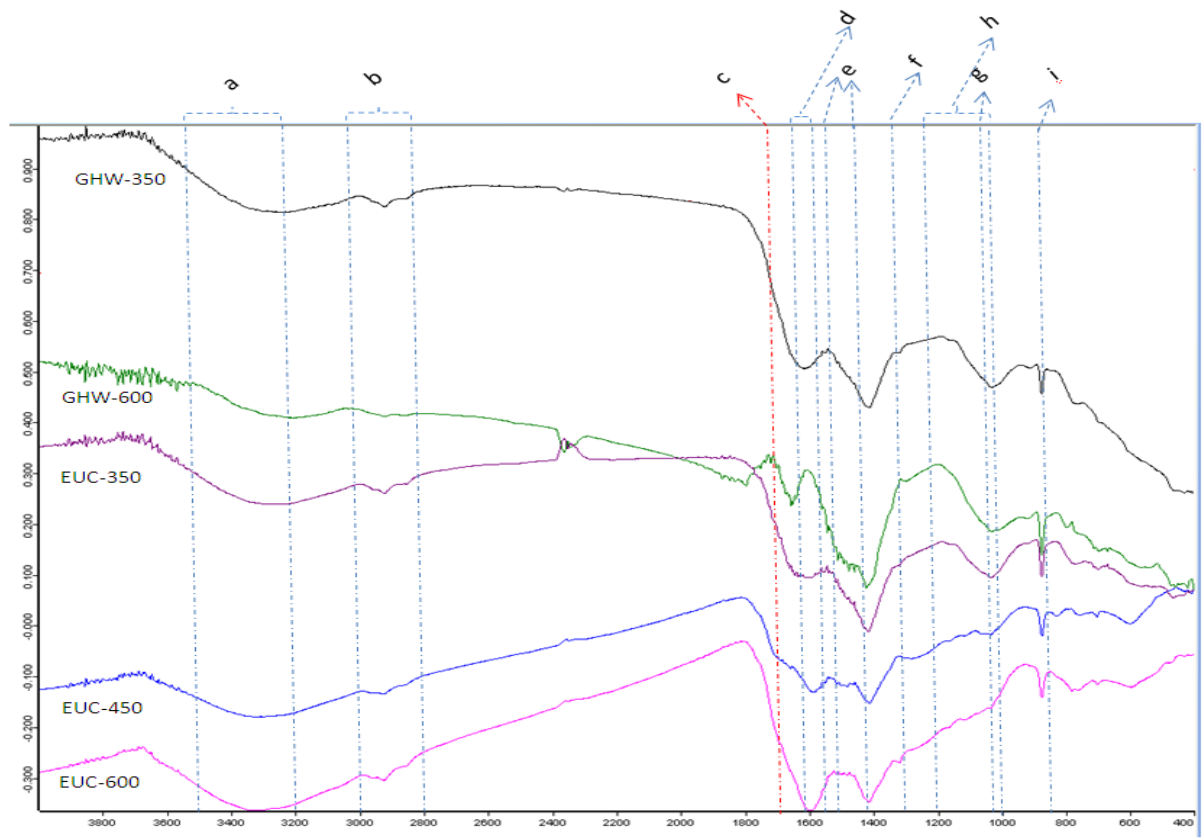
In many instances, we also characterized by GC/MS the identities of small organic compounds released from different biochars. This characterization was carried out as required to answer specific research questions. One example is given below, where the organic components of aqueous extracts of GHW-450 and GHW-600 were characterized (Table 4).

Table 4. Compounds identified in aqueous extracts of two biochars. From [15].

| RT (min) | Compound | Class | GHW-450 | GHW-600 |
|---|---|---|---|---|
| 18.368 | Lactic acid | hydroxy acid | Y | Y |
| 19.288 | Hexanoic acid | n-alkanoic acid | Y | |
| 19.537 | Hydroxy-acetic acid | hydroxy acid | Y | Y |
| 23.099 | Ethandioic acid | dicarboxylic acid | | Y |
| 24.0623 | 4-hydroxy-butyric acid | hydroxy acid | Y | |
| 26.963 | Benzoic acid | benzoic acid | Y | Y |
| 27.006 | Urea | urea | Y | |
| 27.646 | Octanoic acid | *n*-alkanoic acid | Y | |
| 27.952 | Glycerol | polyol | Y | Y |
| 29.235 | Succinic acid | dicarboxylic acid | Y | Y |
| 29.371 | 2-Methyl benzoic acid | substituted benzoic acid | Y | |
| 29.564 | 2-Methyl butanedioic acid | dicarboxylic acid | Y | Y |
| 29.659 | Glyceric acid | hydroxy acid | Y | Y |
| 30.610 | Nonanoic acid | *n*-alkanoic acid | Y | |
| 31.879 | Glutaric acid | dicarboxylic acid | Y | |
| 31.986 | 2,4-bis[hydroxy] butanoic acid | hydroxyl acid | Y | |
| 32.171 | Benzenepropanoic acid | aromatic organic acid | Y | |
| 33.159 | Decanoic acid | *n*-alkanoic acid | Y | |
| 34.439 | Butane-1,2,3,4-tetraol (Erythritol) | polyol | Y | |
| 34.462 | Pentane-1,2,5-triol | polyol | Y | |
| 34.815 | 5-Oxo-pyrrolidine-2-carboxylic acid (Pyroglutamic acid) | substituted heterocyclic amine | Y | Y |
| 34.825 | Piperidine-2-carboxylic acid | substituted heterocyclic amine | | Y |
| 35.078 | 2-Hydroxy-pentandioic acid | dicarboxylic acid | Y | |
| 32.297 | Erythronic acid | sugar acid | | Y |
| 32.300 | Threonic acid | sugar acid | | Y |
| 35.941 | 3-Hydroxy-benzoic acid | substituted benzoic acid | Y | |
| 37.539 | 1H-benzoimidazole,1-(2-ethoxyethyl)-2-(4-methoxyphenyl) | substituted imidazole | Y | |
| 38.208 | 2,4,5-Trihydroxypentanoic acid | hydroxy acid | Y | |
| 38.837 | Ethane-1,2-diol (Ethylene glycol) | diol | Y | |
| 39.048 | 1,6-Anhydroglucose | anhydrosugar | Y | |
| 39.329 | Ribitol | reducing sugar | Y | |
| 43.618 | Mannitol | sugar alcohol | Y | Y |
| 46.100 | Hexadecanoic acid | *n*-alkanoic acid | Y | Y |
| 46.699 | Myo-inositol | polyol | Y | Y |
| 49.643 | Octadecanoic acid | *n*-alkanoic acid | Y | Y |
| 55.116 | 1-Monohexadecanoylglycerol | glycerol ester | Y | |
| 55.119 | 2,3-bis[(hydroxyl)propyl]-hexadecanoic acid | carboxylic acid | Y | |
| 57.130 | Melezitose | trisaccharide | | Y |
| 57.135 | Trehalose | disaccharide | Y | |
| 57.916 | Monooctadecanoylglycerol | ketoglycerol | Y | |

***FTIR***

Likewise, FTIR analyses were carried out as needed to characterize biochar surfaces. Examples are given in Figure 4 below.




a –OH stretching`
b Aliphatic CH stretching.
c Aromatic carbonyl/carboxyl C=O stretching
d aromatic C=C vibration.
e Aromatic C=C ring stretching.
f Aliphatic CH2 deformation.
g Aliphatic ether C–O– and alcohol C–O stretching.
h C-O stretching vibration from carbohydrates.

Figure 4. FTIR spectra of KBr pellets for 5 different biochars.

### *CEC and Acid Group Content*

We also characterized cation exchange capacity (CEC) and anion exchange capacity (AEC) as a function of pH of a number of biochars (Fig. 5). CEC is a quality which can control the behaviour of important nutrient cationic species in the soil (e.g., $NH_4$, Ca, Mg, Zn, etc.), while AEC can affect nutrient anions such as $NO_3$ and $PO_4$. In Figure 5 (top) it is seen that CEC increases as pH increases for all the tested biochars. AEC does not depend on pH, and is higher for higher HTT biochars (Fig. 5, middle). Results are from the M.Sc. thesis of Eyal Cohen, Hebrew University.

To examine the cause of the pH-dependence of biochar CEC, Boehm titrations were conducted to determine the distribution of surface acid groups. This method was modified by us for use for biochar, and a detailed description can be found in [16]. Results of the Boehm titration of several biochars are given in Table 5. The pH-dependence of the CEC was found to depend on the content of lactonic acid groups, and less so on the content of phenolic acid groups, at biochar surfaces (Fig. 5, bottom).

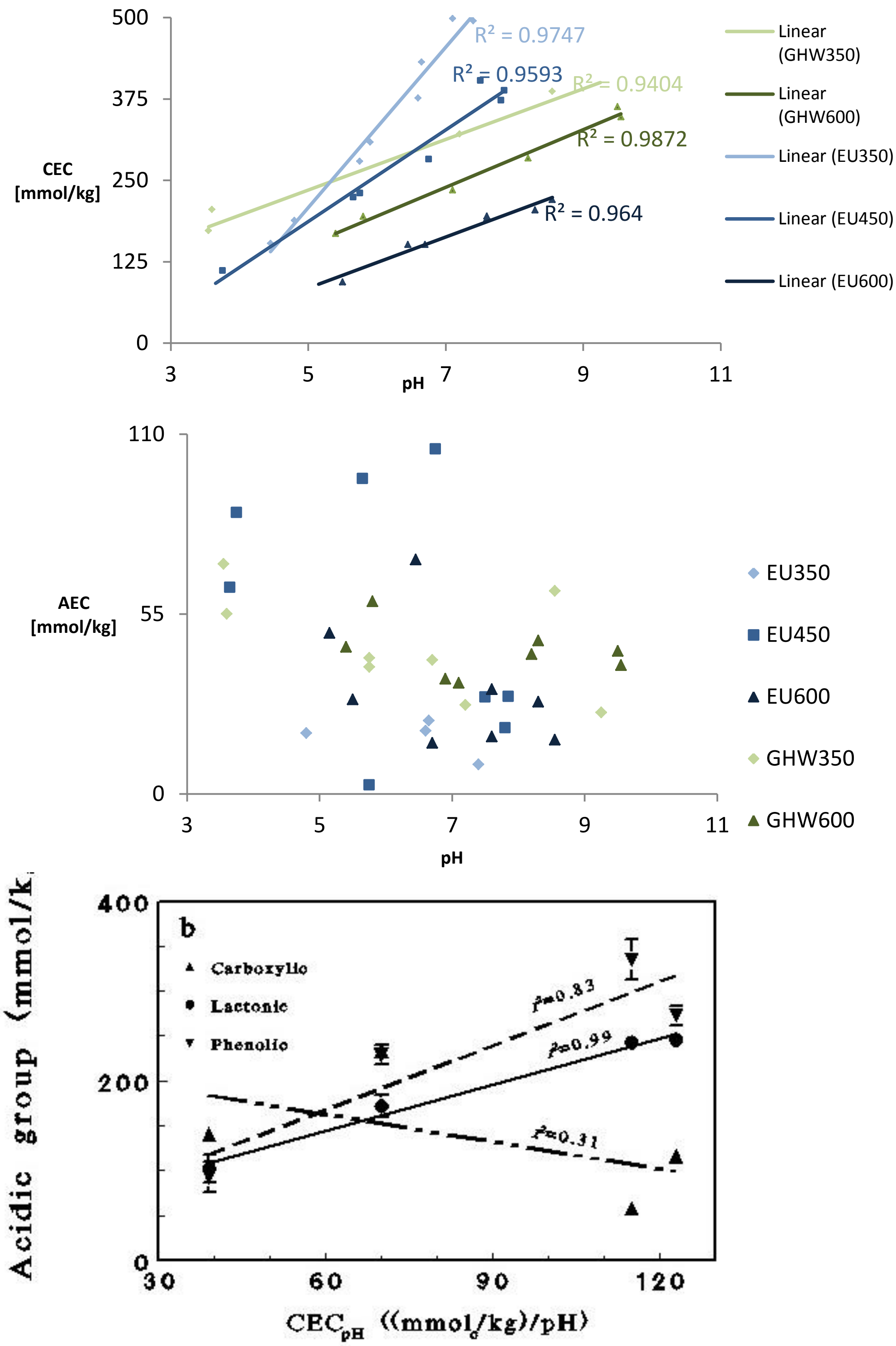



Figure 5. Upper and middle panes: CEC (upper) and AEC (middle) as a function of pH for different biochars. Results from the M.Sc. thesis of Eyal Cohen, Hebrew University. The slope of the CEC vs pH regressions are shown in the bottom pane as a function of biochar surface acidic functional groups for the 3 EUC biochars and a cornstraw biochar.

Table 5. Results of modified Boehm acidity titrations for total acidity (TA), carboxylic, lactonic and phenolic acidities, and cation exchange capacity (CEC).

| Sample | Total Acidity (TA) (mmol/kg) | Carboxylic Acid Groups (mmol/kg) | Lactonic Acid Groups (mmol/kg) | Phenolic Acid Groups (mmol/kg) | CEC ($mmol_c$/kg) | Slope CEC vs pH regression ($mmol_c$/kg/pH unit) |
|---|---|---|---|---|---|---|
| $CS_{Ac}$ | 635 ± 21 | 58 ± 3 | 243 ± 6 | 335 ± 22 | 509 ± 11 (pH 7.4) | 115 ± 8.4 |
| | | | | | 383 ± 19 (pH 6.3) | |
| | | | | | 222 ± 25 (pH 4.9) | |
| EUC-350 | 635 ± 8 | 116 ± 7 | 246 ± 10 | 273 ± 11 | 602 ± 30 (pH 8.7) | 123 ± 8.1 |
| EUC-450 | 633 ± 3 | 233 ± 3 | 172 ± 12 | 229 ± 11 | 492 ± 25 (pH 8.7) | 70 ± 6.5 |
| EUC-600 | 328 ± 6 | 141 ± 3 | 102 ± 16 | 93 ± 17 | 210 ± 10 (pH 8.7) | 39 ± 3.4 |
| EUC-800 | 260 ± 3 | 45 ± 1 | 60 ± 14 | 155 ± 14 | na | na |

Notes: Mean ± standard error given. pH-relevant CEC of EUC biochars was computed from regressions of CEC vs pH shown in Figure 5 (bottom). CEC values for $CS_{Ac}$ (cornstraw) biochar were computed from regression of CEC vs pH published by us [CEC ($mmol_c$/kg) = 115·pH – 342 ($r^2$ = 0.99)] [17]. Results of Modified Boehm titration for EUC-450 and EUC-600 biochars were published in [16].

### *Adsorption of Pesticides*

Biochars often exhibit high adsorption and retention capacity towards many organic compounds, including soil-applied herbicides and insecticides. Qualities of biochar which impact its adsorption ability include the extent of crystallinity of the carbonaceous structure, porosity, and specific surface area (SSA), all of which grow as pyrolysis temperature increases. SSA of biochar produced from Eucalyptus wood chips, for example, increases from 13 $m^2\ g^{-1}$ at production temperatures below 400°C to more than 200 $m^2\ g^{-1}$ at an HTT of 800°C (Table 2). Other adsorption-impacting qualities of biochar that vary as a function of feedstock and pyrolysis conditions include pH, cation exchange capacity (CEC), surface group functionality, and surface heterogeneity. These qualities can also impact desorption kinetics, which may be hindered. A soil amendment with such adsorption characteristics can have either positive or negative impacts on pest management in agricultural soils. On the one hand, enhanced adsorption to the solid phase can reduce leaching of soil-applied herbicides and insecticides and protect pesticides from degradation. On the other hand, strong adsorption of pesticides on biochar can result in their inactivation, or can potentially increase herbicide injury in rotational crops due to herbicide accumulation in the soil. Yet, bioassays that specifically address the impact of biochar added to soil on the efficacy of purpose-applied pesticides against their target pests are few. For this reason, research into this topic was also undertaken under the auspices of this project. The results have been published in two articles [18, 19].

To summarize briefly, we found that activity of a soil fumigant (1,3-dichloropropene) against nematodes was not affected by adding 1.3 t/dunam of a biochar with a low SSA (3 $m^2\ g^{-1}$) [19]. However, to achieve full pesticidal activity at a biochar amendment level of 2.6 t/dunam, the fumigant dose had to be doubled. It was calculated that the maximum manufacturer's recommended fumigant dose would not have been effective against the pest had the biochar an adsorption ability greater by half an order of magnitude. This is realistic for a biochars with SSAs of 100s of $m^2$/g. In the other study, the influence of a low SSA and high SSA biochars on the efficacy of two widely used herbicides, s-metolachlor and sulfentrazone, against the weed Green

Foxtail was tested [18]. In that study too, it was found that the use of high SSA biochar for agronomic purposes can considerably reduce availability of soil-applied pesticides. In the best case, amendment with a biochar having a high SSA at levels up to 2.6 t/dunam can greatly increase the pesticide dose required to obtain adequate pest protection. In the worst case, biochar amendment may render soil-applied pest control agents ineffective. In so much as the half-life of biochar in soil is 100s to 1000s of years, sustainable soil stewardship requires that this effect be taken into account when applying biochar to soils, an essential and non-renewable resource for food production. Until a more comprehensive set of data and predictive models become available, application of the injunction: *primum non nocere*, first, do no harm, is a precaution worth adopting regarding the use of biochar in field soils. For now, based on the results of this and previous studies, it appears that pest control requirements would be best served by biochars having low SSAs, and at rates no greater than 2 t/dunam. By and large, biochars produced from wood at low HTTs have low SSAs (Table 2), as do those produced from agricultural wastes at all HTTs (Table 2).

## Content and release of nutrient minerals from different biochars

The release of nutritional elements from biochars has often been suggested to contribute to plant nutrition and improved plant performance. To examine this for various plant biomass-derived biochars, we performed a series of experiments measuring the release of various nutritional elements from different biochars as a function of pH. Table 6 shows the range of concentrations of cations released from the various EUC and GHW biochars over a range of pH values. It can be seen that relatively high concentrations of Ca, Mg, K and P are released from the different biochars over a range of pHs.

Table 6. Release of nutrients from EUC (350, 450, and 600) and GHW (350 and 600) biochars over a range of pH from 3.5 to 10. Results from M.Sc. thesis of Eyal Cohen, Hebrew University.

| **Feedstock** | **EUC** | **GHW** |
|---|---|---|
| EC [ms/cm] | 1.4-3.5 | 1.4-6.3 |
| P [mmol/kg] | 3.3-19 | 4.4-67 |
| Ca [mmol/kg] | 34-679 | 50-1500 |
| Mg [mmol/kg] | 12-107 | 11-460 |
| K [mmol/kg] | 88-206 | 207-460 |
| Mn [mmol/kg] | 0.02-0.5 | 0.1-2.5 |
| Zn [mmol/kg] | 0.015-1.5 | 0.01-1 |

An example of the kinetics of release of Ca from different biochars at pH 4 is given in Figure 6. It is seen that release continues over the course of several days before reaching equilibrium. This was the case for most nutrients, with the exception of K, which was released nearly instantaneously from all the biochars. Figure 7 presents final release of different nutrients as a function of pH. It can be seen that for the most part, release decreases as pH increases, with the exception of K, whose release is not pH-dependent. XRD analysis revealed the presence of KCl, which would account for non-pH dependent K release.

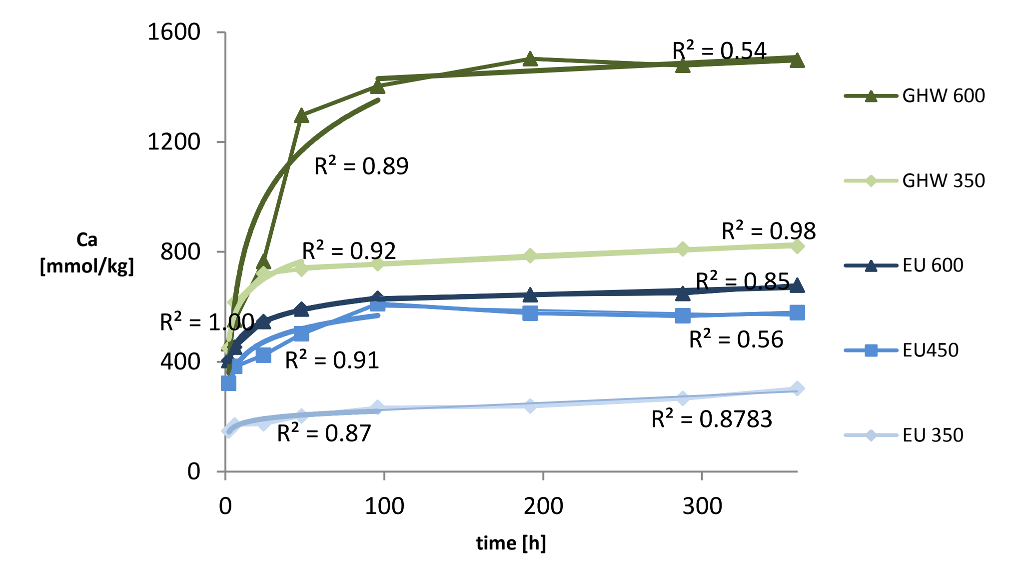
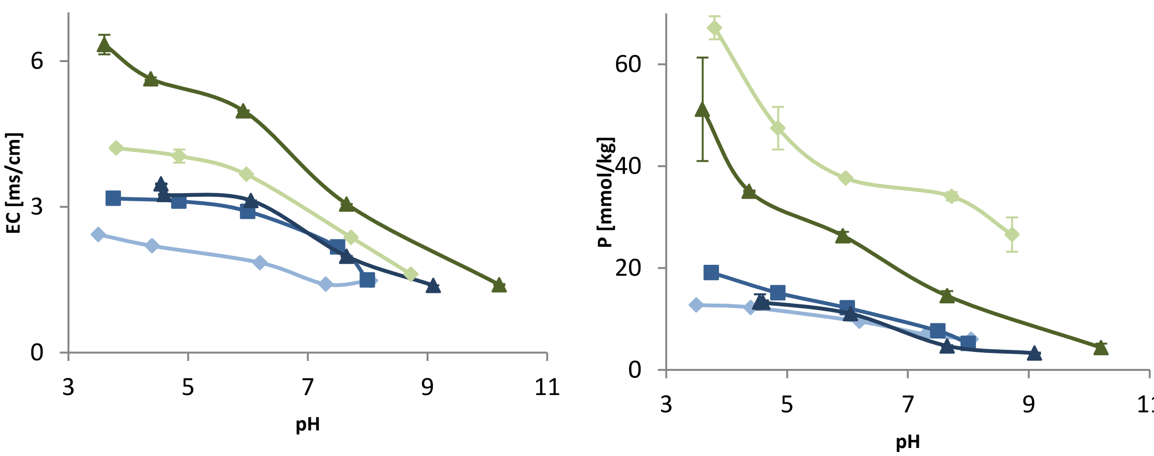
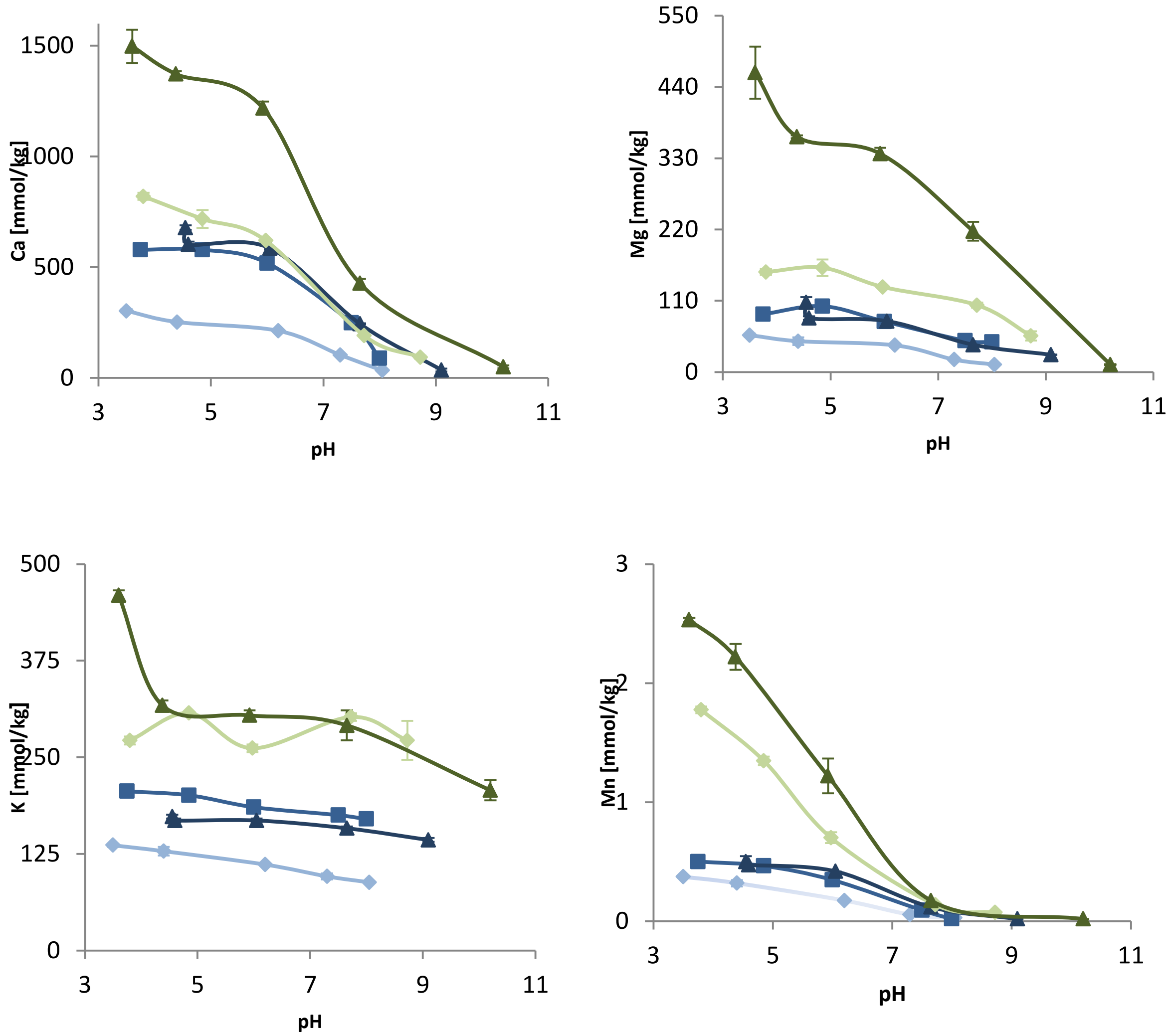



Figure 6. Kinetics of Ca release from 5 biochars at pH 4. Results from M.Sc. thesis of Eyal Cohen, Hebrew University.





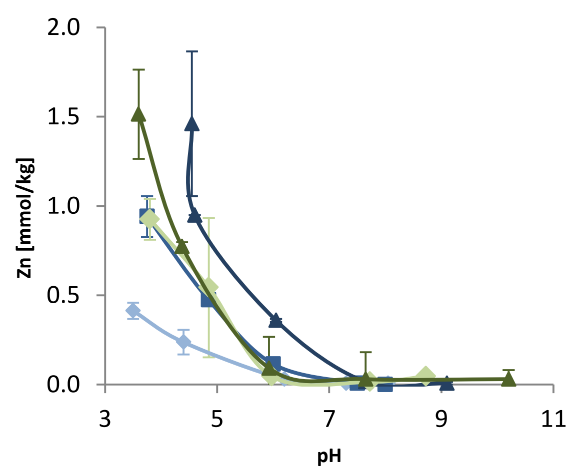




Figure 7. Final release of different nutrients as a function of pH.

Legend:

dark green triangles: GHW-600
light green diamonds: GHW-350
dark blue triangles: EUC-600
medium blue squares: EUC-450
light blue diamonds: EUC-350
Results from M.Sc. thesis of Eyal Cohen, Hebrew University

Despite the large releases of nutritional elements, for the most part, plant-biomass derived biochar will not be able to provide sufficient nutrients for the needs of crops that require intensive fertilizer inputs. This is because the release of the nutrients decreases with time, while plant requirements increase over time. This is seen in a model of P release per day from the different biochars, versus the needs of growing lettuce (Fig. 8). Such a result can be seen for all the elements we modelled. The meaning is that biochar derived from plant biomass is not itself a fertilizer; it must be used in conjunction with either chemical or organic fertilizers. This may not be the case for biochars produced from manures or sludge, which have a high initial content of nutritional elements, and may be a good subject for future research.

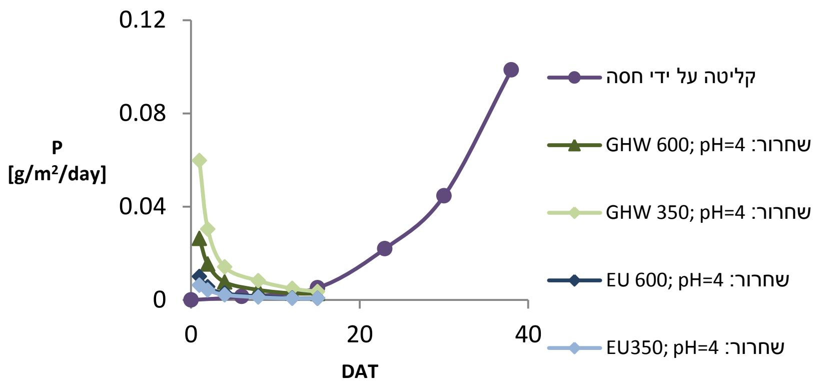



Figure 8. Release of P from different biochars over time, compared with lettuce requirements.

## Effect of biochar additions on soil hydraulic characteristics

This part of the research dealt with the physical aspects of biochar amendment, and primarily answers the question if and how the addition of biochar modifies the hydraulic properties of the soil. In principal, the addition of biochar can change soil hydraulic properties, mainly by changing mean particle size and the mean pore size of the particles. In this study, we focused on changes caused directly by mixing biochar in soil, primarily sandy soils. Our assumption was that the most pronounced changes would be expected in these soils. Experiments were also done to examine the question of whether soil properties change over time (on the assumption that biochemical changes in soil may change aggregation patterns), but the results of this part of the study were not clear (and probably were not very significant in sandy soils).

The main finding was that water retention increases in soils amended with biochar, while changes in hydraulic conductivity were negligible. However, significant changes in water retention were apparent only in the dry range of the water retention curve. The significance of this finding is that in intensively irrigated agriculture there is probably no great benefit (nor damage) from the addition of biochar from a physical point of view, however, in non-irrigated agriculture, it will probably be much more significant as the slight addition to the moisture content from the addition of biochar may make the difference between a wheat field that survives the dry periods between rainfall episodes and a wheat field that doesn’t survive.

### Materials and Methods

#### *Soil and biochar*

In these experiments, two soils were studied, a sandy soil (from the Mikhmoret area) and a Hamra soil. Particle size distribution was measured by sieving for the sandy soil and by the hydrometer method for the Hamra soil. The biochar was produced from eucalyptus wood chips. Before use, the biochar was ground by mortar and pestle. For each treatment, air-dried sieved soil (<4 mm) was mixed with a known amount of biochar and stored until it was used.

### *Measurement of hydraulic properties*

To cover a wide range of suctions, soil hydraulic properties were measured by different methods, with each method covering a different range. For low suction values ($-10 \le h \le 0$, where *h(m)* is the matric potential), hydraulic properties were measured using the HYPROP device, (UMS, Germany), the middle range ($-50 \le h \le -5$) used a pressure plate (Soil Moisture Equipment Corp., CA, USA), and the high suction range ( $-3 \times 10^{-4} < h < -30$) was measured with a WP4C Dewpoint Potentiometer (Decagon Devices, WA, USA). Below we briefly review each of the measurement methods.

#### Evaporation method (HYPROP)

In the evaporation method, the hydraulic parameters of the soil are calculated by measuring the flow of water evaporating from the soil and the matric potential. The system consists of a sampling cell containing two tensiometers that are connected to a computer. After packing the soil in the measuring cell, the soil is saturated with water, and from that moment the water is allowed to evaporate from the surface. The cell is weighed periodically, so that the evaporative flow rate can be calculated. In addition to the weights, the matric potential was measured at two depths. Based on these measurements, we can estimate the parameters associated with the water retention curve of the soil and the hydraulic conductivity function.

#### Pressure plate method

This method is a well-known standard method. The soil samples were placed on a ceramic plate, brought to a saturated state, and then subjected to an external pressure that ranged from 0.5 to 15 atmospheres. After reaching equilibrium, samples were removed from the pressure plate and the soil water capacity was measured. Using this method it is possible to evaluate parameters associated with the retention curve in the measured pressure ranges.

#### Dewpoint measurement

With this method, the matric potential is measured over a wide range of low matric potentials ($-3 \times 10^{-4} < h < -30$). The idea behind this method is to measure the relative humidity above the soil sample and then afterwards to cool a mirror placed in a measurement cell to the dew point (the temperature at which a drop of water is formed on top of the mirror). The relationship between dew point and the above ground water vapor pressure allows one to determine the soil matric potential.

### *Data Analysis*

Matric potential was obtained as a function of the water capacity, and therefore quantitative analysis of the results required adjustment of the data to the retention curve. The most common function used for the retention curve is the Van Genuchten-Mualem function

$$\frac{\theta-\theta_r}{\theta_s-\theta_r}=\left[1+\left(\alpha|h|\right)^n\right]^{-m} \qquad (1)$$

Where $\theta, \theta_r, \theta_s$ are the saturated moisture content, the residual moisture content and the soil moisture content, respectively, $\alpha\,(L^{-1})$ and $n\,(-)$ are the parameters related to the hydraulic properties of the soil and $m = 1 - 1/n$. Since the Van Genuchten-Mualem retention curve was developed with the assumption that the distribution of water in soil is comparable to the distribution of water in a collection of many very small capillaries, this model is not suitable for the "dry range" of the water retention curve. The reason for this is derived from the fact that at low moisture contents, the influence of the surface area becomes much more important. Therefore, for the dry range of the curve, we used the model of [20].

$$\omega = \sqrt[3]{\frac{A_{svl}}{6\pi\rho_w\psi}} SA\rho_w \qquad (2)$$

where $\omega$ is the weight determined moisture capacity, $A_{svl}\ (J)$ is the Hamaker constant, for the interaction between solids and gas, $\rho_w\,(kg{\cdot}m^{-3})$ is water density and $SA(m^2{\cdot}kg^{-1})$ is the specific surface area. In fact, this model links the water capacity to the specific surface area of the soil and not the pore radius, and is therefore more appropriate when most of the water is located near the solid surface. The parameters of both models were obtained by solving the appropriate optimization problem and use of the Isqnonlin function in MATLAB ©.

**Results and Discussion**

Figure 9 presents a retention curve in the low moisture range for a sandy soil with biochar concentrations between 0 and 5 percent. In general the behavior of the curve is suitable for the accepted results found in the literature that describe a retention curve for low moisture conditions [20]. For most measurements, the clean sand (no biochar) had a lower water retention value than sand mixed with biochar. Also it can be seen that at most suctions, as the percentage of biochar is higher, the water retention is greater. In any case, it should be noted that the curve represents the results in the dry range $(0 < \theta < 0.04)$, for which a classical retention model (i.e., the Van Genuchten-Mualem model) is not appropriate. Quantitative analysis of the retention curve shown in Figure 9 requires a model that is applicable in the dry range of the retention curve, where secondary capillary forces and surface forces are dominant [21]. Based on the model of [20] (see Equation 2.1 of that paper) and the experimental results, the specific surface area of each treatment was calculated.

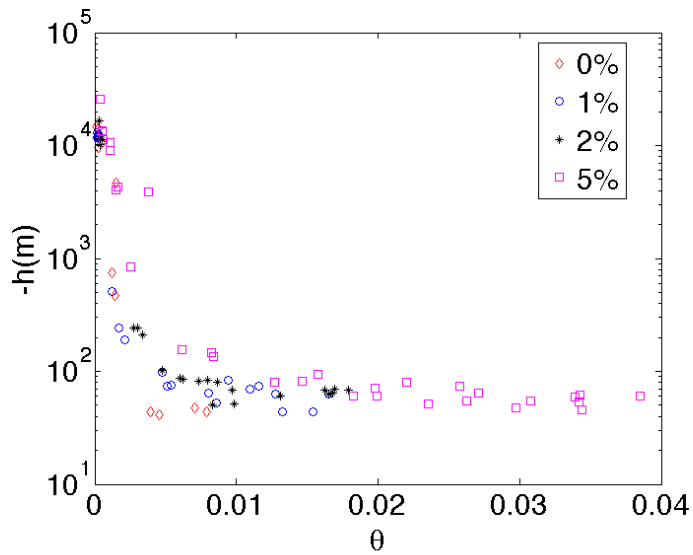



Figure 9. Retention curve (minus the matric potential of as a function of the volumetric water capacity) at low water capacities in sandy soils amended with different percentages of biochar (see legend). The measurements were done using the WP4C device (see methods section).

Figure 10 shows the specific surface area of the different treatments. It can be seen that the addition of biochar significantly increases the specific surface area of the soil (a difference of over 350% from 0 to 5% biochar). These results are not surprising for two reasons. First, it is generally known that the specific surface area (SSA) of biochar can be high [22] and secondly, the specific surface area of clean sand is low (<<1 $m^2$ / g). In fact, the results show that the increase in water retention at low water capacities by the addition of biochar is due to high specific surface area, and therefore more water adsorption on the solid surface.

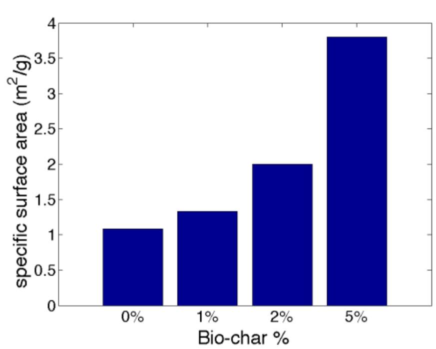



Figure 10: Specific surface area of different treatments as obtained from the model [20].

Figure 11a shows the retention curve in the low water content range for the Hamra soil. In this figure you can see the suitability of the measurements for the [20] model. The Hamra soil had a better fit for the model. It should be noted that fitting was done at matric potentials below -1000 m, since at these levels it can be assumed that these potentials a model based on increased capillarity would be more suitable. It is interesting to see that for the Hamra soil, no increase in water retention with an increased level of biochar was observed, except for the 5%

treatment at the wet end of the curve. Actually, the fact that the changes in the specific surface area among the treatments were not significant or unidirectional (Figure 11b) strengthens this conclusion.

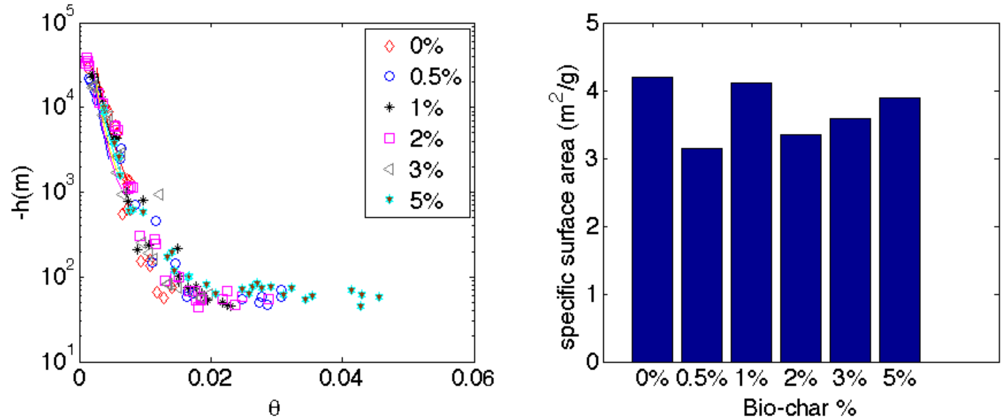



Figure 11: Retention curves at low water contents (a) and SSA (b) of a Hamra soil at different biochar concentrations. Note that the lines of the retention curve represent the suitability of the model [20].

The results seem to indicate that for a coarse textured soil (sand) with a low initial SSA, the addition of biochar significantly increased the SSA and consequently, also water retention. In contrast, when the soil texture was finer (Hamra), and the initial SSA higher, the addition of biochar had almost no effect on the hydraulic properties of the soil. It should be noted that these conclusions are suitable for extremely dry conditions where the contribution of capillarity to water retention is relatively small.

Figure 12 shows the retention curves for low capillarity as obtained by the Hyprop system for sandy soils with varying biochar concentrations. The results indicate that even at low suction levels, the addition of biochar improves soil water retention, where the most significant differences were for biochar concentrations of 5%. The results also show that there was no significant difference in the retention curves after the addition of 1% or 2% biochar.

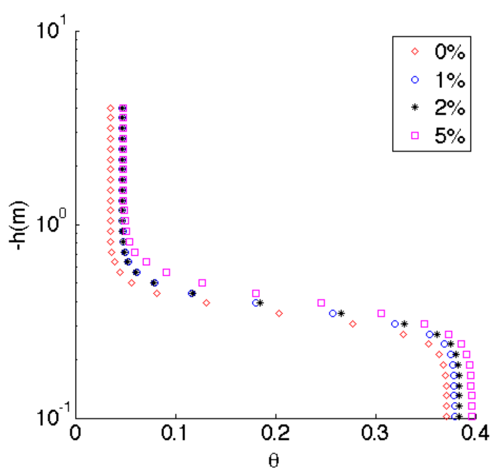



Figure 12: Retention curves for a sandy soil at different biochar concentrations as obtained by the Hyprop system.

It should be noted that retention curves obtained over the range tested has two steps, each one representing a different mechanism related to water retention. The first step (Fig. 12) is associated with capillary retention, whereas the second step (for example Fig. 9) is associated with water retention on the surface area of a solid, i.e. a function of the specific surface area. It can be seen that the addition of biochar affects both processes, although the impact is significantly greater at high suctions levels.

### Conclusions

In conclusion, this study examined the effect of biochar on the hydraulic properties of a sandy (beach sand) and a loamy (Hamra) soil. The results indicate that the addition of biochar increased water retention, especially for the sandy soil at high suction levels. The results further indicate that biochar addition increased the SSA of the soil and therefore also its water retention, which can be explained by a mechanism related to water adsorption on a solid surface. Furthermore, in the ranges where water is influenced by capillary forces, water retention was improved as a result of the addition of biochar. In practical terms, the results indicate that biochar has the potential to increase water availability for plants, mainly for non-irrigated crops, since irrigated crops have relatively higher water contents and therefore the effect of biochar on them will be relatively small. The results also indicate that the effect of biochar on heavy soils would be expected to be relatively small, since the relative contribution of biochar to the SSA would be negligible. It should be remembered that in this study we focused on the direct effects of biochar on soil and did not examine processes that might be influenced by the presence of biochar (e.g. aggregation), which in turn have an impact on the hydraulic conductivity of the soil.

## Impact of biochar additions on crop yield, quality, disease severity, and microbial populations in pot experiments

### Basil

#### *Background*

Sweet basil (*Ocimum basilicum* L.) is an annual herb crop grown in polyethylene-covered structures in Israel; its production is mainly found along the ridge above the Syrian-African Rift, south of the Sea of Galilee and around and north of the Dead Sea. Winter crops are planted from October to December in detached growth media or directly in soil. Fifteen- to 20-cm-long pieces of shoots of sweet basil are harvested repeatedly several times a season. Following each harvest side buds grow and plants continue growing by branching. Increasing energy costs over the last 10 years have discouraged growers from heating their greenhouses and, consequently, the prevalence of humidity promoted diseases such as gray mold (*Botrytis cinerea*) have increased significantly. Recently we have encountered severe downy mildew (*Peronospora belbahrii*) in sweet basil production.

#### *Materials and Methods*

Experiments were carried out in a greenhouse in Kefar Menachem. The polyethylene covered greenhouse measure 27 x 27 m, 3.5 m gutter height. Day-time temperature was kept at 25-30°C. Fertigation was done with on-pipe drippers of 1.2 l/h 3 times per day, 5-10 min each irrigation. A 17-10-27 NPK fertilizer was used to administer 100 ppm N. Sweet basil (cv. Peri) plants received from Hishtil nurseries were planted on 29.9.13 (first exp.) and on 5.1.14 (second experiment) in a coconut fiber based growing medium. The experiment was conducted in 100 × 50 × 15, five boxes (replicates) per treatment, each planted with 15 plants. Treatments consisted of no biochar (control), and biochar mixed in the growing medium at either 1 or 3% by weight. The biochars were produced using the Udine unit from Yard Waste (YW) and date palm fronds (Palm), as well as commercially obtained citrus wood (CW; at 1% only). Fifteen cm long sweet basil shoots were cut from each replicate once every week; shoots were counted and weighed. Ten shoots were sampled from each replicate for testing postharvest quality at selected dates after incubation at 10-20°C. Microorganism populations were evaluated by plating washings of washed roots on specific growth media that promote the growth of fungi, yeasts, *Trichoderma*, bacteria, pseudomonads and actinomycetes. Severity of typical symptoms downy mildew on leaves was evaluated once each week after first symptoms appeared. The intensity of yellowing of leaf blades and of sporulation on the underside of leaves were evaluated on a 0-100 scale where 0=healthy leaf and 100=complete coverage of the leaf.

## *Results*

The first experiment focused on the effect of biochar on plant growth. Treatments with the 1% yard waste and date palm biochars resulted in significantly higher cumulative yield (13%) as expressed in number of shoots and in their weight (Fig. 13). The date palm and citrus biochar had more canopy than the untreated control as measured by whole canopy technical harvest on 19.12.13 (Fig. 14). Postharvest quality of the shoots was tested by evaluating their wilt intensity on mid-December. The 3% yard waste biochar induced better postharvest keeping (Fig 15).

The microbial populations in the rhizosphere of the sweet basil roots were evaluated during the month of December 2013. The different biochars selectively induced higher populations of bacteria in general, pseudomonads and streptomycetes (YW 3%), and also of general fungi (1-3% YW and 1% Palm), yeasts (1% YW and 1-3% Palm) and of *Trichoderma* spp. (1% YW and 1% Palm) (Fig. 16).

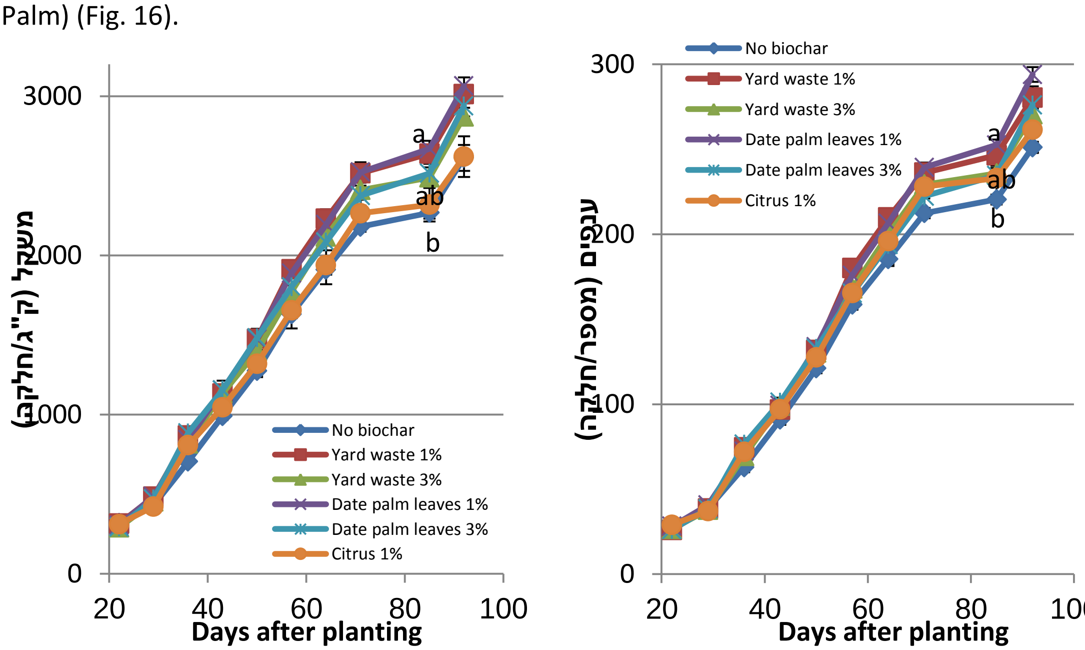



Fig. 13 Effect of biochar on sweet basil yield accumulation. Yield of basil shoots is presented as weight (left) and number (right)

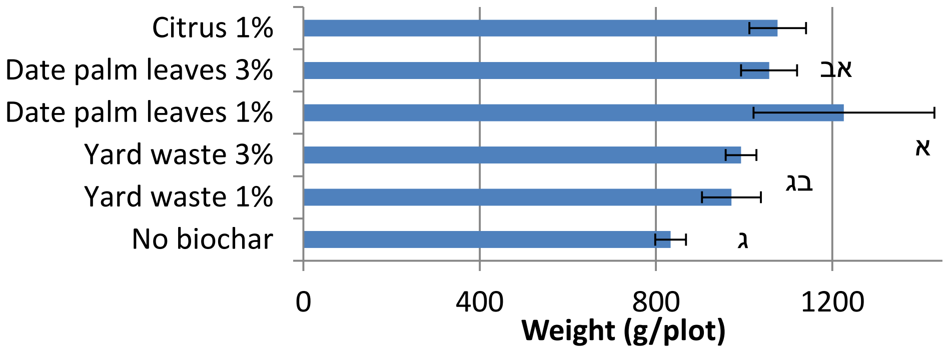



Fig. 14 Weight of sweet basil shoots harvested on 19.12.13 (technical harvest)

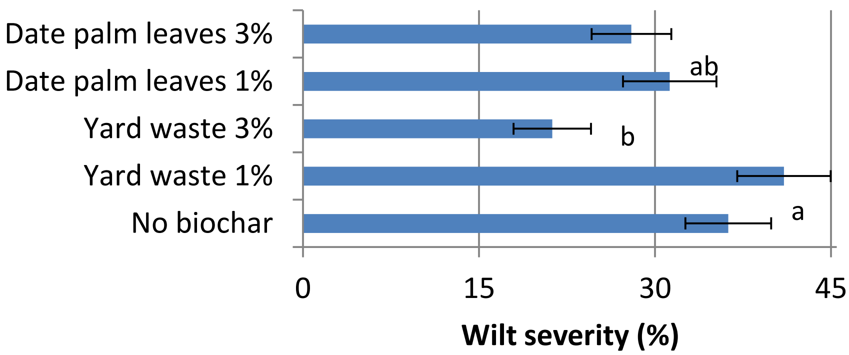
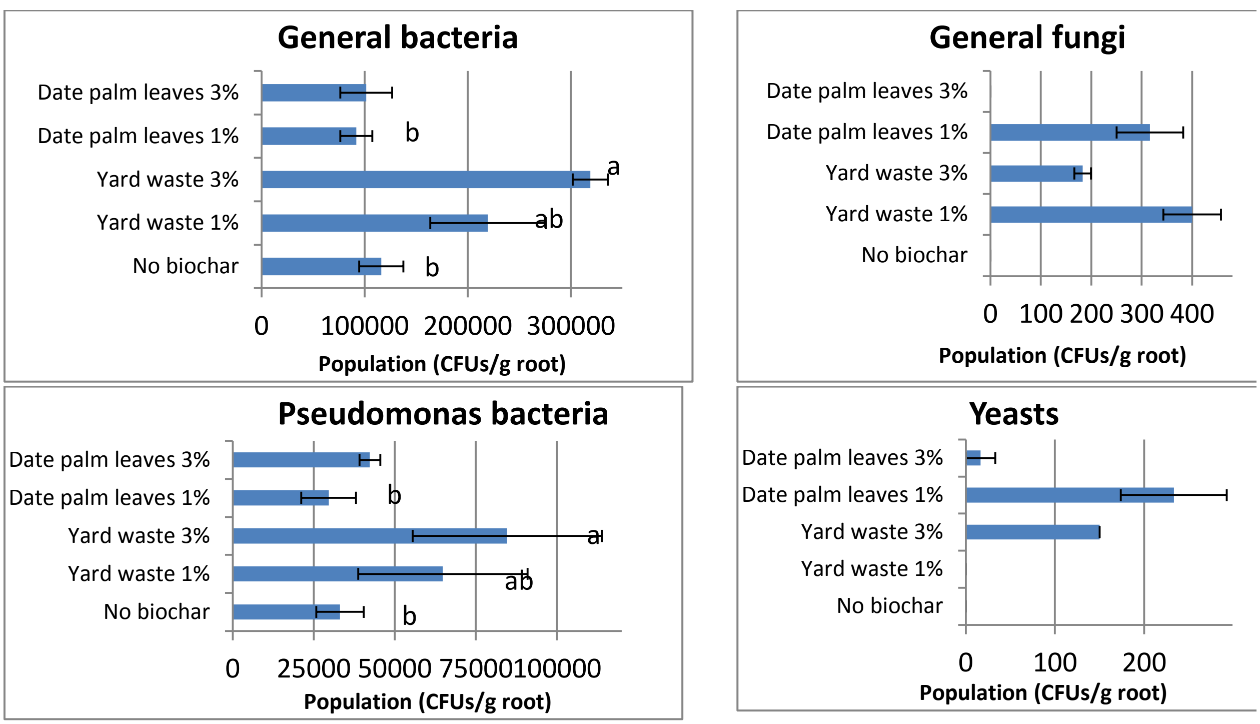



Fig. 15 Postharvest test carried out with sweet basil shoots that were harvested on 15.12.14



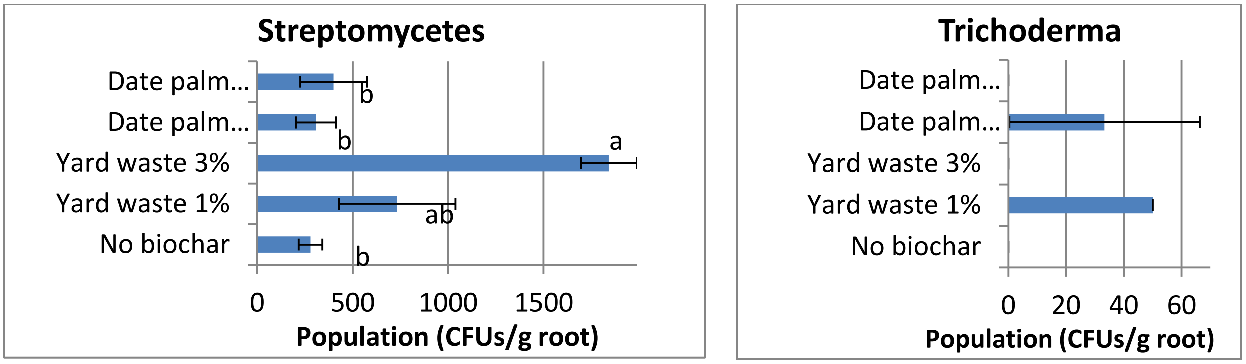



Fig. 16 Populations of microorganisms on sweet basil roots

The second planting was done in January 2014 and the yield accumulation was followed for four months. The 3%YW and 1-3% date palm induced 10-12% higher shoots yield (Fig. 17). Post-harvest quality tested on 9.2.14 revealed less weight loss in shoots that were harvested in the 1-3% Palm biochar treatments (Fig. 18). Postharvest test at the end of March 2014 revealed that 1% Palm treatment induced greater weight of shoots of the on harvest date and 10 days later, and better appearance of the shoots at 10 days after harvest. All biochars reduced the severity of downy mildew on the harvested shoots (Fig. 19).

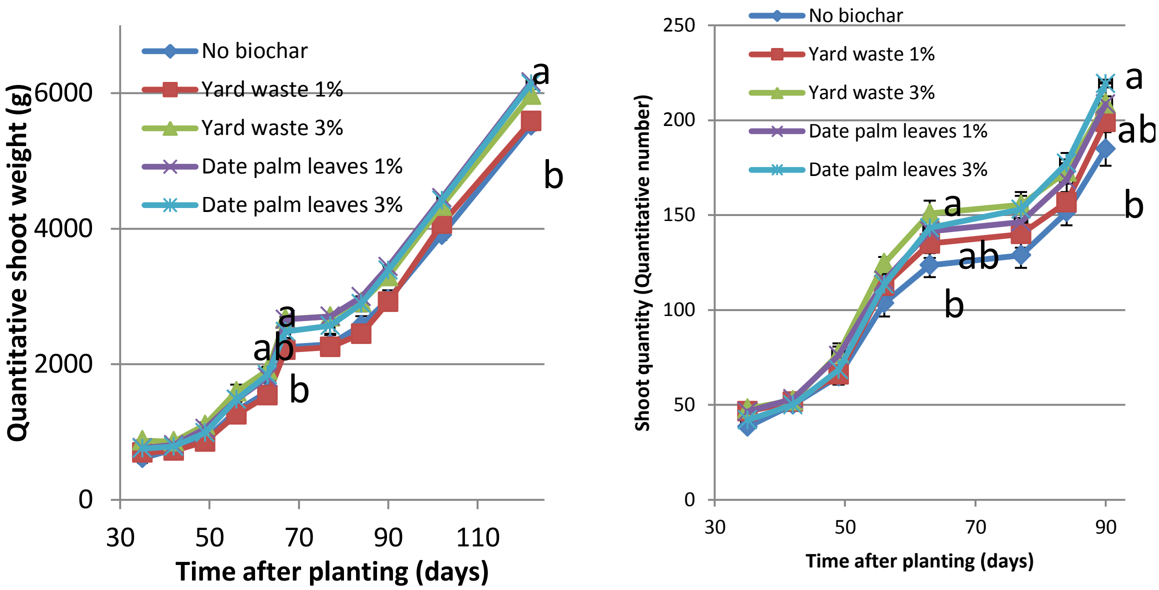



Fig. 17 Effect of biochar on sweet basil yield accumulation. Yield of basil shoots is presented as weight (left) and number (right)

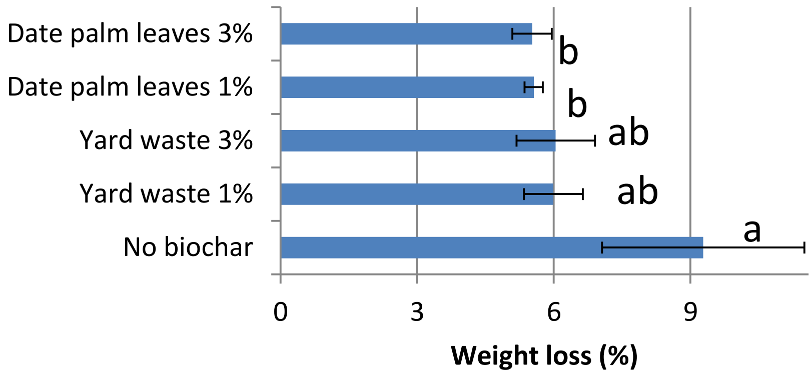
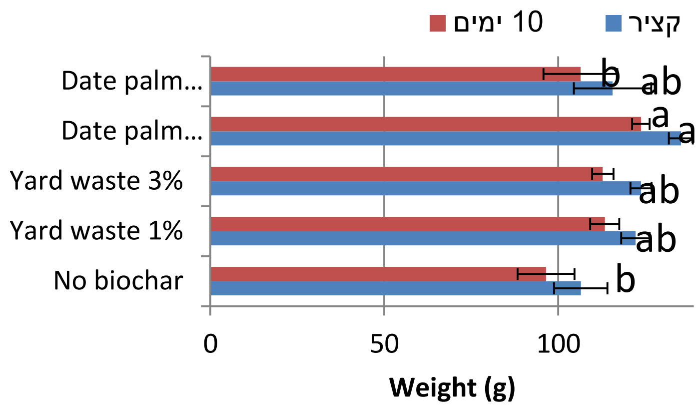



Fig. 18 Postharvest test carried out with sweet basil shoots that were harvested on 9.2.14



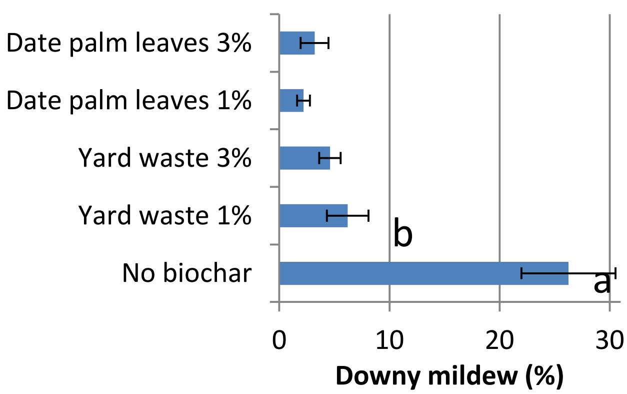




Fig. 19 Postharvest test carried out with sweet basil shoots that were harvested on 30.3.14

Initial symptoms of downy mildew were observed ca 50 days after planting. Date palm biochar induced ca 40% lower severity of symptoms of downy mildew during 49-63 days after planting (Fig. 20). Similar results were obtained at 73 and 93 days after planting (Fig. 21). In the same dates grey mould was reduced by all biochars by more than 62%.

In conclusion, the activity of biochars tested in sweet basil crop was variable, some of the biochars were more effective than the others in improving canopy growth, improving yields, and in inducing resistance to foliar diseases. In general, there was an improvement in yield and resistance to wilting and disease in the biochar-treated plants.

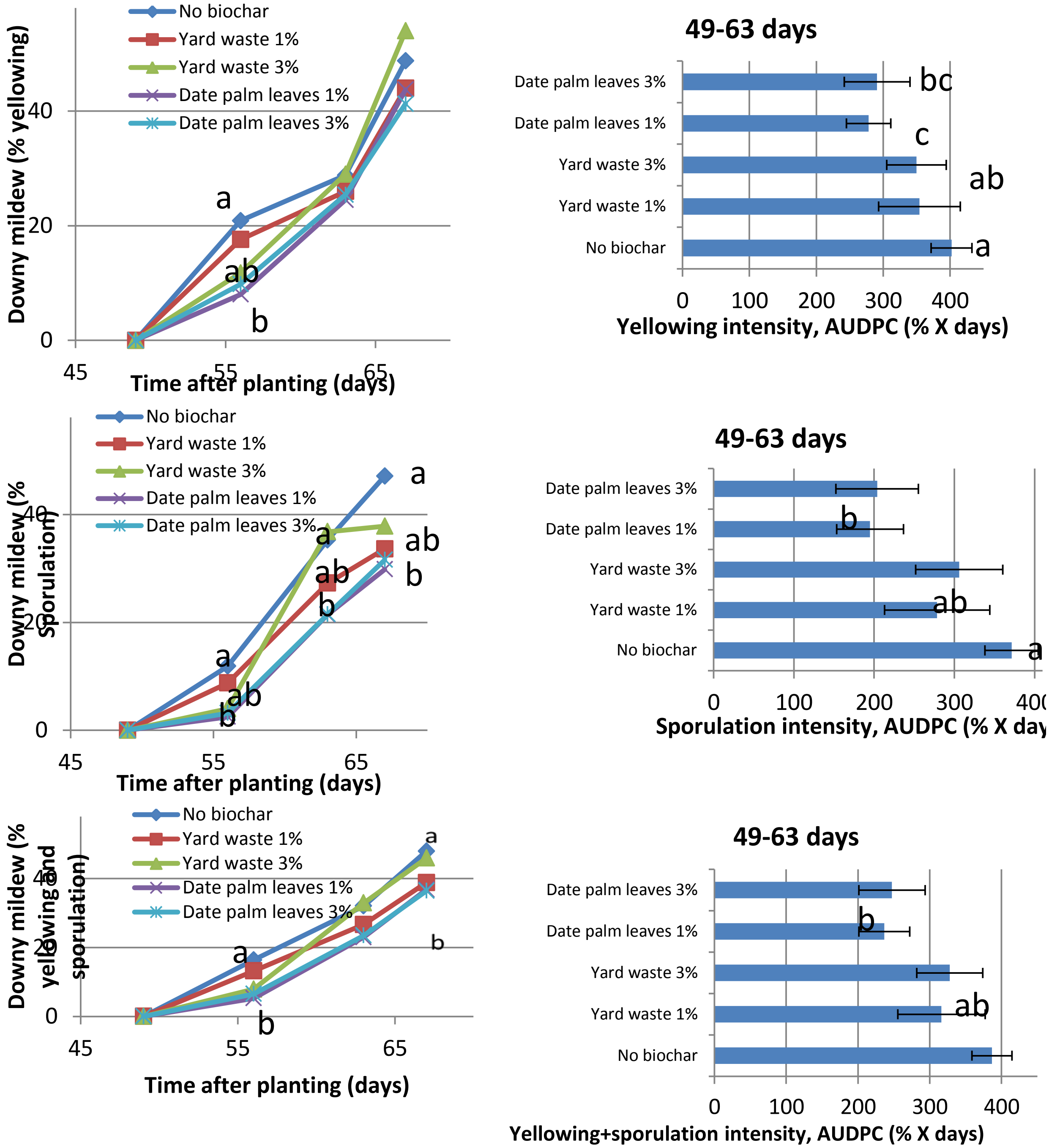



Fig. 20. Severity of downy mildew symptoms expressed as percent of symptoms on leavesat sampling dates (left) and as area under disease progress curves (AUDPC, right) of the epidemics presented on the left column.

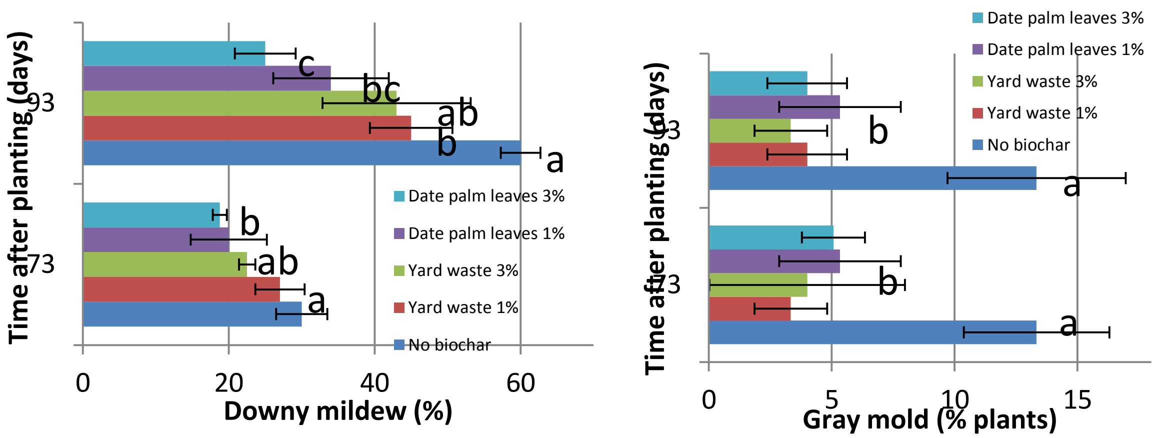


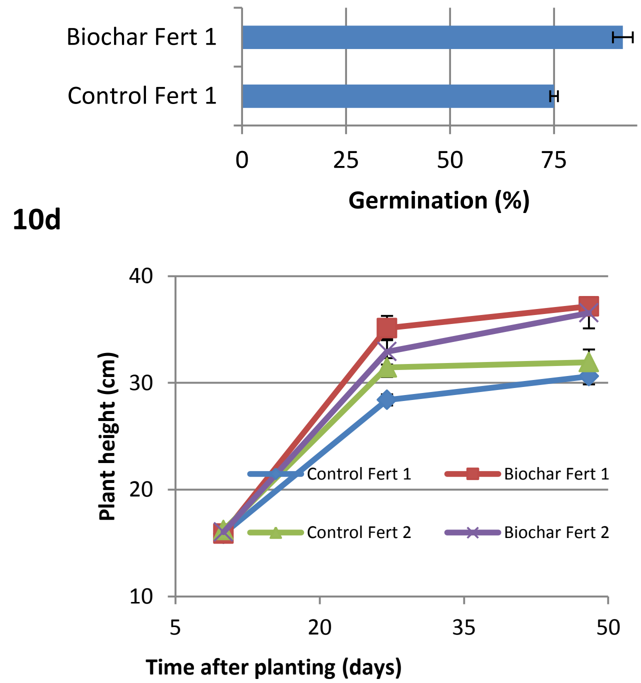

Fig. 21. Severity of downy mildew at late sampling dates (left) and of grey mold (right) at same dates.

**Wheat**

A disease-sensitive variety of wheat was grown from seeds in 15 kg pots filled with dune sand mixed with 0.25% compost. Two fertilizer treatments were made: Treatment 1' consisted of 70 mg/kg urea, 35 mg/kg super phosphate, and 70 mg/kg KCl; Treatment 2' was the same as 1', with the addition of urea 40 days after the seeds were sown. For each treatment, half of the pots had an addition of 1% by weight biochar (GHW-450), for a total of 4 treatments (1+, 1-, 2+, and 2-; where plus indicates with biochar and minus without biochar) with 12 replicate pots per treatment. Wheat growth and severity of the damages caused by the cereal leaf aphid (*Rhopalosiphum maidis*) were evaluated.

For germination %, only Treatments 1+ and 1- existed (treatment 2 being the addition of urea after 40 days). There was a statistically significant increase in germination % in the biochar treatments (Fig. 22) (at $\alpha = 0.05$). By 48 days after sowing, the plant height of the above-ground biomass was greater in the biochar treatments (Fig. 22; $\alpha = 0.05$)). On the background of Fertilizer treatment 1, seed yield in the biochar treatment was greater, while on the background of the extra urea dose in Fertilizer treatment 2, the yields in the biochar and control pots were the same ($\alpha = 0.05$). This indicates that the biochar was able to replace some fertilizer (Fig. 23). Density of the cereal leaf aphid was significantly reduced in both biochar treatments (Fig. 24; $\alpha = 0.05$).

Figure 22. Germination percent in Fertilizer Treatment 1 with and without biochar.
Plant height (cm) over the full course of the growing experiment.



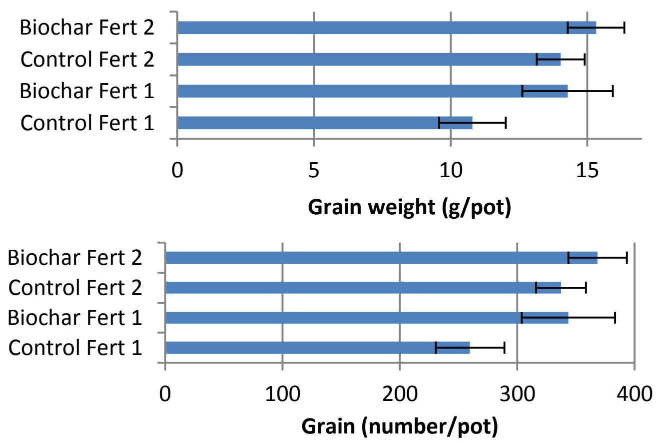
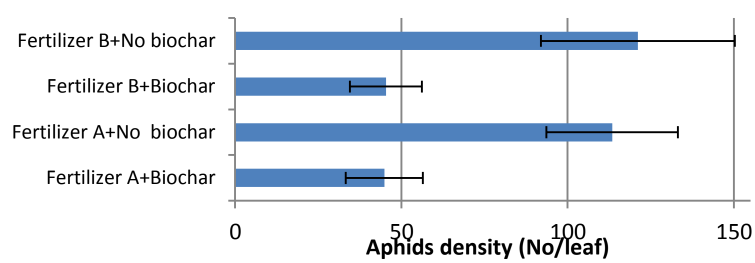




Fig. 23. Grain weight and number at the close of the experiment.

Fig 24. Density of aphids in the various treatments. Evaluation was made 125 days following the sowing.



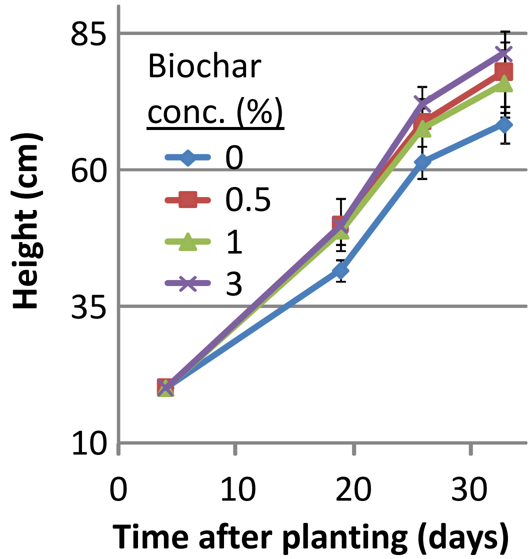

## Tomato

The impact of biochars prepared from greenhouse waste (pepper plants collected at the end of the growing season), olive pomace residues from olive oil pressing, and eucalyptus chips on the disease severity of *Botrytis cinerea* were tested in tomato. The biochars were ground into a powder of less than 1 mm particles. Each biochar powder was mixed with a coconut fiber:tuff (unsorted to 8 mm) (7:3 vol.:vol.) potting mixture. Plants of tomato cv. 1402 (Hazera Genetics, Ltd., Brurim M.P. Shikmim, Israel) were obtained from a commercial nursery (Hishtil, Ashkelon, Israel) at 40 to 50 days after seeding and transplanted into 3 L pots containing the potting medium without or with biochar at 0.5 to 3% by weight. Plants were fertigated proportionally with drippers 2-3 times per day with 5:3:8 NPK fertilizer (irrigation water was planned to have total N, P and K concentrations of 120, 30 and 150 mg $L^{-1}$, respectively; EC 2.2 dS/m), allowing for 25-50% drainage. Plants were maintained at 23 to 27°C in a pest- and disease-free greenhouse 16-72 days and then transferred to a controlled temperature chamber where the disease was allowed to develop under high humidity conditions following inoculation of intact or detached leaves.

Two types of assays were conducted: AL= Intact leaves attached to the plant; DL= Leaves detached from the plant. Both types of assays were carried out under in a humidity chamber at 20±1°C, 97±3% RH, and 1020 lux light intensity.

*Botrytis cinerea* (isolate BcI16; [23]) culture and conidia separation was carried out according to [24]. The conidia suspension was then filtered through cheesecloth. The concentration of conidia was determined using a haemocytometer and a light microscope, and adjusted to $5\times10^5$ cells/ml. To facilitate germination of *B. cinerea* conidia and subsequent leaf infection, 0.1% glucose was added to the final conidial suspension together with 0.1% $KH_2PO_4$ [25, 26]. For detached leaves assays, five leaves/plant from at least five plants were each inoculated with a 10 µl drop of a $5\times10^5$ conidia/ml suspension. The severity of the resulting necrotic lesion on each leaf was determined according a scale of 0 to 100% [27]. Whole plants were sprayed with the conidia suspension (2 mm/plant) and incubated in a polyethylene bag during the entire period of disease development. Five to six plants were used for each treatment.

The results are tabulated in Table 7. Data in each row labeled by a common letter are not significantly different according to Fisher's protected LSD test. Nt = not tested. In nearly all cases, the presence of biochar reduced the disease severity, without relation to the type of feedstock, HTT, or assay type. In addition to improved resistance to disease, biochars generally had a positive impact on pant growth, shown in one example for tomato grown in potting medium amended with different amounts of OP-350 biochar. These results are published in [28].



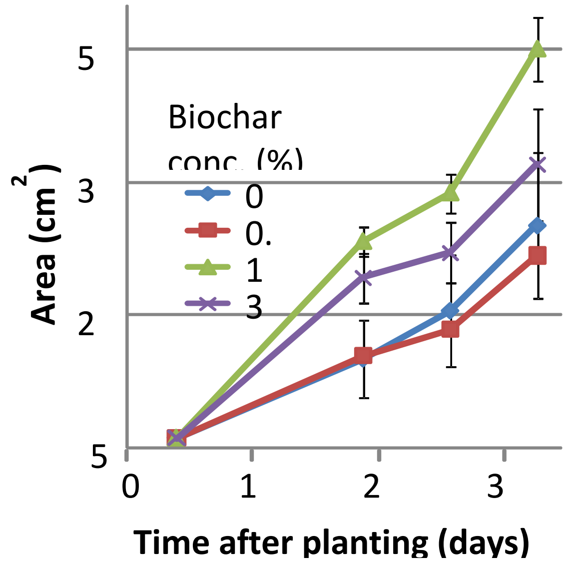
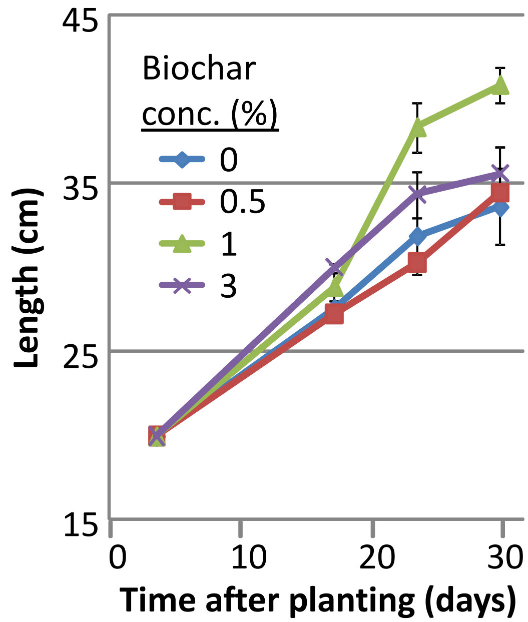




Fig. 25. Influence of OP-350 biochar on growth of tomato plants: height (top left panel), leaf area (top right panel), leaf length (bottom right panel)




In addition to effect of biochar on *B. cinerea* disease severity in tomato, we examined the effect of biochar on development of late blight caused by *Phytophthora infestans*, as seen in Figure 26.

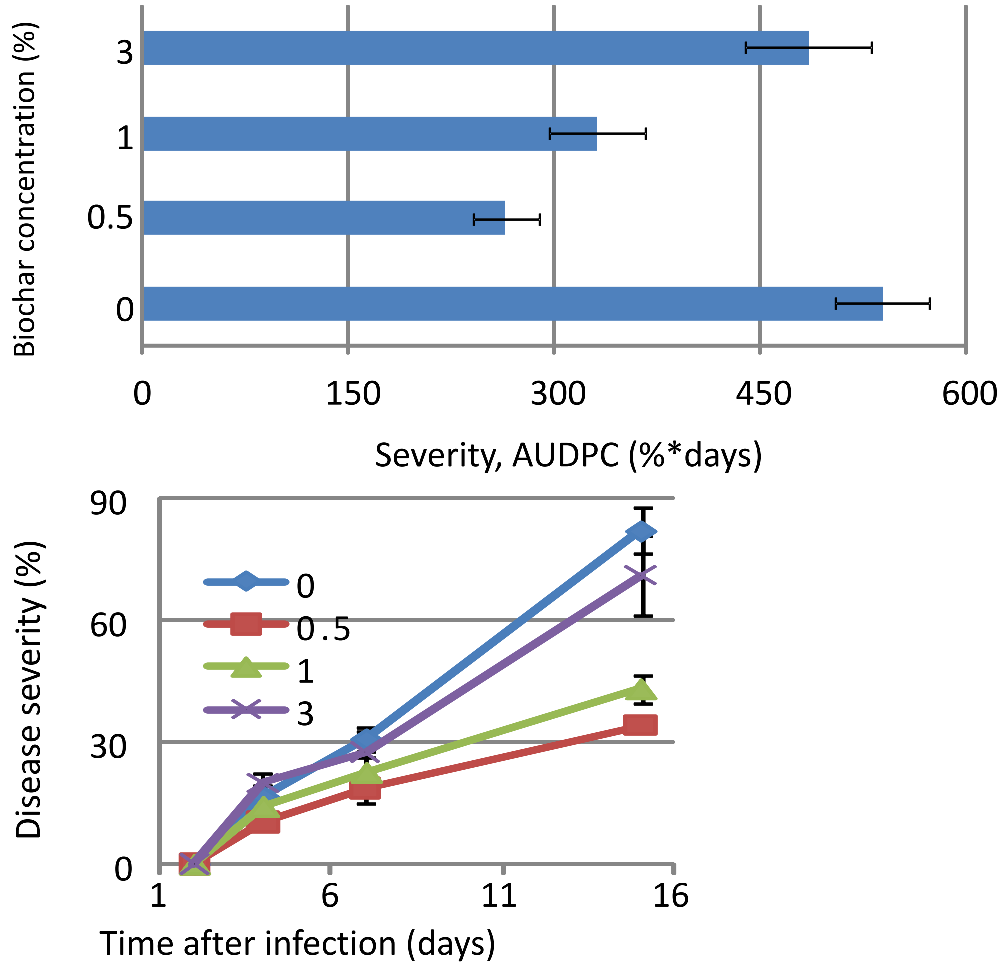



Fig. 26. Severity of late blight in tomato plants grown for 50 days in pots amended with EUC-350 biochar in a greenhouse growth chamber and infected with sporangiospores ($10^4$/ml) of *Phytophthora infestans*. Severity of the disease is presented as disease progress curves (top) and as area under disease progress curve (AUDPC, bottom).

Table 7: Effect of adding biochars produced from different feedstocks at HTTs of 350 and 450°C on the severity of tomato leaf gray mold. From [28].

| Biomass source | Pyrolysis temperature (°C) | Assay method | Plants age (days after planting) | Days after infection by *Botrytis cinerea* | Disease severity (±SE) at biochar concentrations (%) | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | 0 | 0.5 | 1.0 | 3.0 |
| Greenhouse waste | 350 | AL | 29 | 12 | 58.0 ± 7.8 a[4] | 40.0 ± 2.2 b | 35.0 ± 2.7 b | 34.0 ± 4.0 b |
| Greenhouse waste | 450 | AL | 72 | 14 | 50.0 ±13.6 a | nt | 10.3 ± 1.7 c | 17.0 ± 3.6 b |
| Olive pomace | 350 | DL | 23 | 7 | 57.8 ± 6.5 a | 33.8 ± 3.1 b | 34.5 ± 3.0 b | 32.0 ± 4.6 b |
| Olive pomace | 450 | DL | 16 | 10 | 34.2 ± 1.7 a | nt | 15.0 ± 1.5 b | 11.0 ± 0.6 b |
| Olive pomace | 450 | AL | 21 | 5 | 16.4 ± 3.1 a | nt | 8.0 ± 2.6 b | 12.9 ± 2.4 ab |
| Eucalyptus wood | 350 | DL | 23 | 7 | 63.8 ± 5.7 a | 50.1 ± 6.8 ab | 31.7 ± 3.5 c | 44.5 ± 5.5 b |
| Eucalyptus wood | 350 | AL | 47 | 10 | 58.0 ± 6.8 a | 25.0 ± 3.3 b | 20.0 ± 4.2 b | 27.0 ± 1.1 b |

## Field Experiment in Arava Yair Station R&D: Growth, Disease Resistance, Post-Harvest, Soil Chemistry, Microbiology

### Introduction

The experiment was conducted in a 25 mesh, 5 dunam net-house in the Yair R&D station, in the Arava. The soil is a fine sand; compost is added each year at a rate of 5 $m^2$/dunam before the start of the growing seasons. Biochar was incorporated into the soil to a depth of 15 cm manually. Each plot has an area of 4 x 0.5 m, and including the paths, the plot area was 1.6 x 4 m. Plots of treatments were arranged in randomized blocks in five replicates. Each plot was planted with 20 pepper plants cv. Subak in two rows. Standard agronomic practice is followed. The irrigation water is saline (av. 3.5 dS/m).

### 2011/12 Season

The biochar experiments started in the 2011/12 season with two treatments: (i) control (standard agronomic practice of the region) and (ii) 1.3 kg/$m^2$ GHW-450 biochar (equivalent to ~0.5% by weight at 20 cm depth). The biochar was first evenly spread on the soil surface as a crushed powder, and then worked into the soil using hoes to a depth of approximately 15 cm. This first year was considered a preliminary evaluation using half the ultimate intended biochar dose, to check that the biochar had no deleterious effects on the growth and development of the pepper plants. Indeed, the preliminary test showed that the biochar had no deleterious effects on either growth or yield of the pepper plants, and there was even evidence that fruiting began earlier in the biochar plot (Fig. 27). Moreover, there were no deleterious effects on fruit quality (Table 8).

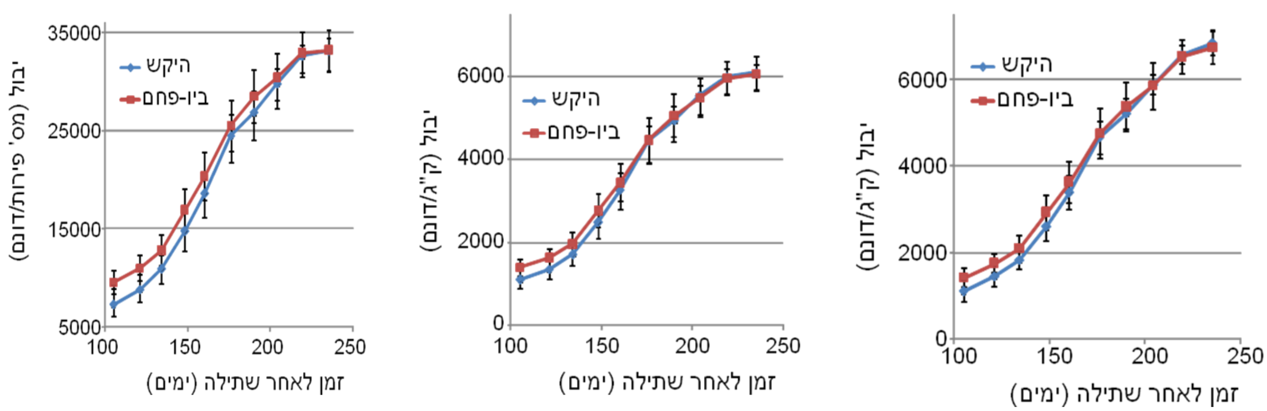



Fig. 27. Number of pepper fruits per dunam (left), export quality yield (middle) and total yield (right) for the 1st season the field trial 2011-2012.

Table 8. Fruit quality 2011-2012.

| Date | Treatment | Single fruit weight (g) | Seed weight (g) | Cuticle thickness mm) | Total dissolved solids (Brix) | Glucose (mg/dL) |
|---|---|---|---|---|---|---|
| 14.12.11 | Control | 160.0±4.51 | 1.6 | 5.7 | 8.2 | 4764 |
| | Biochar | 162.8±1.80 | 1.9 | 5.6 | 8.1 | 5168 |
| 7.2.12 | Control | 201.2±5.23 | 3.9 | 6.5 | 8.6 | 2628 |
| | biochar | 199.5±5.85 | 4.2 | 6.1 | 8.5 | 3068 |

Over the course of the growing season, there was an unplanned infestation by the broad mite, which was not affected by the biochar treatment, but which did lead to rather high variability between the replicate blocks. In addition, powdery mildew disease began to feature in mid-November 2011. The disease severity was evaluated at the end of December 2011, and it was significantly reduced in the biochar treatment as compared with the control (Figure 28). The disease was expressed both in % of leaf coverage (שכיחות) and in severity (חומרה). On 2/2/2012, the disease was again evaluated with respect to severity, leaf fall, and total disease symptoms (Fig. 29). All the disease symptoms were significantly lower in the biochar blocks than in the control blocks (Fig. 29). In the final evaluation on 23/4/2012, the disease was evaluated only on young branches that developed after the winter. Again, the disease severity in the biochar plots was significantly lower than in the control plots (Fig. 30).

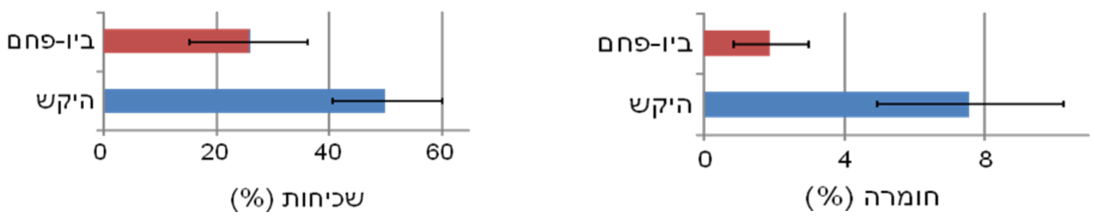



Fig. 28. Powdery mildew in biochar (red) and control (blue) treatments. Left panel: % of leaf coverage; Right panel, disease severity. 29/12/11.

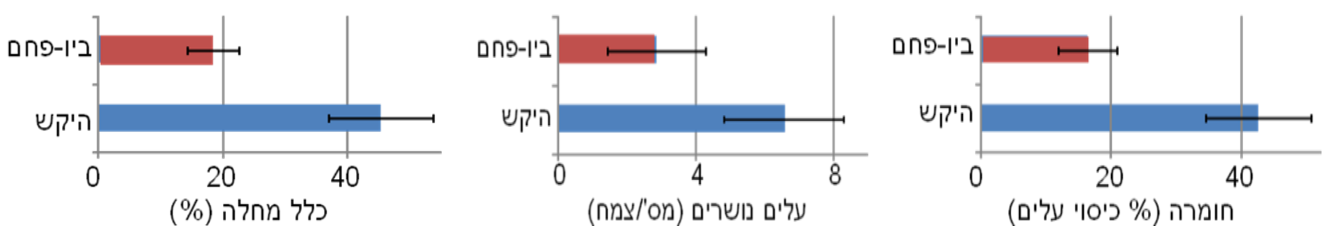
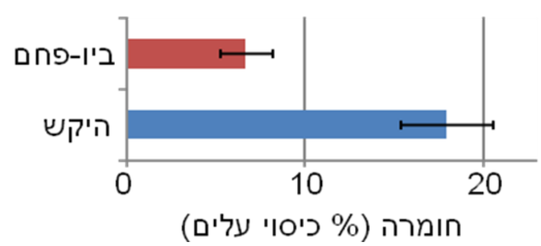



Fig. 29. Powdery mildew 2/2/12, in terms of disease severity (right panel), fallen leaves (middle panel), and total disease (left panel) in the biochar (red) and control (blue) treatments.

Fig. 30. Disease severity on young leaves, 23/4/12 in biochar (red) and control (blue) treatments.




## 2012/13 Season

### *Background*

Before the 2012/2013 growing season, the experiment was expanded to include three more treatments of biochar applied before planting at a rate of 2.6 kg/m$^2$, and the original biochar treatment of the previous growing season was treated with an additional 1.3 kg/m$^2$ GHW-450 biochar (Table 9).

Table 9. Treatments of the field experiment in Yair experimental station

| Treatment (soil amendment) | # | Biomass | Pyrolysis temp. (C) | Dose (kg/m$^2$; %) | comment |
|---|---|---|---|---|---|
| No biochar | I | | | | application: 8/2012 |
| GHW-450 2X0.5 | II | Greenhouse waste | 450 | 1.3; 0.5 (twice) | 1st application: 7/2011, 2$^{nd}$ application: 8/2012 |
| GHW-450 | III | Greenhouse waste | 450 | 2.6; 1.0 | application: 8/2012 |
| GHW-350 | IV | Greenhouse waste | 350 | 2.6; 1.0 | application: 8/2012 |
| EUC-350 | V | Eucalyptus | 350 | 2.6; 1.0 | application: 8/2012 |

Compost was applied in the area at a rate of 5 m$^2$/dunam before the 2011/2012 growing season. Biochar was incorporated into soil to a depth of 15 cm on 10.8.12. Treatment in each plot was applied on area of 4 x 0.5 m and including the paths the plot area was 1.6 x 4 m. Plots of treatments were arranged in randomized blocks in five replicates. Each plot was planted with 20 pepper plants cv. Subak on 13.8.12 for the 2012/2013 growing season. Agrotechnical activities included removal of the shading net on 24.9.12, wash of the mesh net on 3.10.12 and spread of the shedding net on 16.2.13. Fertigation and plant protection activities were as recommended in the region except for the powdery mildew control activities. Plant protection application included exmite, floramite, persimilis, sulfur dusting, heliosufre, tracer, orius and aphidius. The number of set fruits was evaluated on 18.10.12 (67 days after planting). Yield was harvested from 18.11.12 until 7.4.13, 11 harvests in total. The fruits were sorted on the harvest day. On 23.1.13 the intensity of canopy growth was evaluated according to a 0-100 scale. Powdery mildew was evaluated according to incidence of infected leaves, the severity of symptoms on leaves (0-100% coverage index), and the number of shed leaves and the calculated severity incorporating data of severity and shed leaves.

### *Results 2012/2013 season*

The number of larger set fruits 67 days after planting was higher in biochar treatment IV (GHW-350) than in the untreated control (I; Fig. 31). The canopy vigour was more intensive in the two GHW-450 treatments (II, III, Fig. 32). The total yield in the control treatment (I) was 8.1 kg/m$^2$ and in the biochar treatments it reached 10.1-11.8 kg/m$^2$ (Figs 33-34). The harvest in mid-December yielded the highest yield as compared with other periods and in this time the highest yield was obtained in the bi-annual GHW-450 (II) and the GHW-350 (IV) treatments (Fig. 33). The highest total yield was obtained in these two treatments (Fig 34). In January all biochar treatments yielded higher cumulative yield as compared with the control (Fig. 34). The weight of export quality fruits accumulated up to 7.6 kg/m$^2$ and in the biochar treatments it was 9.3-11.1 kg/m$^2$ at the end of the season (Figs 35-36). Similarly to the total yield, the export quality yield was the highest in the bi-annual GHW-450 and the GHW-350 treatments (Figs 35). In January 2013 the cumulative export quality yield was higher in the biochar treatments as compared with the control (Fig. 36). Similar results were observed with the number of the export quality fruits (Figs 37-38).

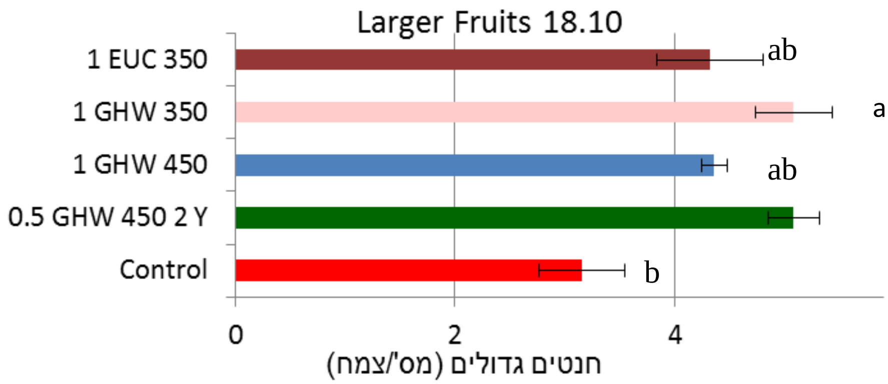



Fig. 31 Effect of biochar on the number of large set fruits on 18.10.12 (67 days after planting), growing season 2012-13

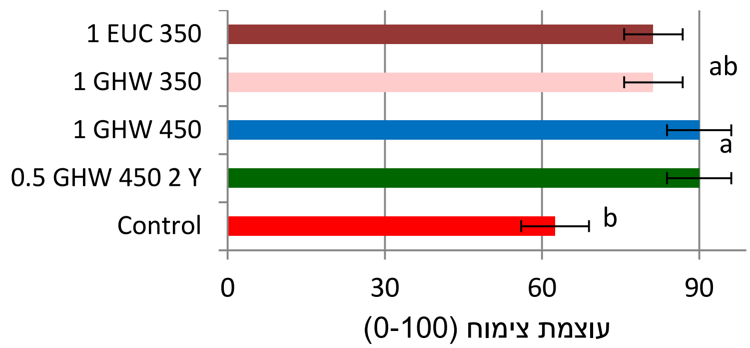



Fig. 32 Effect of biochar on growth intensity on 23.1.13 (163 days after planting), growing season 2012-13

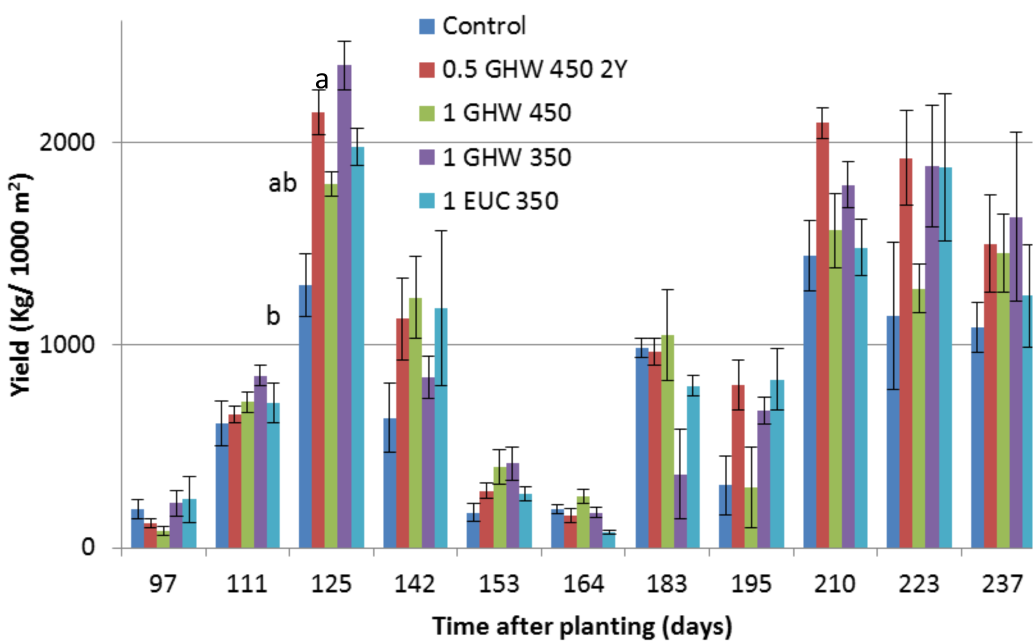



Fig. 33 Weight of the total yield in each harvest date Yair experiment 2012-2013

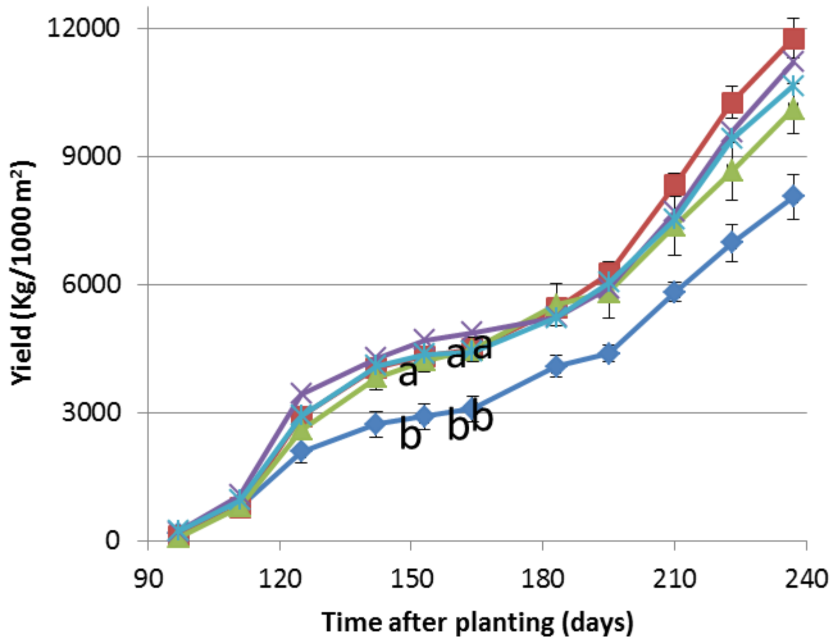



Fig. 34 Cumulative weight of the total yield, Yair experiment 2012-2013

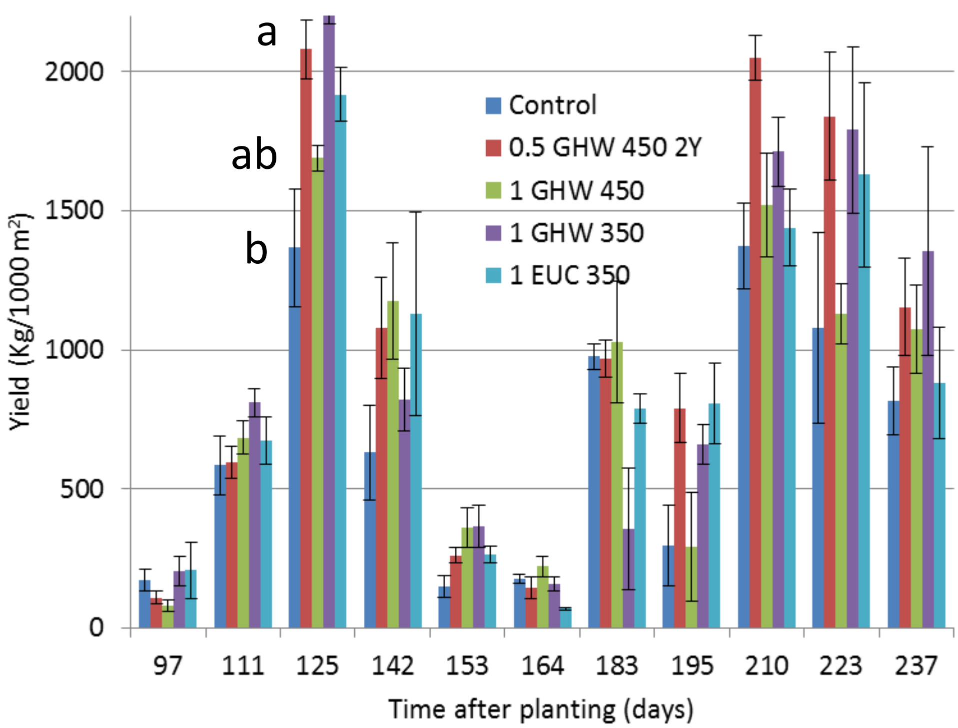



Fig. 35 Weight of the export quality yield in each harvest date Yair experiment 2012-2013

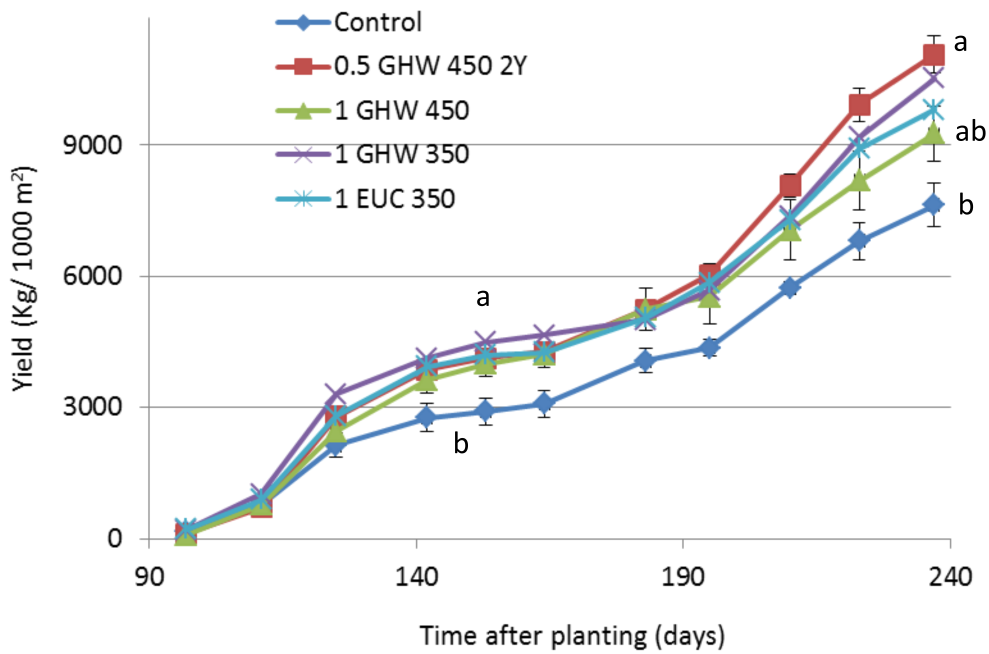



Fig. 36 Cumulative weight of the export quality yield, Yair experiment 2012-2013

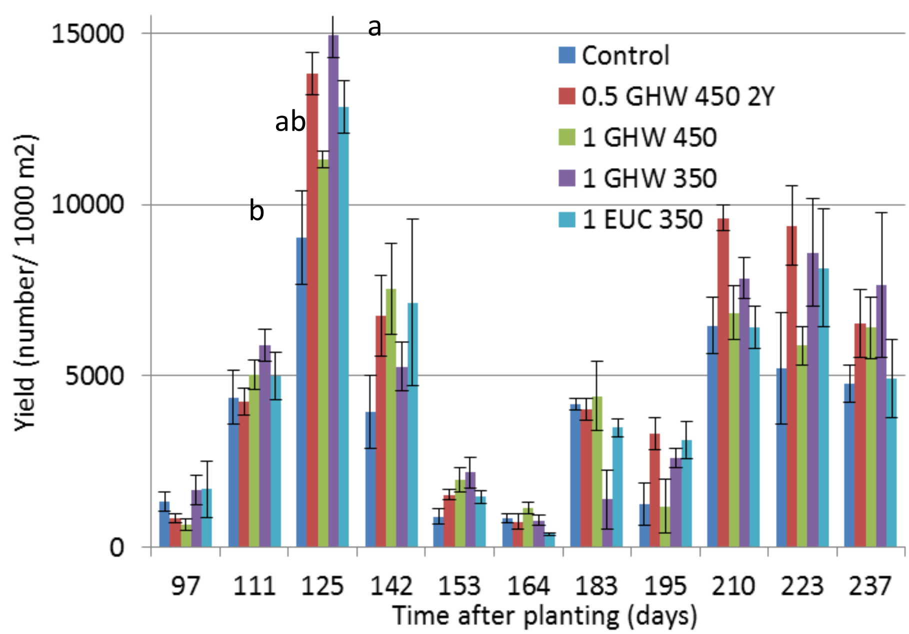



Fig. 37 Number of the export quality yield in each harvest date Yair experiment 2012-2013

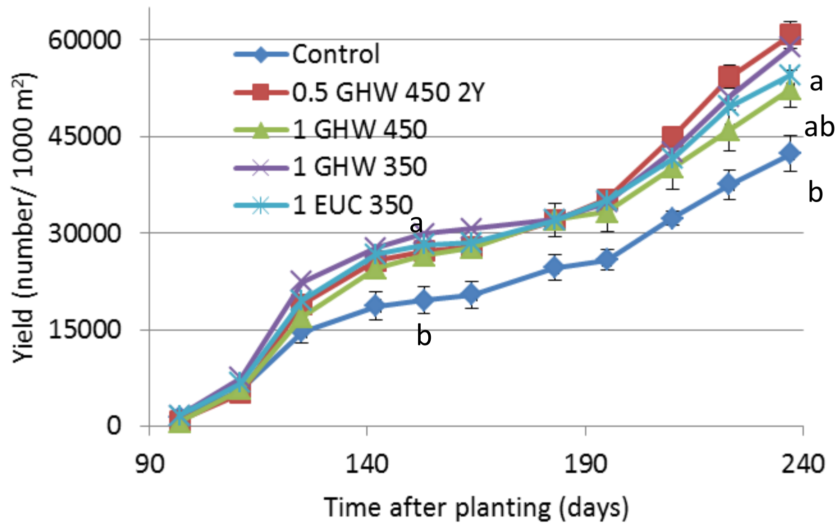



Fig. 38 Cumulative number of the export quality yield, Yair experiment 2012-2013

Powdery mildew was first observed in the experiment on mid-December 2012. The incidence of diseased leaves was 30% on 20/12/12 and it was suppressed by 50% by the biochar treatments (Fig. 39). In mid-January, the disease incidence was high and there was no difference between the treatments, yet the severity of disease was reduced by the GHW-350 and EUC-350 treatments (Fig. 40). Powdery mildew severity in the control treatment was 42% on 29/1/13 and was reduced by all biochar treatments, whereas on 7/3/13 it was reduced only by the GHW-350 and EUC-350 treatments (Fig. 41). Shed leaves could be counted at the end of March-beginning of April 2013. The calculated disease severity reached 50% and the GHW-350 treatment was still effectively reducing the disease to half of that of the untreated control (Fig. 42).

Broad mite damages were observed during the months of Sept.-Oct. 2012 and reached 11% of the plants by mid-Oct. In spite of the variability between replicates, it was found that the incidence of affected plants was low in the biochar treatments (Fig. 33).

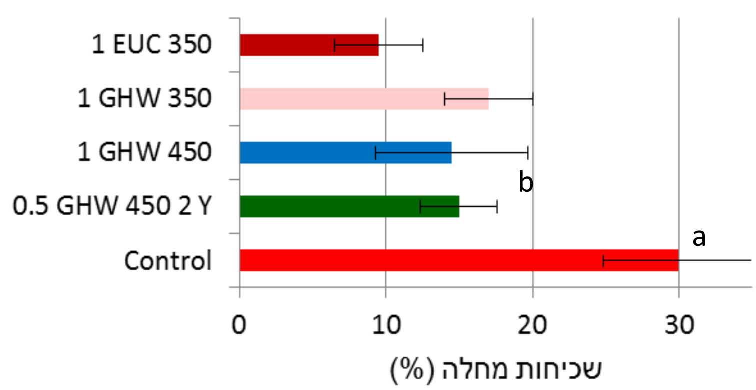



Fig. 39 Incidence of pepper powdery mildew on 20.12.12

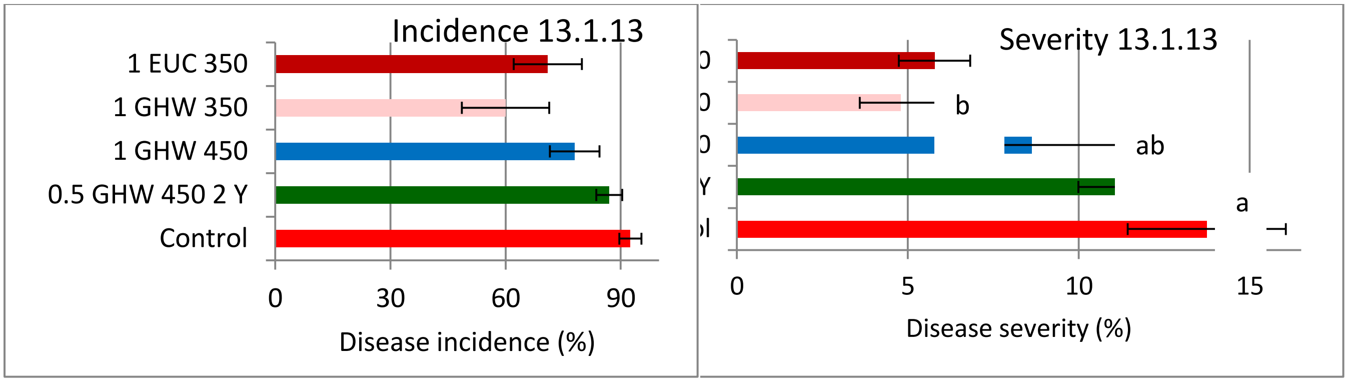



Fig. 40 Incidence (left) and severity (right) of pepper powdery mildew on 13.1.13

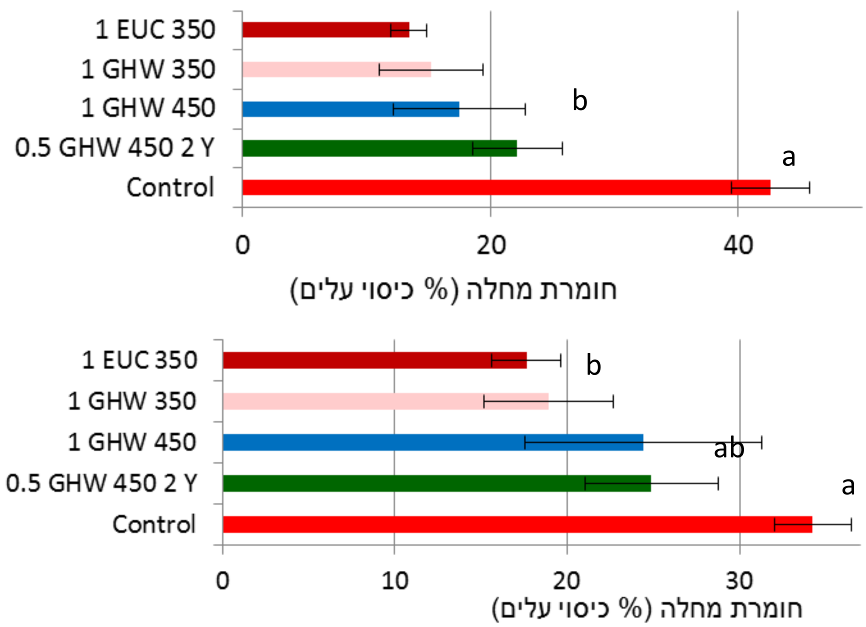
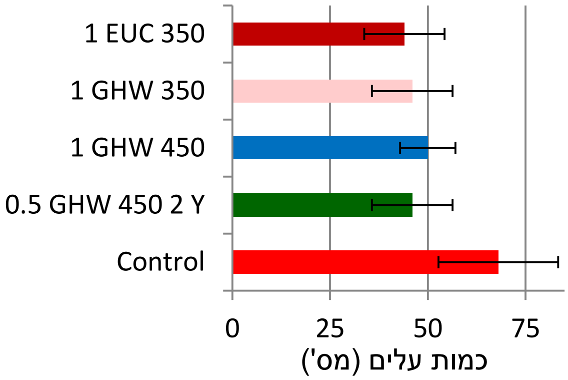
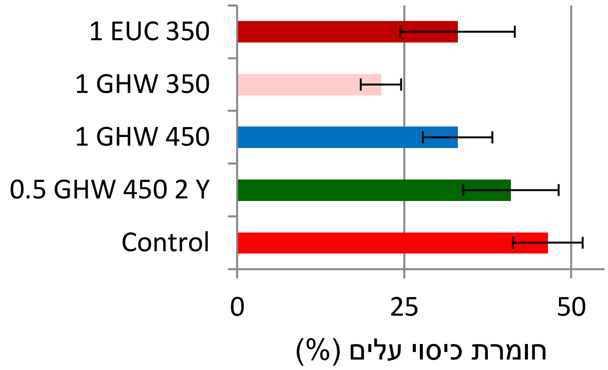



Fig. 41 Severity of pepper powdery mildew on 29.1.13 (upper) and 7.3.13 (bottom).



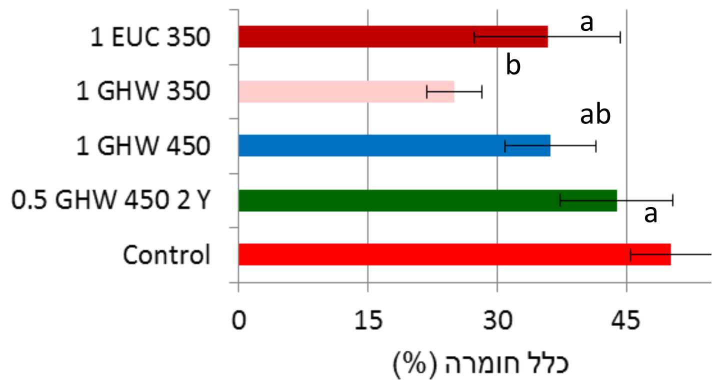




Fig. 42 Severity of intact leaf coverage (upper right) by pepper powdery mildew, shed leaves (upper left) and calculated severity of disease on 7.4.13.

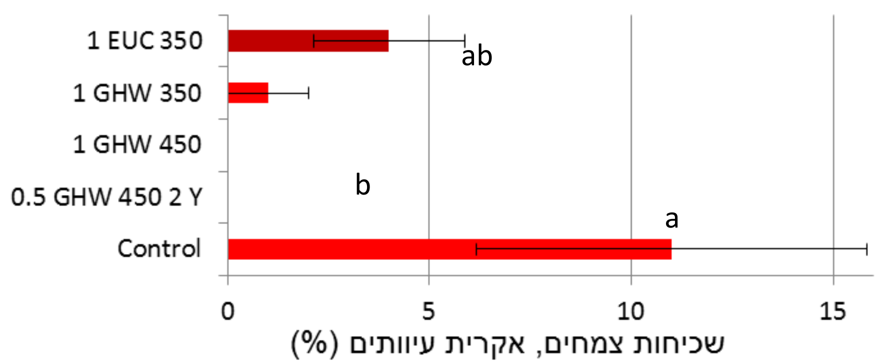



Fig. 43 Incidence of broad mite infested plants on 18.10.12

To summarize the results of the 2012-2013 growing season, no deleterious effects on the sweet pepper were observed. The biochar treatment resulted in increased growth response, earlier yield and a greater fruit yield. Powdery mildew was suppressed by the biochar, leading to systemic induced resistance phenomenon under field conditions.

## 2013/14 Season

### *Background*

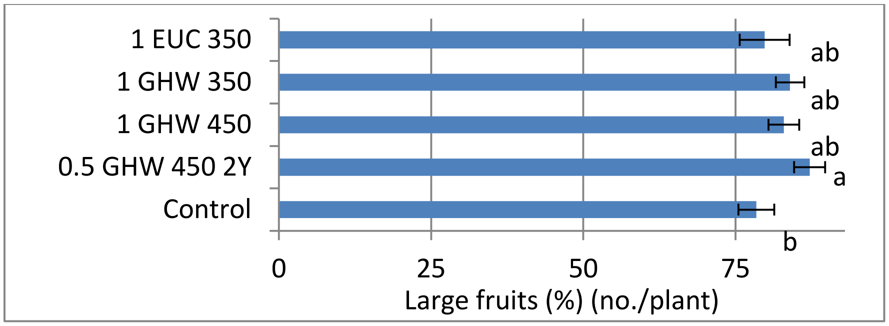
The plants (cv. Subak) for the 2013/2014 growing season were planted on 7.8.13 following no additional biochar application. The agro-technical activities in the field that were carried out were removal of the shading net on 16.9.12, wash of the mesh net on 4.10.12 and spread of the shedding net on 21.2.14. The number of larger set fruits was counted on 21.10.2013 (76 days after planting). Yield was harvested from 19.11.12 until 14.4.13, 12 harvests in total. The fruits were sorted on the harvest day. The height of the plants and the vigor of the canopy were evaluated on 25.11.13-2.12.13. Powdery mildew was evaluated as mentioned above.

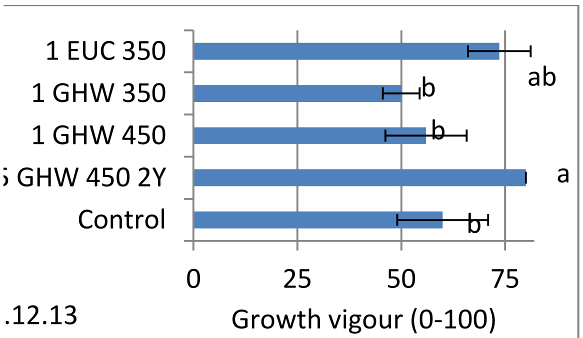
Postharvest simulation carried out in Yair station facilities evaluated the parameters of rot presence, malformation, color abnormalities, aged-appearance, and firmness on December, February and March harvests. On 26.12.13 and 28.1.14 fruits were transferred to the Volcani Center. In the department of Plant Pathology, the fruits were challenged with a suspension of *Botrytis cinerea* conidia and incubated at 20°C in a humidity chamber to allow gray mold development on the fruit and on the stem end. In the department of Postharvest Science of Fresh Produce (Prof. Elazar Falik and coworkers) non-challenged fruits were incubated 12-14 days at 7°C and 3d at room temperature and evaluated for characteristics of firmness/ flexibility, fruit and fruit stem rot, irregular shape, color fit to type, chilling injury, light color 'cheek', weight loss, total soluble solids (TSS) and visual appearance.

### *Results 2013/2014 season*

There was no biochar application before the planting of the 2013-2014 season. The number of large set fruits counted 76 days after planting was greater in the twice-applied GHW-450 than in the control (Fig. 44). Higher plants at 110 days after planting were observed in the same treatment whereas the canopy vigor was similar in all treatments (Fig. 45). Total yield was not high (8.0 kg/m$^2$) in the control, and was up to 9.4 kg/m$^2$ in the biochar treatments (Fig. 46), that is to say, higher in all the biochar treatments than in the control except for GHW-350. A similar trend was observed in the number of fruits (Fig. 47). Export quality yield was 7.0 kg/m$^2$ in the control and it was 7.9-8.3 kg/m$^2$ in biochar treatments, significantly higher than in the control except for GHW-350 (Fig. 48). The portion of export quality fruits out of the total yield decreased from 96% at the beginning of the season to 88% at its end. The percent export was lower in the biochar treatment at the beginning of the season but changed less drastically and it was 90% at the end of the season (Fig. 49). The weight of a single fruit was lower at the season end in the EUC-350 and GHW-450 treatments (Fig. 50).

Fig. 44 Number of large set fruits on pepper plants in the biochar experiment on 21.10.13 (76 days after planting), Yair stn 2013/2014 growing season



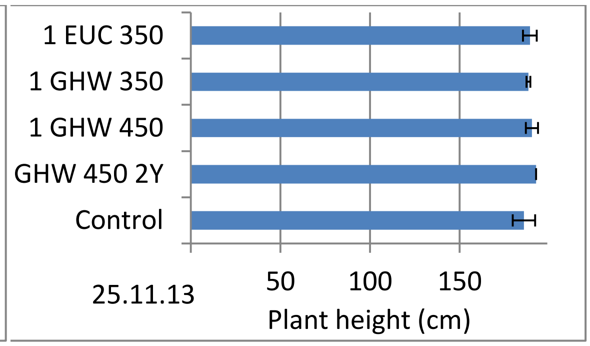




Fig. 45 Pepper plants height (25.11.13, right) and growth vigor (2.12.13, left) in the biochar experiment, Yair stn 2013/2014 growing season

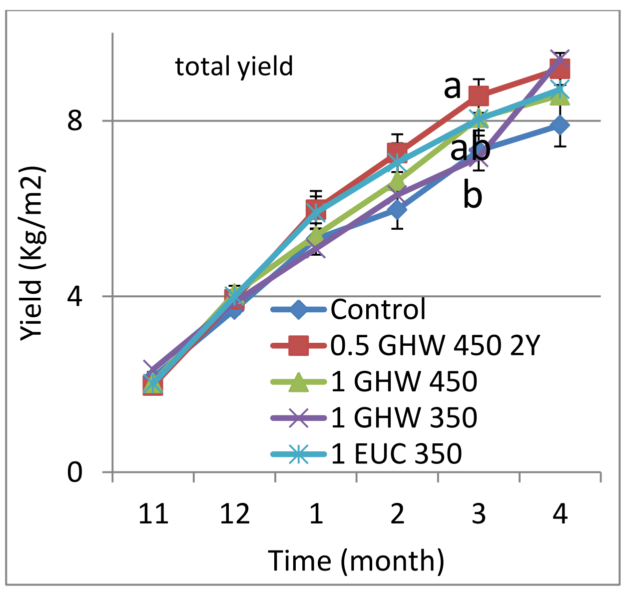



Fig. 46 Cumulative weight of the total yield, Yair experiment 2013-2014

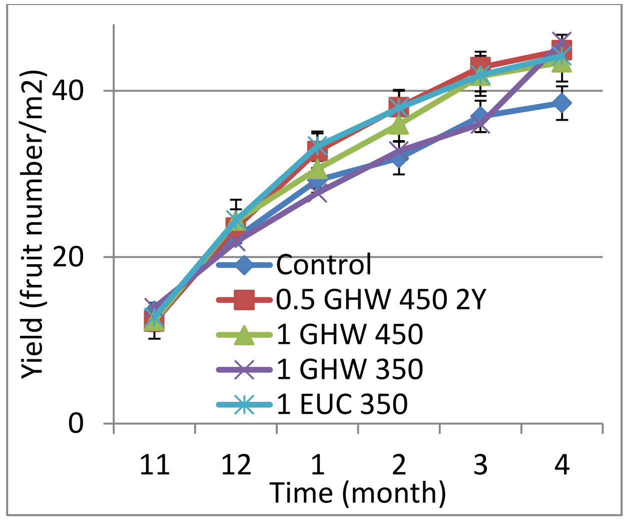



Fig. 47 Cumulative number of the total yield, Yair experiment 2013-2014

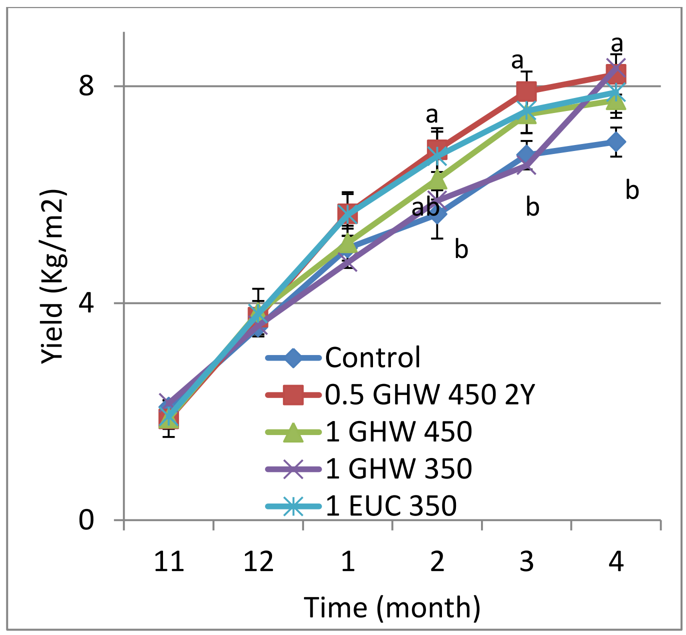



Fig. 48 Cumulative weight of the export quality yield, Yair experiment 2013-2014

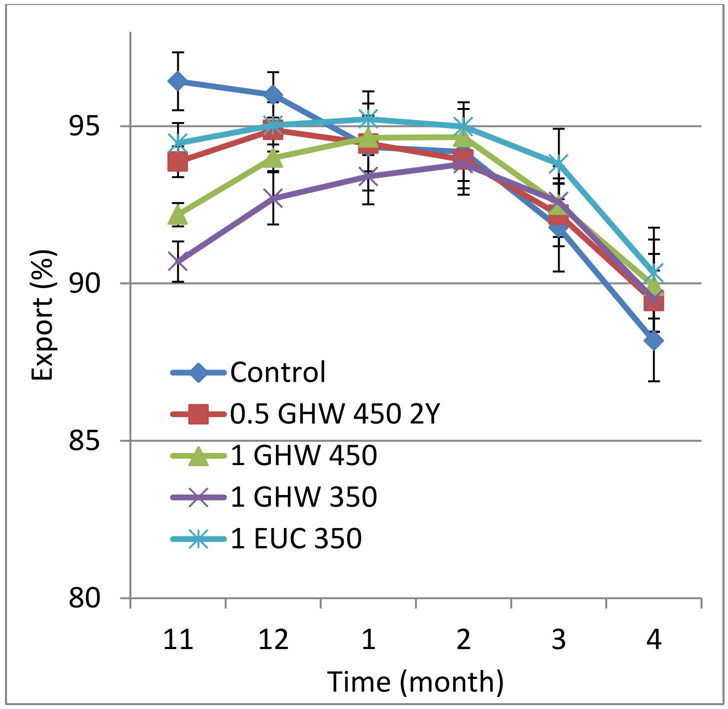



Fig. 49 Cumulative percent of the export quality yield, Yair experiment 2013-2014

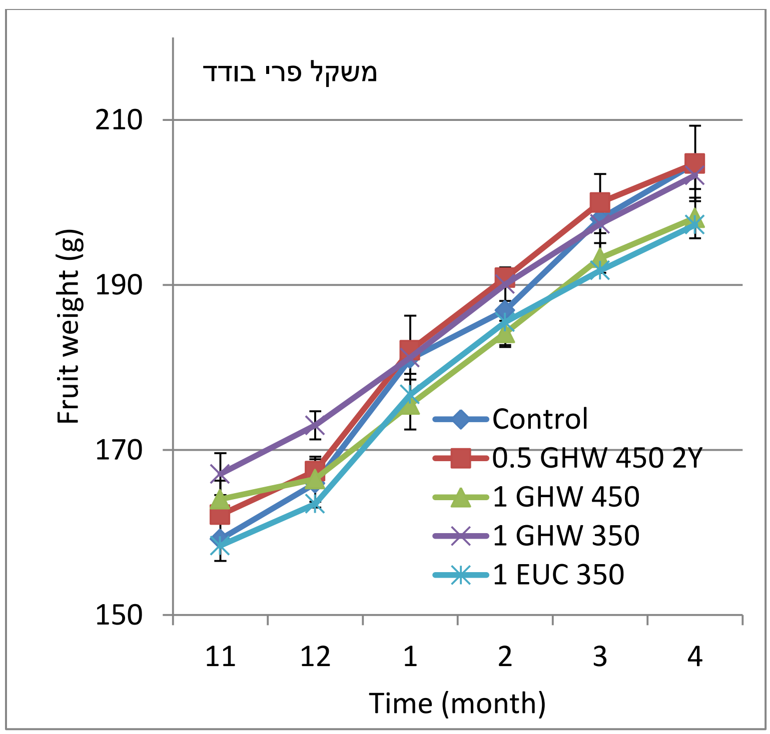



Fig. 50 Cumulative weight of a single fruit, Yair experiment 2013-2014

Powdery mildew initiated at the beginning of Dec. 2013. Disease severity was low on 8.12.13 was and reached 25% on 26.12.13. The incidence of infected leaves was 76-84 and 97% in the two evaluation dates (Figs 51-52). The incidence of infected leaves was not affected by the biochar treatments (Fig. 51-52) and the disease severity was reduced in the second date by ca. 40% (Fig. 52). Powdery mildew severity on mid-January was high and it was reduced by one third by the biochar treatments (Fig. 53). At the beginning of March there were no differences between the treatments. On 14.4.14 the disease was evaluated on the newly formed canopy and was reduced by 40% by the biochar treatments (Fig. 54). At the end of the month of April disease became very severe and there were no differences between treatments.

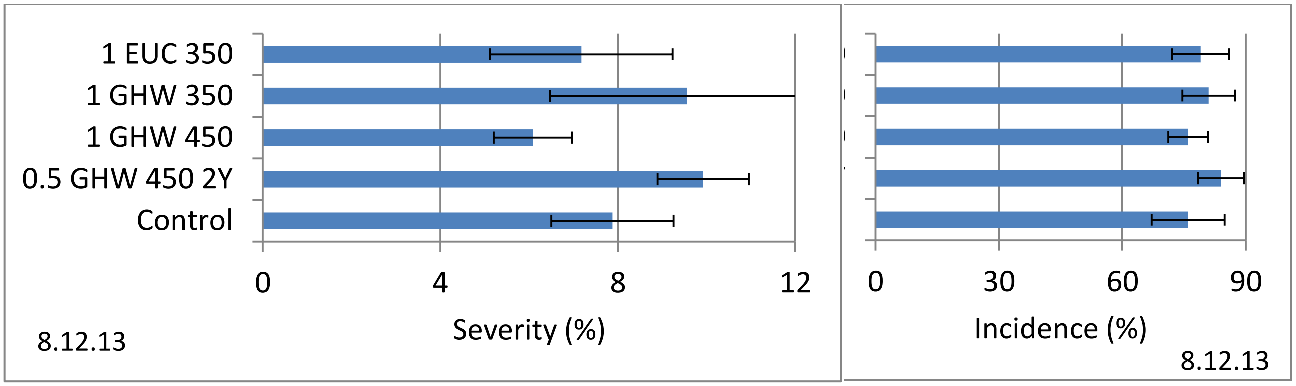



Fig. 51 Incidence of powdery mildew infected leaves (right) and severity of the disease symptoms (left) on 8.12.13 in Yair stn biochar experiment 2013/2014

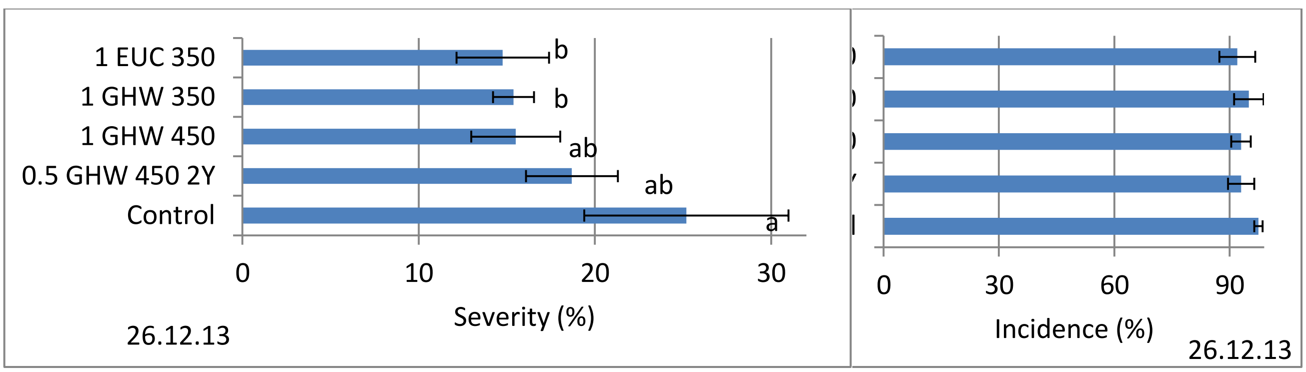
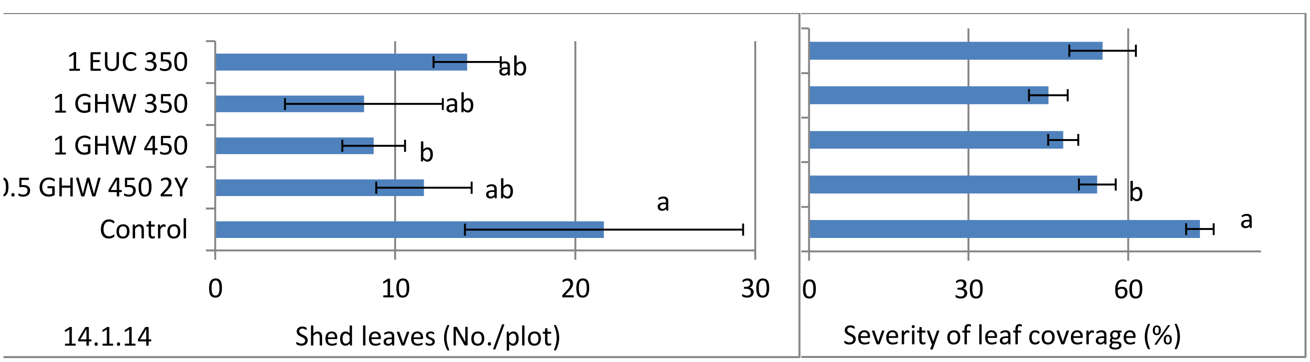



Fig. 52 Incidence of powdery mildew infected leaves (right) and severity of the disease symptoms (left) on 26.12.13 in Yair stn biochar experiment 2013/2014



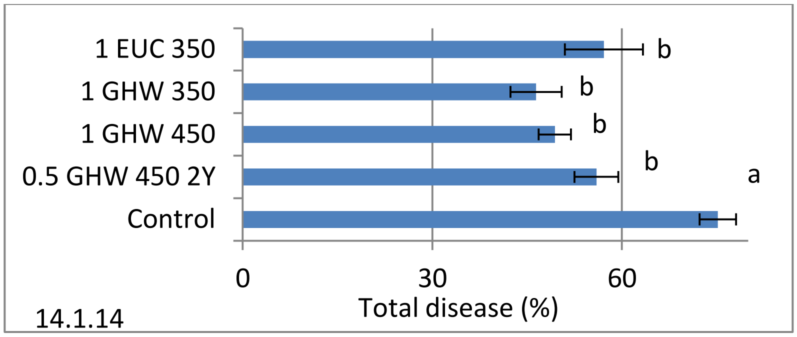
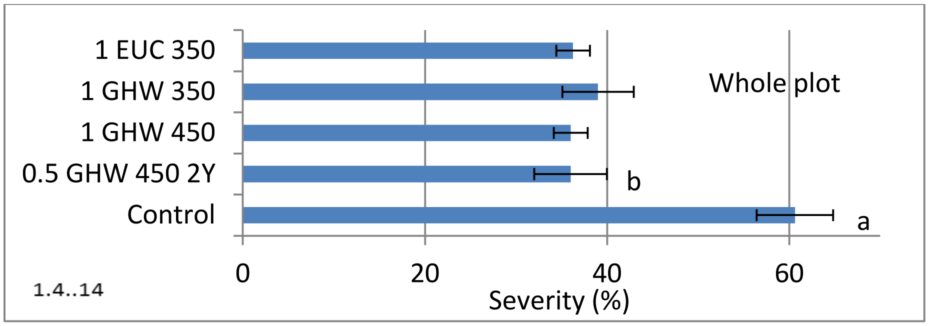
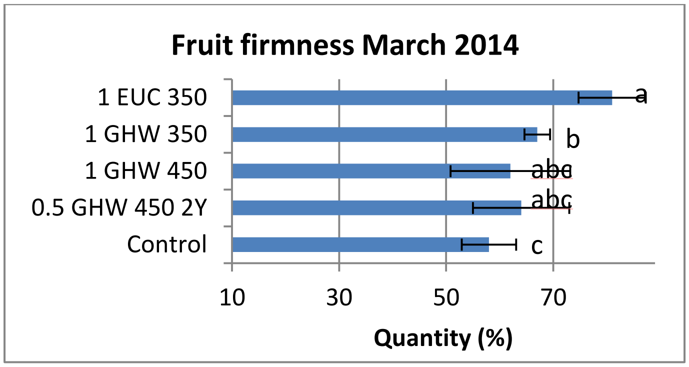


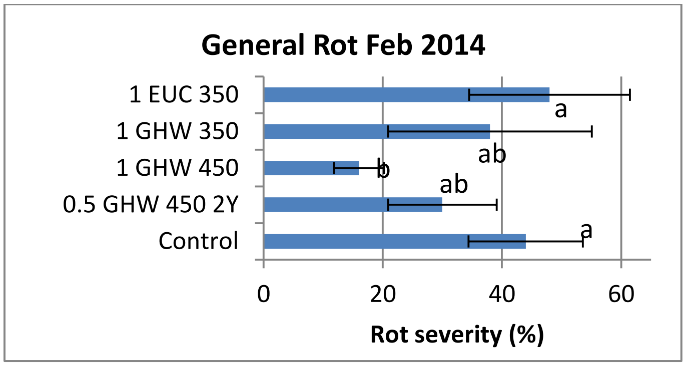

Fig. 53 Severity of intact leaf coverage (upper right) by pepper powdery mildew, shed leaves (upper left) and calculated severity of disease on 14.1.14 in Yair stn biochar experiment 2013/2014

Fig. 54 Powdery mildew severity on newly formed canopy of pepper plants evaluated on 1.4.14 in the Yair stn biochar experiment 2013/2014




Tests of postharvest parameters that were run in Yair stn revealed no differences between treatments. In February the fruit rot was reduced by the GHW-450 treatment. Fruit firmness was increased by the EUC-350 treatment in March and decreased the number of color-abnormal fruits and stem end rot. The aged-looking fruits were fewer in EUC and GHW treatments (Fig 55).



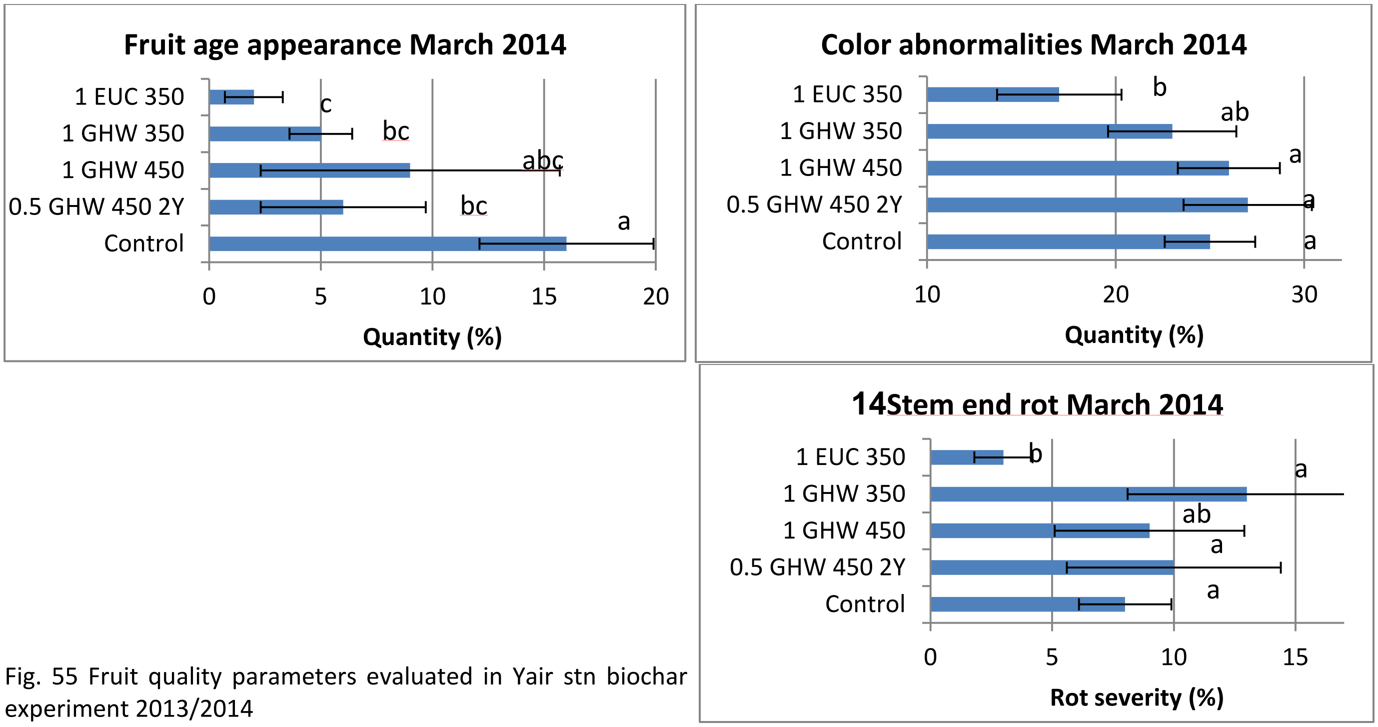



Fig. 55 Fruit quality parameters evaluated in Yair stn biochar experiment 2013/2014

### *Post-harvest handling of pepper fruit*

Fruits were harvested on 26.12.13 and on 28.1.14. The fruits were subjected to *B. cinerea* infection (Elad's lab) and to a test of postharvest quality after simulation of transport and shelf life (Eli Falik lab).

### *Post-harvest infection of fruits by Botrytis cinerea*

The fruits were inoculated by *B. cinerea* conidial suspension and incubated at 20°C. Following the first harvest the disease severity on the fruit surface was 1.9-9.1% and on the fruit stem it was 3.6-31.7%. Fruits from EUC-350 and GHW- 350 resulted in decreased fruit stem infection (Fig. 56 ). After the second harvest disease severity on the fruit surface was 2.5-13.1% and on the fruit stem it was 3.2-5.5%. Gray mold on the fruit stem was lower in the EUC-350, GHW-350 and the 0.5% (two years) GHW-450 treatments (Fig 56). No significant differences were observed between biochar treatments in gray mold severity on the fruit.

### *Post-harvest routine tests*

In the first post-harvest set of tests, no significant effect of the field treatment was observed except for a somewhat higher fruit stem rot in fruits that originated from the GHW-450 1% treatment (Table 10). In the second post-harvest set of tests, the fruits from the biochar treatments had lower chilling injury level (Table 11). In a parallel experiment where the biochar (type?) was applied on July 2013 (same growing season), the treatment resulted in lower fruit rot after the post-harvest routine (Table 11).

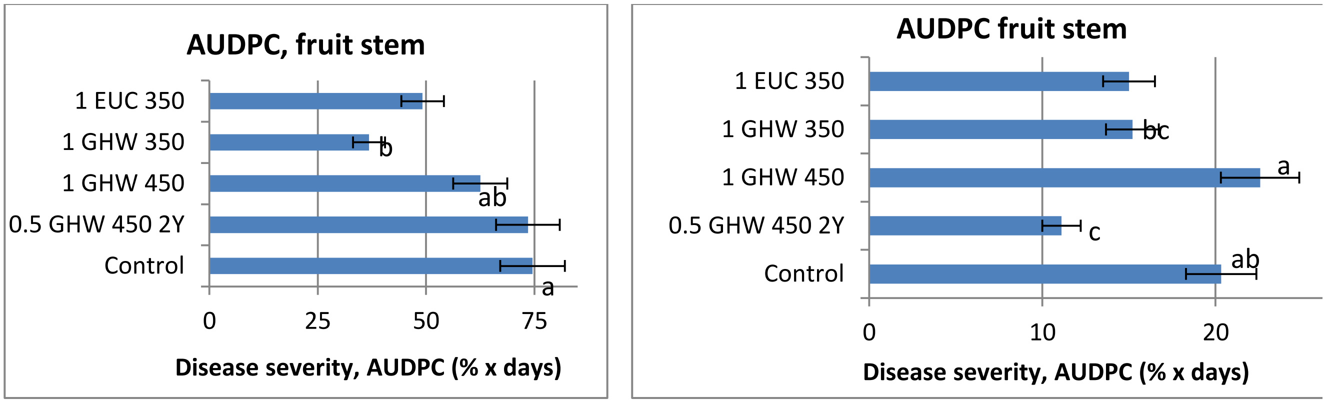



Fig. 56 Infection of fruit stem following spray of *Botrytis cinerea* conidia on fruits harvested in the biochar experiment in Yair Stn on 26.12.13 (left) and 28.1.14 (right). Results are presented as AUDPC during 18 days incubation in humidity chamber at 20°C.

Table 10. Fruit harvested in the Yair biochar experiment and tested at post-harvest conditions from 26.12.14

| Treatment | Weight loss (%) | Flexibility (mm deformation) | Total soluble solids, TSS (%) | Fruit rot (%) | Fruit stem rot (%) | Appearance (1-5) |
|---|---|---|---|---|---|---|
| Control | 4.1 | 1.9 | 6.7 | 36.4 | 5.9 | 1.7 |
| 0.5 GHW 450 2Y | 4 | 2.2 | 6.8 | 40.1 | 6.6 | 1.6 |
| 1 GHW 450 | 3.3 | 2.2 | 6.6 | 30.1 | 12.0 | 1.8 |
| 1 GHW 350 | 4.4 | 1.9 | 6.8 | 34.8 | 6.5 | 1.7 |
| 1 EUC 350 | 3.2 | 1.9 | 6.6 | 38.5 | 7.5 | 1.7 |

Fruits incubated 14d at 7C and 3d at room temp, evaluated 12.1.14
Some fruit stem rot was observed
Fruit infection by *Alternaria*, usually diameter < 6 mm. Few *Penicillium* and *Rhizopus* infections
Many fruits with yellow-orange cheek

Table 11. Fruit harvested in the Yair biochar experiment and tested at post-harvest conditions from 28.1.14.

| Treatment | Firmness (1-5) | Fruit rot (%) | Shape (1-4) | Color (1-4) Min. | max. | Chilling injury from field (%) | Light color 'cheek' (%) | Appearance (1-5) |
|---|---|---|---|---|---|---|---|---|
| Control | 2.6 | 12.3 | 2.4 | 3.0 | 3.3 | 7.4 | 3.5 | 2.1 |
| 0.5 GHW 450 2Y | 2.5 | 12.3 | 2.4 | 2.9 | 3.3 | 1.8 | 10.5 | 2.1 |
| 1 GHW 450 | 2.5 | 8.8 | 2.4 | 2.9 | 3.3 | 3.5 | 8.8 | 2.3 |
| 1 GHW 350 | 2.6 | 10.9 | 2.4 | 2.9 | 3.3 | 3.4 | 7.3 | 2.2 |
| 1 EUC 350 | 2.5 | 13.4 | 2.4 | 3.0 | 3.3 | 0.0 | 4.2 | 2.2 |

Fruits incubated 12d at 7C and 3d at room temp, evaluated 12.2.14
There was no fruit stem rot; Fruit infection by Alternaria, usually diameter < 6 mm.

In conclusion, in spite of the fact that the biochar was applied to soil before the 2012/2013 season, during the 2013/2014 growing season we still observed some disease reduction and yield increase. The post-harvest tests revealed no deleterious effect of biochar on fruit quality in storage and shelf. There was some reduction in stem *B. cinerea* induced post-harvest rot in the biochar treatments.

### *Plant Leaf Sampling and Analysis*

On December 26, 2013, plant leaves were sampled for nutritional analysis, as follows: Each block consists of 2 rows, one facing east, the other facing west. For blocks 801, 802, and 803, we sampled 4 subsamples consisting of 10 leaves each, from each block. E(east) and W(west), and also N(north, i.e., northern half of the 5 m long block), and S(southern half of block). Leaves were sampled from a height of 130-160 cm above ground. Only fully-opened, not diseased, and not torn or deformed young leaves were sampled. For all the rest of the blocks, the number of subsamples was reduced to 2 per block, one on E and one on W side, 10 leaves per subsample. This is because it was difficult to find enough leaves that fit all the criteria. Leaves were taken along the length of the block, more-or-less evenly distributed, within the limits of finding appropriate leaves. Bags were labeled by block number followed by designation: E for east or W for west. They were further labeled N or S for blocks 801,802, and 803.

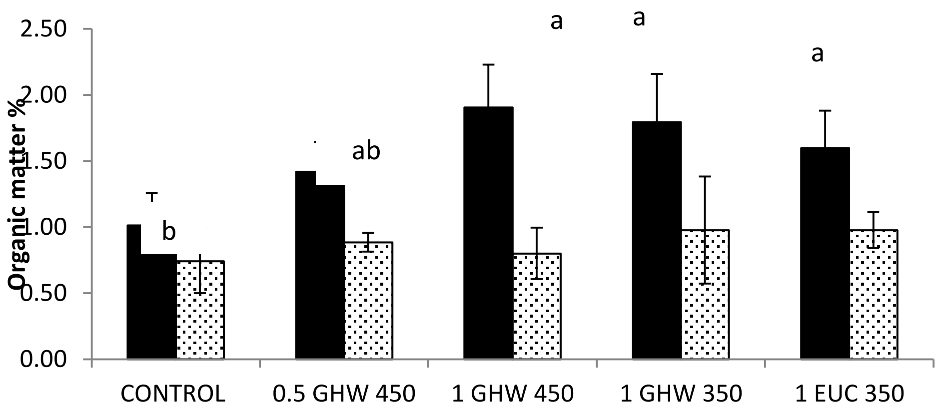
The plant material was placed in a 60$^{o}$C drying oven for several weeks, and weight was monitored to verify that a constant dry weight was reached. The contents of the bags were then ground to a fine powder, and subsamples were treated by concentrated acid digestion following standard procedures, and analyzed for the following elements: N, P, K, Ca, Mg, Zn, Fe, Mn, and Na. All subsamples were analyzed, and then results were averaged, for a total of five biological replicates per treatment, where each biological replicate was made up of 20 to 40 leaves sampled along the length of the two rows on each block.

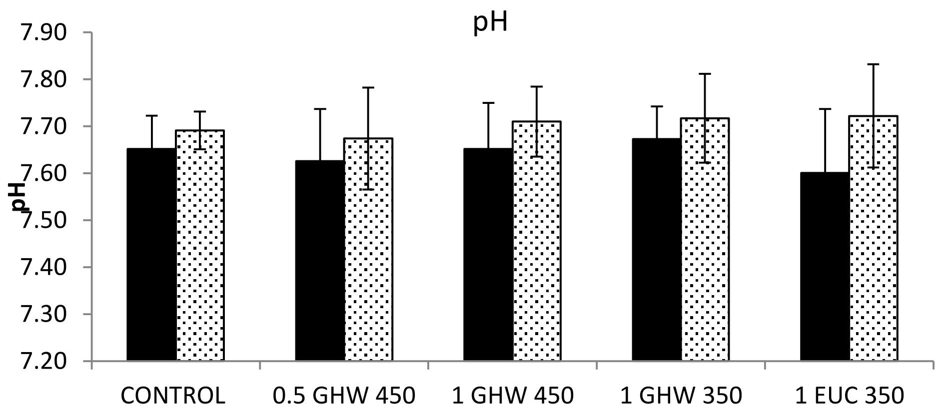
No differences in any concentrations of any elements were found between any of the treatments (not shown). The lack of difference demonstrates that the biochar treatments had no nutritional impacts on the plants, yet, nevertheless, plant growth, fruit yield, and disease resistance were all improved. This finding is similar to our previous findings in pot experiments, that is to say, there is an essential Biochar Effect that is separate from nutritional aspects.

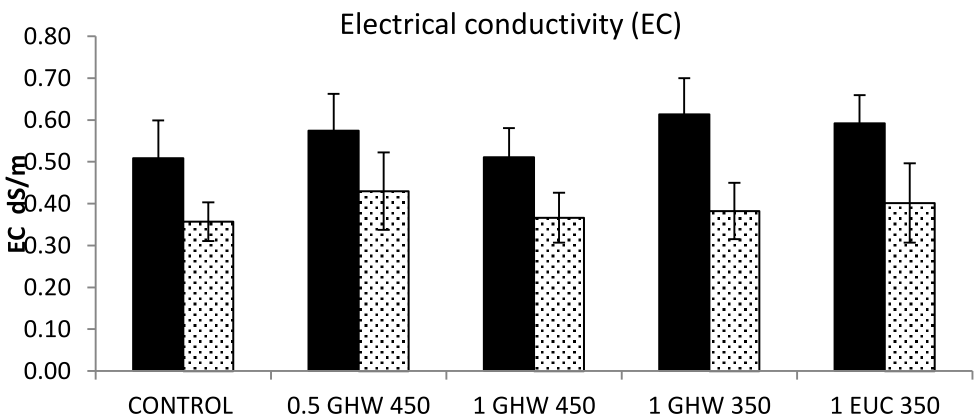
### *Soil Sampling and Analysis*

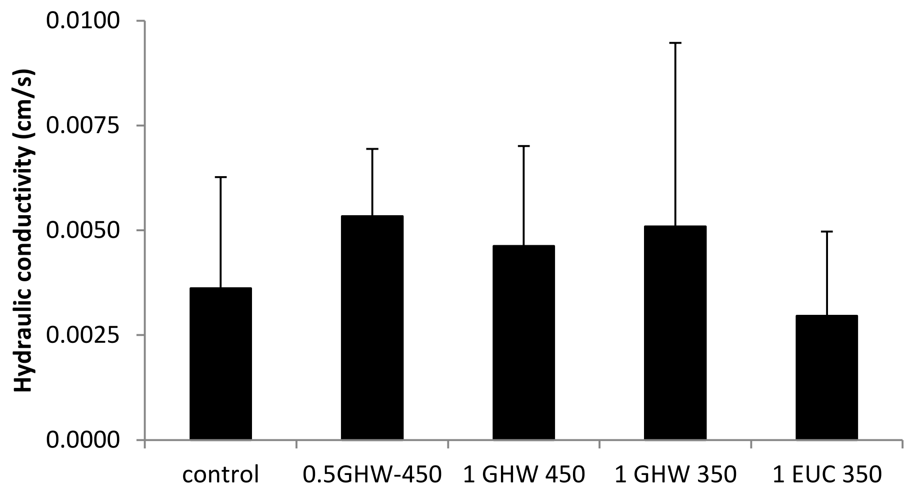
Soil samples from two depths; surface (0-15 cm) and subsurface (15-30 cm) were collected on 8.05.2014 from experimental site in Arava. Five sub samples were collected from each treatment and mixed properly to draw a composite sample for each treatment. The same procedure was followed for each depth, and composite samples collected were air dried for analysis. Several different extracts were made: (1) water extract (7 g soil to 35 mL DDW), for analysis of pH, EC, Cl, IC, TOC, Mg, Ca, Na, and K; (2) KCl extract (5 g soil to 25 mL 1M KCl) for $NO_3$ and $NH_4$; and (3) Olsen P extract (2 g soil to 20 mL 0.5 M $NaHCO_3$ at pH 8.5 for $PO_4$. In addition, soil organic carbon (SOC) was analyzed by titration following potassium permanganate wet oxidation.

With the exception of SOC (Fig. 57a), no differences in any of the soil determinants between any of the treatments and the control soil (no biochar) were found, including pH, EC, hydraulic conductivity and infiltration (Fig. 57 b-e). There were various depth-related differences in some determinants, but those were also unrelated to biochar treatment.

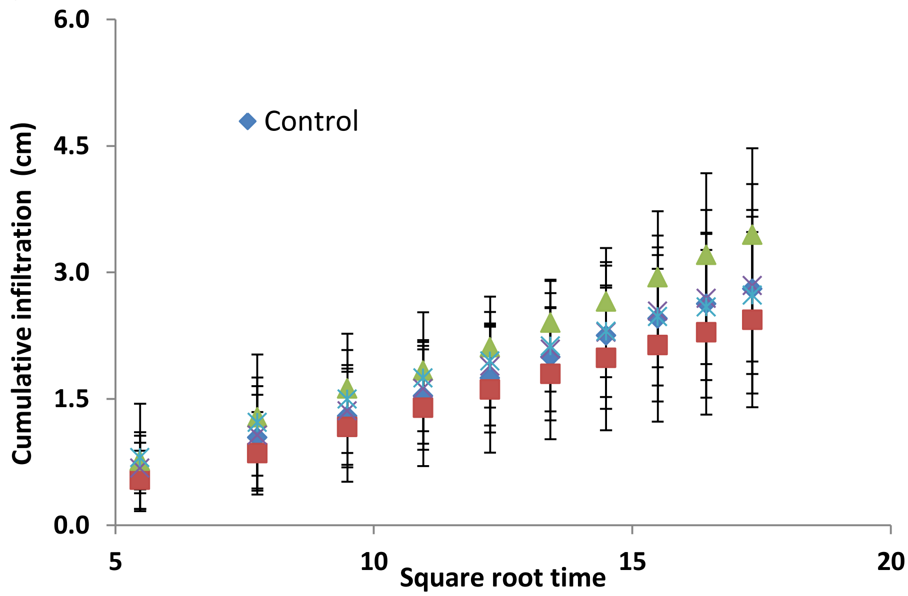

Organic matter %
2.50
2.00
1.50
1.00
0.50
0.00
a
a
a
ab
b
CONTROL
0.5 GHW 450
1 GHW 450
1 GHW 350
1 EUC 350
(a)


pH
pH
7.90
7.80
7.70
7.60
7.50
7.40
7.30
7.20
CONTROL
0.5 GHW 450
1 GHW 450
1 GHW 350
1 EUC 350
(b)


Electrical conductivity (EC)
EC dS/m
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
CONTROL
0.5 GHW 450
1 GHW 450
1 GHW 350
1 EUC 350
(c)




(d)




(e)

Fig. 57. Various soil determinants from Arava experiment. Surface samples in solid black and subsurface in dotted pattern. (a) Soil organic carbon (SOC) content in the different treatments. Significant differences were only obvious in the shallow soil (0-5 cm). Columns labeled with the same lower case letter were not significantly different on at an α of 0.05 (using Tukey HSD test). *P*-value 0.0009. (b) Soil pH. (c) Soil EC. (d) Soil hydraulic conductivity. (e) Soil infiltration.

### *Microbiology*

In order to determine the impact of biochar amendment on the rhizosphere bacterial community composition in large-scale greenhouse experiments, we applied denaturing gradient gel electrophoresis (DGGE) to 16S rRNA gene amplicons from greenhouse pepper roots, sampled from control and EUC-350 treatments 8/5/2014 (details in soil sampling section; Figure 58). A clear distinction between the root-associated bacterial communities in the amended and non-amended soils was not observed in uPMGA clustering of the DGGE band patterns. Nonetheless, previous observations in controlled small scale experiments demonstrated that biochar stimulates root-associated bacterial community shifts at low taxonomic levels, and therefore it is possible that these differences are not visible by DGGE. Currently, 16S rRNA gene amplicons are being sequenced using the Illumina platform, and we expect that this high-resolution platform should enable us to identify differences between the two soils.

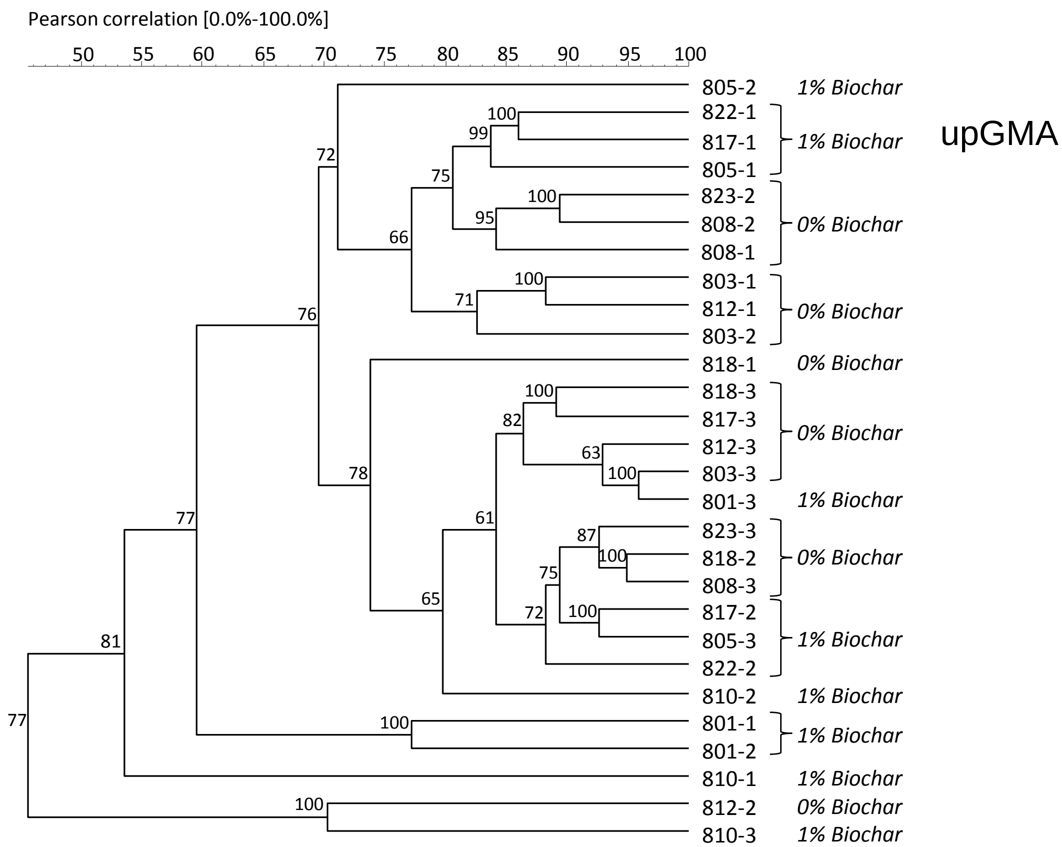



Figure 58**.** uPMGA tree depicting DGGE analysis o 16S rRNA gene amplicons from greenhouse pepper root –associated bacterial communities.

## Mechanisms Responsible for the Biochar Effect

Given that in both our pot and field experiments, we observed clear improvements in growth and induction of systemic resistance to disease in a number of pathogen-crop-biochar systems, with no relationship to either nutritional aspects or soil physical aspects, we conducted several different experiments to help elucidate the mechanisms underlying “The Biochar Effect”. The first experiment involved the first ever study of biochar impact on defense-related gene expression, carried out in strawberry [29], the second involves the first-ever study employing mutants with various defense-pathways knocked out, a third experiment involved examining the microbial community structure of the biochar-impacted rhizosphere [30], and the fourth experiment took a holistic approach by examining not only the impact on biochar on plant growth and disease, but also the simultaneous impacts on the rhizosphere microbial community and community diversity.

**Biochar mediates systemic response of strawberry to foliar fungal pathogens**

Reference: Meller Harel, Y., Elad, Y., Rav David, D., Borenstein, M., Schulcani, R., Lew, B., Graber, E.R. (2012) Biochar mediates systemic response of strawberry to foliar fungal pathogens. Plant and Soil, 357:245-257. Ref [29].

***Abstract***

Background and Aims: Various biochars added to soil have been shown to improve plant performance. Moreover, a wood biochar was found to induce tomato and pepper plant systemic resistance to two foliar fungal pathogens. The aim of this study was to explore the ability of wood biochar and greenhouse waste biochar to induce systemic resistance in strawberry plants against *Botrytis cinerea*, *Colletotrichum acutatum* and *Podosphaera apahanis*, and to examine at the molecular level some of their impacts on plant defense mechanisms. Methods: Disease development tests on plants grown on 1 or 3% biochar-amended potting mixture, and quantification of relative expression of 5 plant defense-related genes (*FaPR1*, *Faolp2*, *Fra a3*, *Falox*, and *FaWRKY1*) by real-time PCR were carried out. Results: Biochar addition to the potting medium of strawberry plants suppressed diseases caused by the three fungi, which have very different infection strategies. This suggests that biochar stimulated a range of general defense pathways, as confirmed by results of qPCR study of defense-related gene expression. Furthermore, primed-state of defense-related gene expression was observed upon infection by *B. cinerea* and *P. aphanis.* Conclusion: The ability of biochar amendment to promote transcriptional changes along different plant defense pathways probably contributes to its broad spectrum capacity for disease suppression.

**Induced systemic resistance in tomato (*Solanum lycopersicum*) against *Botrytis cinerea* by biochar amendment involves jasmonic acid signaling**

Reference: Mehari, Z.H., Elad, Y., Rav-David, D., Graber, E.R., Meller Harel, Y. Induced systemic resistance in tomato (*Solanum lycopersicum*) against *Botrytis cinerea* by biochar amendment involves jasmonic acid signaling. In revision in Molecular Plant Pathology.

***Abstract***

When added to the soil, biochar, a solid co-product of biomass pyrolysis, has been seen to be a novel inducer of systemic resistance to foliar pathogens in tomato, strawberry, and pepper. To identify the induced resistance pathway mediated by biochar in the tomato – *Botrytis cinerea* pathosystem, we studied (a) the effect of plant genetic variations affecting salicylic acid (SA), ethylene (ET) or jasmonic acid (JA) in response to biochar-mediated induced resistance; (b) variations in the early cellular response of $H_2O_2$ burst associated with biochar-mediated resistance; and (c) the transcriptional changes of 12 defence-related genes induced by biochar amendment upon *B. cinerea* inoculation of detached leaflets. Amendment of potting mix with greenhouse waste biochar produced at 450ºC resulted in ca 50% reduction in *B. cinerea* disease severity in all tested genotypes with the exception of a JA deficient mutant, *def1*. Stronger and earlier $H_2O_2$ accumulation was observed as a result of the biochar amendment subsequent to *B. cinerea* inoculation in all the systems with the exception of the *def1* mutation. Finally, biochar amendment induced priming of early as well as late-acting defence responses in a JA-dependent manner, particularly in the genes *Pti5* and *Pi2*, which are known to be crucial in resistance against *B. cinerea*. These results are suggestive that biochar-mediated IR in the *B. cinerea*-tomato pathosystem involves the JA pathway.

### Impact of biochar application to soil on the root-associated bacterial community structure of fully developed greenhouse pepper plants

Reference: Kolton, M., Meller Harel, Y., Pasternak, Z., Graber, E.R., Elad, Y. Cytryn, E. (2011) Impact of biochar application to soil on the root-associated bacterial community structure of fully developed greenhouse pepper plants. *Applied and Environmental Microbiology* 77: 4924 - 4930. Ref [30].

***Abstract***

Adding biochar to soil has environmental and agricultural potential due to its long-term carbon sequestration capacity and its ability to improve crop productivity. Recent studies have demonstrated that soil-applied biochar promotes the systemic resistance of plants to several prominent foliar pathogens. One potential mechanism for this phenomenon is root-associated microbial elicitors whose presence is somehow augmented in the biochar-amended soils. The objective of this study was to assess the effect of biochar amendment on the root-associated bacterial community composition of mature sweet pepper (*Capsicum annuum* L.) plants. Molecular fingerprinting (denaturing gradient gel electrophoresis and terminal restriction fragment length polymorphism) of 16S rRNA gene fragments showed a clear differentiation between the root-associated bacterial community structures of biochar-amended and control plants. The pyrosequencing of 16S rRNA amplicons from the rhizoplane of both treatments generated a total of 20,142 sequences, 92 to 95% of which were affiliated with the *Proteobacteria*, *Bacteroidetes*, *Actinobacteria*, and *Firmicutes* phyla. The relative abundance of members of the *Bacteroidetes* phylum increased from 12 to 30% as a result of biochar amendment, while that of the *Proteobacteria* decreased from 71 to 47%. The *Bacteroidetes*-affiliated *Flavobacterium* was the strongest biochar-induced genus. The relative abundance of this group increased from 4.2% of total root associated operational taxonomic units (OTUs) in control samples to 19.6% in biochar-amended samples. Additional biochar-induced genera included chitin and cellulose degraders (*Chitinophaga* and *Cellvibrio*, respectively) and aromatic compound degraders (*Hydrogenophaga* and *Dechloromonas*). We hypothesize that these biochar-augmented genera may be at least partially responsible for the beneficial effect of biochar amendment on plant growth and viability.

### Holistic Approach: Higher diversity in root associated bacteria and overall changes in microbial metabolic potential is associated with biochar-stimulated plant resistance to pathogens and improved plant growth

The “biochar effect”, the phenomenon in which biochar soil amendment promotes plant growth and suppresses foliar disease has been well demonstrated in the course of this and other studies. However, the mode of action that explains this phenomenon is still a mystery. In this study, we applied a holistic approach in order to decipher the “biochar effect” in a series of comprehensive greenhouse experiments using tomatoes. We monitored the effect of biochar on tomato plant development by analyzing physiological parameters, minerals and metabolic profiles as well as their resistance to the foliar fungal pathogen Botrytis cinerea. In tandem, rhizosphere bacterial community succession was analyzed by high-throughput sequencing and by carbon-source utilization profiling.

Results showed that although tomato growth phase had a substantially higher impact on plant metabolite production and bacterial community composition than biochar amendment, addition of biochar did result in significantly different microbial community composition, when sequences were analyzed at high phylogenetic resolution (above the 97% cutoff level). At these taxonomic levels the root-associated bacterial community diversity and richness was significantly higher in the biochar-amended soils relative to the non-amended soils (Figure 59). There are several recent studies that have demonstrated a strong correlation between microbial diversity and ecosystem functioning and plant protection. Therefore, it may be suggested that the biochar-stimulated increase in plant growth, and protection towards foliar pathogens, may be at least partially due to increased microbial diversity.

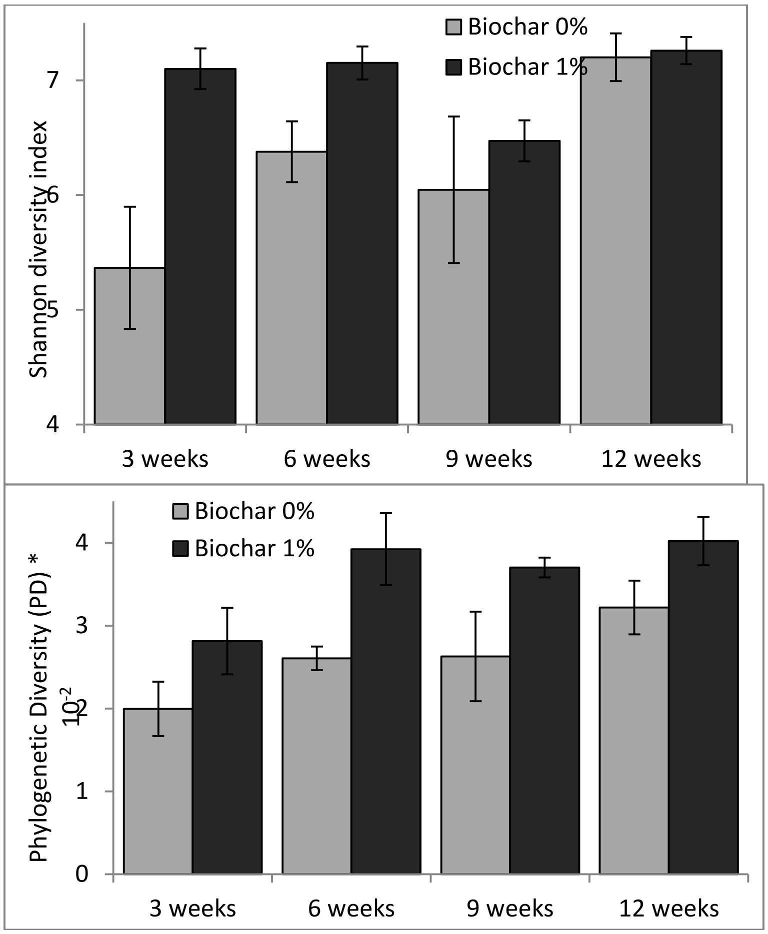



Fig. 59. Alpha-diversity root associated bacteria. Top panel – Shannon diversity; bottom panel, Phylogenetic diversity

Concomitant to the observed increased bacterial diversity in the biochar amended soils, we also observed significant differences in the carbon utilization profiles of biochar-amended and non-amended root-associated bacteria (visualized by the Biolog©) as portrayed in Figure 60.

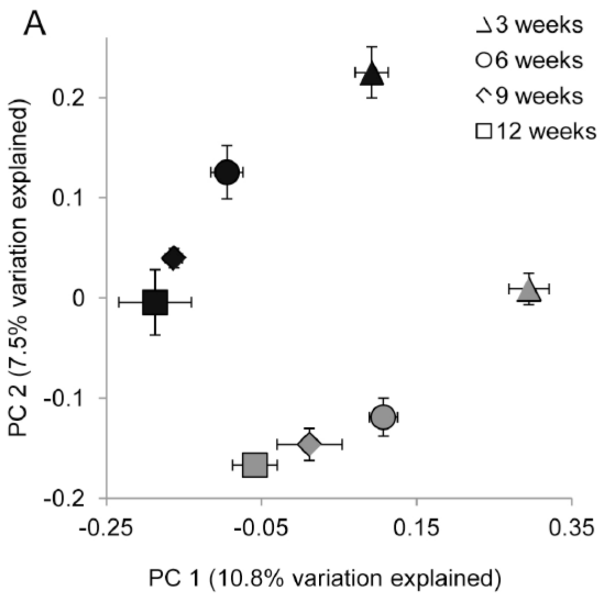



Fig. 60. Temporal changes in bacterial carbon utilization profiles in roots from biochar-amended (black) and non-amended (grey) plants

In order to "zoom in" and specifically pinpoint elements associated with the "biochar effect", we evaluated disease severity, bacterial community composition and microbial carbon source utilization in identical biochar-amended tomato plants that contained different fractions of biochar (whole biochar, carbon skeleton of biochar stripped of associated organic components, oil similar to that associated with biochar and biochar skeleton re-associated with stripped oil. Figure 61 clearly shows that all of the fractions repress foliar disease, however, whole biochar and biochar skeleton appear to be most effective in disease suppression. This is supported by microbial metabolic profiling of the root-associated microbial communities (Figure 62), which shows that carbon source utilization by all of the fragments that contained biochar skeleton was significantly different than that of non-amended soils or soils that contained oil alone.

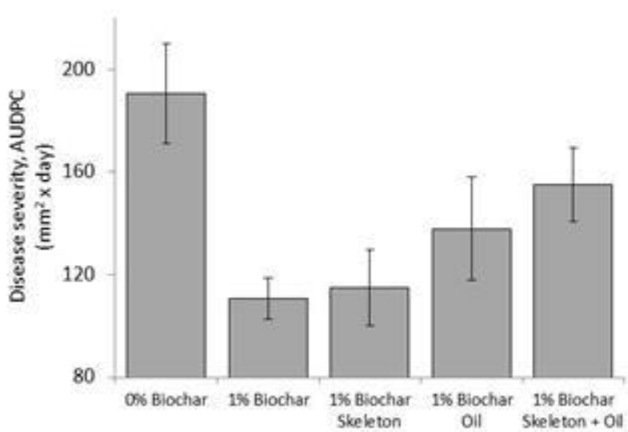



**Figure 61:** Disease severity of tomato plants grown with different fractions of biochar and in non biochar controls inoculated with the foliar pathogen *Botrytis*.

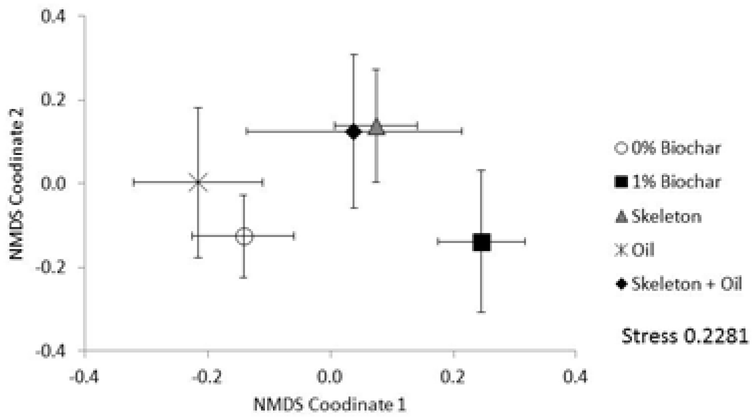



**FIGURE 62:** CARBON SOURCE UTILIZATION OF ROOT ASSOCIATED MICROBIAL COMMUNITIES.

Collectively, this study suggests that the biochar skeleton may be the primary driver of the "biochar effect" and that this effect may be due to increased microbial diversity and metabolic flexibility. To the best of our knowledge, this is the first time that a mechanism has been proposed to explain the "biochar effect". Understanding this mechanism may be crucial for increasing the beneficial effects of biochar as a soil amendment in the future.

## Economic Analysis

### Biochar life cycle in agriculture

The life cycle of biochar begins and ends with vegetation (Fig. 63). By and large, plant residues are the feedstock for making biochar. Biochar can be produced in various sized pyrolysis units in accordance with the desired products: gas and/or liquid biofuels, heat, biochar (intended for agricultural use), or charcoal (intended for energy). When biochar is added to soil, it is intended for further crop production which has agricultural waste residues as its byproduct (Fig. 63). While not being part of this cycle, charcoal for energy can also be produced using modern clean-burning pyrolysis units, replacing existing charcoal kilns that pollutes the air and are a heavy burden on the nearby residents.

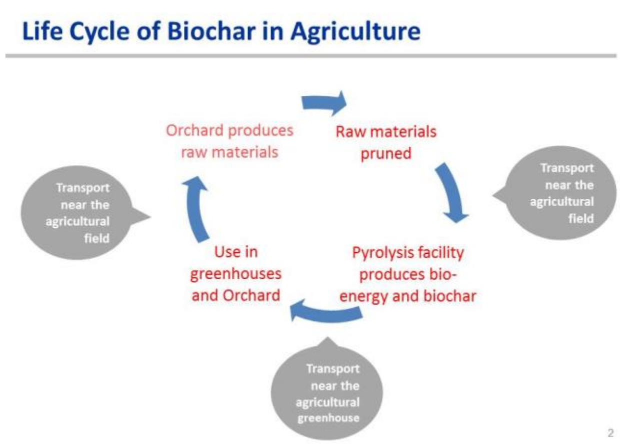



Fig. 63. Life cycle of biochar in agriculture

## Biochar feedstocks and estimated annual production

Raw materials for making biochar are varied and include manures, greenhouse wastes, and pruning waste from fruit orchards and citrus groves. Other waste sources include tree stumps that constitute a serious environmental nuisance; these stumps could be a major source of feedstock for biochar.

### *Agricultural wastes*

In areas where tree stumps are processed for charcoal, residents living near the kilns (in the northern Samaria region of Israel), often complain of breathing difficulties. That is because the process is done in the most primitive of ways, generally by digging a hole in the ground, filling it with stumps, covering the stumps with soil, and setting the stumps on fire, leaving them to smolder and slowly convert to charcoal over a long time. The gases that are released to the atmosphere during this process are heavily polluting. According to information currently available (Table 12), there are about 95,000 tons of tree stumps per annum in Israel. This estimate is based the number of trunks remaining after replacing an orchard assuming that the productive life of an orchard is 15 years. Currently, citrus occupies 180,000 dunams, other orchard crops 550,000 dunams, and olives 200,000 dunams.

Additional potential feedstocks are citrus prunings (52,000 tons/annum) and other orchard prunings (including olives; 345,000 tons/yr). However, it should be noted that such prunings are usually shredded on site and used in composting.  Olive and grape wastes are 104,000 tons annually and could also serve as pyrolysis feedstocks.

For calculations of reasonable biochar production from these feedstocks (Table 12), orchard prunings were calculated according to 0.31 tons of dry matter (DM) per dunam per year, and greenhouse prunings as 0.34 tons DM per dunam per year. It is assumed that 15% of prunings from areas having phytosanitation problems will be converted to biochar. Biochar amount was calculated according to 280 kg biochar per ton of wood chips (28%). Moreover, it was assumed that 70% of tree stumps that are currently used for primitive charcoal production will be converted to clean-burning modern pyrolysis ovens.

From these data and assumptions, it is estimated that 46,000 tons of biochar can be produced from agricultural wastes on an annual basis. Of this amount, approximately 19,000 tons would be from the conversion of primitive polluting charcoal production to clean-burning modern pyrolysis units, and the remaining 14,000 tons from orchard cuttings that can’t be shredded in part because of phytosanitation problems.

Table 12. Estimated annual quantities of plant agricultural wastes for biochar production.

| Feedstock | Agricultural branch | Waste (ton/yr) | Growing areas (dunams) | Biochar (tons/yr) |
|---|---|---|---|---|
| **Stumps** | **Total fruit trees** | **95,160** | | **18,651** |
| **Annual pruning** | Citrus | 52,300 | 187,000 | |
| | Other orchard trees including olives | 345,178 | 758,760 | **14,497** |
| | Vegetables | 29,078 | 612,808 | |
| | Flowers | 14,668 | 41,488 | |
| | **Total prunings** | **441,224** | | |
| **Related industries** | Olive pomace | 88,100 | 301,000 | |
| | Grape pomace | 16,500 | | |
| | **Total grape and olive waste** | **104,600** | | **13,215** |
| **Total** | | | | **46,364** |

Data source [31]

### *JNF forests*

Wood chips from JNF forests can also be a source of feedstock for biochar (Table 13). The total quantity of wood chips produced annually during regular maintenance of JNF forests was estimated to be 186,000 tons (sourced from 940,000 dunams of pruned trees). It is estimated that only 10% would be pyrolysed at a rate of 280 kg biochar/ton feedstock (28%), giving a total of 15,000 tons biochar. This is only an initial rough estimate and will need to be reviewed after pyrolysis facilities will be constructed in Israel and a re-examination of the feasibility of dispersing the biochar versus other alternative uses of wood chips. It should be noted that in the past, wood chips were used for producing MDF for furniture, but the Israeli factory closed and it is not worthwhile exporting the material. It should also be noted that at this time, large amounts of this waste is simply stored in heaps in the forests for lack of solution; this collected waste can be a direct feedstock for biochar.

Table 13. The possible supply of biochar from JNF forests

| Region | Land area (dunams) | Wood chips (tons/ yr) | Reasonable biochar production (tons/yr) |
|---|---|---|---|
| North | 310,000 | 32,394 | 907 |
| Central | 360,000 | 78,254 | 2,191 |
| South | 270,000 | 75,026 | 2,101 |
| Total | **940,000** | **185,674** | **14,557** |

Data: personal communication, Yaniv Selig, Department of Forest Management, Forestry Management Department, Jewish National Fund - January 2014

### *Yard waste*

Another potential supply of feedstock for biochar is municipal yard waste. It should be noted there is no organized collection of data regarding yard waste in Israel, hence, the following are only general estimates that provide a basis for assessing the future supply of yard waste as a biochar feedstock.

The supply of yard waste was calculated by the number of residents in the country and the amount of municipal pruning waste per resident per year. An initial factor for yard waste per capita per year was taken to be 0.7 tons, which is based on Rehovot municipal collection area with a population of 130,000 residents. The pruning factor used for the rest of the country was calculated on the assumption that as the size of residential plots grow, the amount of cuttings increase (Table 14). Thus, it was assumed that if a family lives on a moshav, the size of the lot around the house is 2.5 dunams, whereas in the city, 35 families live on an area of 500 square meters and will supply yard waste accordingly. Altogether, considering a population of about 8 million, it is estimated that the amount of yard waste per year is about 2 million tons. If 10% is used for biochar production at a rate of conversion of 280 kg biochar per ton waste (28%), 54,000 tons of biochar can be produced annually (Table 14).

This is of course only an estimate since there is no empirical data for comparison. Nevertheless, the average amount of cuttings calculated based on these considerations comes out to be 0.25 tons per resident per year, corresponding to about 0.7 kg per capita per day. This value seems reasonable when compared with data from the Central Bureau of Statistics that reports 1.8 kg total waste production per person per day (plastic, trimmings, other organic waste, etc.).

Table 14. Potential supply of yard waste for biochar

| Sector | Inhabitants | Coefficient of waste per capita | Waste per capita (tons/yr) | Reasonable biochar production (tons/yr) |
|---|---|---|---|---|
| Urban settlements | 6,215,500 | 0.07 | 438,123 | 12,267 |
| Towns with population up to 5000 inhabitants | 552,700 | 0.32 | 176,608 | 4,945 |
| Rural settlements | 641,200 | 0.64 | 409,774 | 11,474 |
| Kibbutzim and moshavim | 285,700 | 3.20 | 912,916 | 25,562 |
| Total | 7,695,100 | 0.25 | 1,937,421 | 54,248 |

Source: Population numbers from [32], data of 2011

In conclusion, supply of biochar from these different feedstock sources are estimated at 46,000 ton/yr from agricultural wastes, 15,000 ton/yr from JNF forests, and 55,000 ton/yr from municipal yard waste, all together, 120,000 ton/yr.

### *Other wastes*

Other wastes can also be feedstocks for biochar, for example, nut shells, coffee grounds, manures, grain husks, corn cobs, olive pits and other fruit pits, and nut shells. These wastes are not considered in the current analysis, but also are in need of a solution, which pyrolysis and biochar may provide.

## Potential demand for biochar

The possible uses for biochar are many, beyond the one dealt with expansively in this research project, i.e., amending soils to improve crop productivity and plant health. One major and obvious advance would be replacing the highly polluting and primitive method of making charcoal used in the West Bank with modern, non-polluting pyrolysis units. Another use for biochar could be as an additive to sludges and manures for stabilization and odor reduction. Biochar may also have an important role in *in situ* remediation of contaminated soils, by adsorbing heavy metals and organic pollutants and reducing soil toxicity. Biochar can also serve as a precursor to activated carbon which is used in hundreds of industrial processes worldwide, or as a cheap filter without additional processing. Table 15 lists reasonable demand for the various possibilities.

Table 15. Potential demand in Israel for biochar

| Uses for Biochar | Units of application | Number of units per year | Amount per unit (ton) | Demand (ton/yr) |
|---|---|---|---|---|
| **Agricultural** | | | | |
| Sludge stabilization/odor control | dunam | 10,000 | 1 | 10,000 |
| Manure stabilization/odor control | dunam | 20,000 | 1 | 20,000 |
| Soil amendment | dunam | 20,000 | 2 | 40,000 |
| **Other** | | | | |
| Grill charcoal production | families | 1,300,000 | 0.04 | 52,000 |
| Activated carbon production | tons | 100,000 | 0.01 | 1,000 |
| Remediate contaminated soils | dunam | 2,000 | 10 | 20,000 |
| **Total** | | | | **143,000** |

## Economic feasibility of pyrolysis units

For this analysis, feasibility of purchasing a pyrolysis unit takes into consideration the biochar and the generated heat, which can be used directly for heating agricultural structures in winter such as greenhouses. The economic calculation is based on the expected price obtained for the biochar, cost and capacity of the units, heat generation, and a general summarizing calculation that reviews costs versus revenues for determining the feasibility of purchasing a unit.

## Prices for biochar

In 2013, the International Biochar Initiative (IBI) published a report entitled: State of the biochar industry: A survey of commercial activity in the biochar field [33]. Among their findings regarding sales of biochar or biochar-containing products were the following:

- In 2013, the biochar industry was in a fledgling state, comprised largely of enterprises selling relatively small volumes of biochar products locally for end uses such as gardening and tree care. Biochar has yet to make a substantial entry into large-scale agricultural operations.
- Unblended biochar and biochar products blended with other materials are sold in many countries at a wide range of retail prices ranging from $0.08 to $13.48 per kilogram (300 NIS/ton to 50,000 NIS/ton). The average price reported was $2.48 per kilogram (918 NIS/ton).
- Companies reported volumes of biochar sales totaling 827 metric tons. 90% of those transactions were made by businesses in North America and Europe, with the remainder made in Asia and Africa.

### *Grill charcoal production for energy*

Today, grill charcoal production in Israel is mainly from primitive, highly polluting charcoal production sites that obtain tree stumps from uprooted citrus groves. The production of grill charcoal creates severe environmental damages, especially respiratory problems for local residents. Two hundred kilograms of charcoal are produced from a ton of wood (20%). Since a farmer receives about 235 NIS per ton of tree stumps, the raw material cost to produce one ton of grill charcoal is about 1175 NIS/ton, while the consumer pays between 3948-5922 NIS/ton (sale prices on the Internet for 2014). Therefore the profit margin for a charcoal producer using the traditional polluting method is large.

### *Additives to sludge and animal wastes*

One of the possible uses of biochar is as an additive to sludge and animal wastes for stabilization and odor control. Compost produced from sludge or animal wastes is sold to the consumer for approximately 47 to 188 NIS/ ton (using a factor of 2 cubic meters compost equal to one ton).

### *Activated Carbon*

Biochar can be processed into activated carbon, a high value industrial product with many uses, including water filtration, flue gas scrubbing, drilling fluids, chemical industries, and more. Activated carbon prices range from 4625 to 7400 NIS/ton; both granular and powdered activated carbon have their uses.

### *Rehabilitation of contaminated soil*

Soil contamination is usually caused by the use of hazardous materials that have leaked or are spilled on the soil surface, mainly from military or civilian industrial factories and gas stations. Both organic and metallic contaminants are common. Soil contamination is likely to cause, beyond direct damage to the soil, pollution of groundwater sources (quite a number of wells in the center of the country have been closed as a result), air pollution (as a result of emission of soil gases), and may prevent the use of the soil for many different purposes. The cost of remediating such sites can exceed millions of dollars per site. Therefore, if biochar can detoxify contaminated soils via its ability to adsorb and trap both organic and metal contaminants, the desirability of using biochar as a solution for rehabilitating soils will be great. If it can be shown in future research that this is a practical solution, it will be important to examine in detail the economic viability of this application.

### *Soil substrate additive*

Today, the market price for biochar can range between 300 to 50,000 NIS/ton, according [33]. In reality, the price will be fixed by how much the consumers will be willing to pay for it, and this will be determined by the benefits or perceived benefits received.

### *Coarse substrate in nurseries*

Coarse substrate in Israel needs to be similar to the market price for tuff which today ranges between 141 to 282 NIS/ton depending on the transportation costs from the Golan Heights (according to the company price list for 2014), where the tuff is processed. In the case of biochar, it can be produced much closer to where it is used and thus save on transportation costs. On the other hand, production costs are higher.

## Cost and price per ton

The price of pyrolysis units ranges between 10,000 to 1,400,000 NIS, depending on the size and capacity of the unit. Production costs per ton, which include repayment of capital costs for the purchase as well as regular operating expenses, but do not include income from co-produced energy, depend on the size of the unit, and range from 700 to 1120 NIS/ton biochar (Table 16).

Table 16. Costs for machinery producing biochar by the pyrolysis method (NIS).

| **Machine** | **Machinery cost (NIS per machine)** | **Amount produced (ton per day)** | **Amount of biochar produced (ton per year)** | **Return on investment[4] per ton per yr** | **Operating costs[5] per ton per yr** | **Total cost[6] per ton for biochar (NIS)** |
|---|---|---|---|---|---|---|
| A[1] | 10,000 | 0.10 | 27 | 45 | 707 | 753 |
| B[2] | 230,000 | 0.50 | 150 | 218 | 482 | 701 |
| C[3] | 1,400,000 | 1.00 | 300 | 664 | 460 | 1,124 |

Assumptions: Machinery costs, output and regular maintenance costs were obtained from various producers:
[1] Unit A is based on information from an entrepreneur at Kibbutz Almog
[2] Unit B is based on the Farmer's Continuous unit, Australia
[3] Unit C is based on Pyreg, Germany
[4] Calculated return on investment – it is assumed that the smallest machine has a 5 year lifespan, the middle machine a 10 year lifespan, and the largest machine a 15 year lifespan.
[5] Hourly operating costs were calculated for a senior technician at 62.5 NIS per work hour, at a rate of 1 hr/day (NZ-Almog), 2 hr/day (Farmer's Continuous), and 4 hr/ day (Pyreg).
[6] Total costs include maintenance, which was calculated at 7% per year for a machine that cost less than 500,000 NIS and 4.5 % per year for the larger machine.

Both Units B and C generate heat in quantities large enough that it may be feasible to use for heating nearby agricultural structures. This can be calculated as follows, with the example using Unit C:

Thermal energy = 150 kwh/h * 7,500 h/yr = 1,125,000 kwh/yr
Amount of fuel oil used per dunam greenhouse per yr = 8000 L * 0.8 kg/L = 6400 kg, at a cost of 24,000 NIS (data for red bell pepper).
Each kg fuel oil has 9800 kcal/kg
9800 kcal/kg *6400 kg = 62,720,000 kcal * 0.001163 kwh/kcal = 73,000 kwh needed to heat 1 dunam of greenhouse per year
Since the thermal energy is 1,125,000 kwh/yr /73,000 kwh/dunam/year, we get enough energy to heat 15 dunams of greenhouse per year, a savings of 24,000 NIS/dunam * 15 = 360,000 NIS/yr.

The meaning is that the cost of Unit C is returned within 5 years (accounting for the unit and other associated costs). The smaller Unit B would return its cost within 2-3 years, assuming it produces a size equivalent amount of heat.

An alternative way to make these calculations for pyrolysis units that produce both usable energy and biochar such as Units B and C are given in Table 17. Using Unit C as a basis for calculations, it is found that total income is 680,000 NIS/yr, the total operating expenses, including energy for operation, manpower, maintenance and other general costs, are 131,800 NIS/yr, and total fixed costs, which include the capital return on the pyrolysis unit for 5 years and on needed infrastructure (capital return 15 years), are 446,000 NIS/yr. The net profit per year is 103,000 NIS. These calculations are supported by a recent report by the Ministry of Environment, which concluded that pyrolysis of agricultural wastes can be economically viable, and recommended continued research and development [34].

Table 17. Income, expenses and net profits or losses per year.

| Subject | Units | Quantities | Price per quantity (NIS) | Total per year |
|---|---|---|---|---|
| **Income** | | | | |
| Electricity | kwh/yr | 697,500 | 0.61[1] | 425,000 |
| Biochar | ton/yr | 267 | 919[2] | 245,000 |
| Biochar addition to compost/sludge/manure | ton/yr | 67 | 150 | 10,000 |
| **Total Income** | | | | **680,000** |
| **Operating expenses** | | | | |
| Energy to operate | kg gas | 495 | 3.5 | 1,700 |
| Manpower | hr/yr | 365 | 62.5 | 22,800 |
| Maintenance | % | 7[3] | | 101,000 |
| Other general costs | % | 5[4] | | 6,300 |
| **Total Operating Costs** | | | | **131,800** |
| **Fixed Costs** | | | | |
| Pyrolysis unit | NIS/yr | 353,000[5] | 1 | 353,000 |
| Shredder | NIS/yr | 0[6] | 1 | 0 |
| Infrastructure | NIS/yr | 93,000[7] | 1 | 93,000 |
| **Total Fixed Costs** | | | | **446,000** |
| | | | | |
| NET PROFIT | NIS/yr | | | 103,000 |

[1] Price per green unit
[2] Average price reported by [33]
[3] Percent of purchase price

[4] Percent of all operating expenses
[5] Capital return per year for 5 years at 7% interest
[6] Cost of shredding is on the farmer, who has this expense in any case
[7] Capital return for needed supporting structure (housing unit and concrete pallet) per year for 15 years at 7% interest

### *Matching orchard size with the appropriate oven*

Today, solutions for treating annual orchard prunings are not sufficient for handling all of the waste, and therefore this waste is an attractive biochar feedstock. It is important to match the amount of waste to the pyrolysis unit. It is possible to produce biochar with a small production unit for a family farm having an orchard 100 dunams in size. On the other hand, larger orchards will need larger machinery, or, alternatively, multiple small units (Table 18).

Table 18. Required size of production units for a given orchard size

| Appropriate orchard size in dunams | Biochar output (ton per day) | Machinery costs (NIS per machine) |
|---|---|---|
| 97 | 0.10 | 10,000 |
| 484 | 0.50 | 230,000 |
| 968 | 1.00 | 1,400,000 |

Appropriate orchard size was calculated by estimating the annual amount of prunings from an orchard based on an annual dry matter amount per dunam for a citrus grove of 0.31 tons. For stone fruit trees, the average amount is 0.25 tons dry matter per dunam per year, and for avocado and other subtropicals, 0.4 tons dry matter per dunam per year [31].

## Environmental Cost-Benefit Analysis

The use of biochar in agriculture, particularly as a soil additive or as component of a growth substrate is new and unknown by most farmers. Therefore, there are no conclusive quantitative findings that can give a clear estimated value as to the benefit for agriculture. Clearly, the findings will be dependent on many local factors and the market price of alternatives. Nevertheless, there is importance in doing an economic cost-benefit analysis for the environment. By definition, the environment should look at the implications of potential long term damages. The additional income received is termed “Environmental benefits” and the “Additional expenses” is termed “Environmental costs”. We were assisted by Mr. Avraham Zilberman and Mr. Asher Eisenkot, both soil and water experts from the Agricultural Extension Service of the Israeli Ministry of Agriculture. Since these estimates are based on existing knowledge, we were careful that the terms used in the calculation would be similar to the terms used for costs and benefits so that they can be easily compared with one another.

The following basic assumptions considered:

1. Biochar can be applied in combination with composted sludge or manure once every five years.
2. Expenses and income are in terms of average NIS prices per dunam for 2014, and the interest rate for capital is taken at 7%, which is the accepted market interest rate for risk-associated agricultural investment.

Table 19 presents a general cost-benefit comparison in economic terms for the use of biochar. The detailed assumptions and methods of calculating each number is detailed below the table. As can be seen in Table 19, the main benefits from the use of biochar are (i) increased yields, ranging from 230 to 1770 NIS/dunam, depending on the crop; (ii) carbon sequestration at 755 NIS per dunam; (iii) soil remediation at 909 NIS/dunam; and (iv) odor abatement at 104 NIS/dunam, with total benefits reaching between 2078 to 3618 NIS/ dunam. On the cost side, the main damages are the risks of reducing pesticide efficacy (300 NIS/dunam) and unknown long term soil damages at 49 NIS per dunam. Total damages could reach 362 NIS/ dunam. The net benefit can range from 1716 to 3256 NIS/dunam. Even without accounting for the potential of biochar use for contaminated lands, and taking into consideration only agricultural benefits and costs, there would still be a net benefit of 807 to 2,347 NIS/dunam.

It should be noted that the farmer needs to pay for treatment and disposal of his wastes, and often, there are no good alternatives, or the costs of the alternatives are high. At this stage, this cost-benefit analysis does not account for such benefits as avoided costs of treating and disposing of wastes. This will be added at a future stage.

Table 19. General comparison of cost and benefits

| **List of benefits (positive values)** | **NIS/dunam** | **List of costs (negative values)** | **NIS/dunam** |
|---|---|---|---|
| Odor prevention | 104 | Increased soil salinity | 4 |
| Disease reduction | 45 | Increased soil pH | 6 |
| Contaminated soil remediation | 909 | Reduced hydraulic conductivity | 3 |
| Increased soil water capacity | 3 | Reduced pesticide efficacy | 300 |
| Carbon sequestration | 755 | Unknown long term damages | 49 |
| Potassium addition | 32 | | |
| Increased yields | 230 - 1,770* | | |
| Total Benefit | **2,078 - 3,618*** | Total Cost | **362** |

*The range in increased yields and total benefit relates to the difference between an extensive crop such as potato (230 NIS/dunam in increased yield), versus an intensive crop such as pepper (1,770 NIS/dunam in increased yield).

### *Environmental benefits of biochar production/use*

This list of the benefits that result from the use of biochar comes from various studies carried out in Israel and around the world. Below is a preliminary assessment for economically quantifying these benefits.

1. **Preventing ammonia other odor emissions during composting or other forms of stabilization –** A possible use of biochar is as an additive to fresh manure or sludge during composting in order to reduce odor emissions. According to literature data, $NH_3$ emissions during composting when biochar is added are reduced by about 50% [35-37]. In Israel,

these claims are being tested currently in a related research, and no conclusions can yet be drawn. A major problem today with composting manure or sludge is the objectionable odors that result. The main alternative solution proposed by the Ministry of the Environment is to conduct the composting in enclosed composting facilities for the first 3 weeks. The cost of an enclosed facility is high, and forms the basis for calculating whether there may be an economic benefit resulting from adding biochar to the composting feedstock. According to research grant requests that were submitted to the Agricultural Investment Authority, the cost of a composting facility in an open area of 120 dunams is five million NIS. These facilities are expected to provide a solution for waste odors.

Calculation assumptions for odor abatement:

1.1 **Storage time**- the waste material is held in the enclosed facility for three weeks.
1.2 **Compost per square meter –** 1 square meter of composting unit can hold 0.8 to 1.2 cubic meters of compost per year, with an average value of 1 cubic meter per 1 square meter of surface.
1.3 **Storage area coefficient** - Every cubic meter of compost that requires 1 square meter for production, requires 3 times that area in order to turn the compost pile.

The storage space that is required for setting up a closed structure is as follows:
M- annual production quantity in cubic meters- in this case 100 thousand cubic meters
W - number of storage days - in this case 21 days
D – days/year - 365 days
U – storage area factor- in this case three cubic meters per dunam.
B - amount of biochar in final compost product - 0.33 cubic meters per cubic meter of compost.
T - Cost per square meter for a light industry structure- 200 NIS per square meter.
F - storage area per dunam
The total required storage space for 100,000 $m^3$ is approximately 17 dunams as calculated below:

F = M * W / D * U
100 * 21/365 * 3 = 17 dunam

It is assumed that about a third of the existing facilities will be enclosed. According to the calculation, the cost of enclosing a facility will run about an additional 3.4 million NIS beyond the five million NIS that were already assumed (a 17,000 square meter structure times 200 NIS per meter for a light industry building).

Therefore, the respective savings by adding biochar to the composting mixture, assuming that a 50% reduction in ammonia emissions meets air quality standards, can be calculated as follows:

F * T * 1000 / (M * B)
17,000 $m^2$* 200 NIS/$m^2$/ (100,000 $m^3$ compost * 0.33 biochar fraction) = 104 NIS/$m^3$ biochar

That is to say, if 33,000 tons of biochar are part of the 100,000 tons of final compost product, there will be a net savings of 3.4 million NIS otherwise needed to build an enclosed system.

**2. Reduction of factors causing plant diseases**

According to the pot and field trial research reported here and published in the scientific literature [24, 28, 29, 38-40], the application of biochar reduces severity of plant diseases by approximately 30 to 50%. However, in conventional agriculture, this is not considered sufficient for plant protection. As a conservative assumption, we assume this level of disease reduction will make it possible to save one spraying from the overall spraying regime. The total cost of a single spraying, including the cost of labor and materials, is estimated to be about 45 NIS per dunam.

It should be noted that this calculation is for conventional agriculture. For organic agriculture, the calculation will be very different, and the effect more significant. This needs to be evaluated in a future project.

### 3. Soil Remediation

Remediation of contaminated sites can cost 10s of millions of NIS per site, either for *in situ* treatment or *ex situ* removal and treatment in a hazardous waste site. The cost of removal, transport, and treatment of contaminated soils in an approved hazardous waste site in Israel is 1000 NIS/$m^3$ contaminated soil, or 1,000,000 NIS/dunam-m. Biochar has been reported to be useful for treating contaminated soils *in situ*, and reducing their toxicity [41-43], at additive rates of 2-10 tons/dunam-m. At an average biochar cost of production per ton of 860 NIS (Table 16), even the highest application rate of 10 tons/dunam-m would cost 8,600 NIS/dunam. This biochar cost is negligible in comparison to the cost of disposing of a dunam-m of contaminated soil in a hazardous waste site. The chance that any given dunam of soil needs to be removed because it is contaminated is low, and can be calculated as the number of known dunams of contaminated soil in Israel (20,000 dunams) divided by the total area of soils in Israel (22,000,000), or 0.0909%, or 909 NIS/dunam.

### 4. Increased soil water capacity (WI)

The use of biochar, a material which is characterized by it high water absorption properties, results in a slight increase in soil water holding capacity [44]. If it is assumed that there is 100% absorption, then one ton of biochar would adsorb one cubic meter of water. Since the application of biochar will be a maximum of two tons/dunam, the economic benefit from water adsorption is marginal and would only be about 3 NIS/dunam.

P- price of fresh water 1.5 NIS per cubic meter.
Q- Amount applied
WI= P*Q
3= 2*1.5

### 5. Carbon sequestration

Biochar, as is well known, does not decompose in soil [8, 45, 46]. One ton of biochar contains approximately 70% carbon. The price of $CO_2$-equivalents according to the Ministry of Environmental Protection is 103 NIS/ton. Assuming an application rate of 2 tons biochar/dunam, the following applies.

Q- amount of applied carbon (in this case 70%*1*2)
C- Atomic weight of carbon (=12)
O- Atomic weight of oxygen (=16)

P- Price per ton of greenhouse gases (in Israel it has been fixed at 103 NIS per ton)
Q*(C+O*2)*P/C
In the case where two tons of biochar are applied per dunam, the savings will be as follows:
0.7*2* (16*2 +12) /12*103 = 755

Therefore, 755 NIS per dunam will be gained by applying 2 tons of biochar per dunam.

**6. Potassium addition (K)**

Potassium is retained as a highly water soluble salt in most biochars, particularly those produced from agricultural wastes. If we assume that biochar contains 0.5 wt % K, and 2 tons BC per dunam are applied [17], it can be assumed that 5 kg of K per dunam was applied. The market price for a kg of potassium is:

Q- amount of biochar per dunam, in this case 2000 kg.
P- Percentage of Potassium in biochar -0.5%
PK- market price of potassium which in this case is 3.2 NIS per kg.
K = Q*P*PK= 32 NIS

**7. Increased yields**

In trials that were done on the application of biochar for growing sweet red pepper in the Arava region of Israel, the results obtained showed a 15% increase in yield in the first two years after application (this report). If we assume that the biochar is added with compost once every five years, and that the yield increases are only in the first 2 years, then the average yield increase over a 5 year period is 6% per year.

Using the standard calculation method of the Israel Extension Service, an additional average increase of 6% pepper yield will be reflected as an annual increase of 0.5 ton per dunam with an increased profit (additional income after subtracting harvest, sorting and packing expenses per ton) of 1,770 NIS per dunam. Because pepper acreage is relatively small, we can make similar calculations for a more extensive field crop such as potato. There, an increase of 230 NIS/dunam was obtained.

### *Environmental costs*

**1. Increased soil salinity (SAL)**

It is assumed that the salinity added to the soil from additions of biochar will be marginal, and only potentially relevant for cases where biochar is produced from feedstocks grown on saline irrigation water. This is because crops grown on fresh water do not contain high concentrations of salts in their membranes, and thus biochar produced from those crops also does not have high salt content [15]. In the Arava experiment, where some of the biochars were indeed produced from crops grown on saline water (GHW biochars), no increased soil salinization was observed (Fig. 57c). Since there is little other research data about soil salinization from biochar application, we assume for the purposes of this analysis that the damage will at most no more than half that from applying coal ash from electricity generating power stations to soil. In Hadas et al. (in preparation), coal ash damages were estimated to be 8 NIS/dunam, so for biochar, the maximum damage is taken conservatively as 4 NIS/dunam.

**2. Increased soil pH**

Studies have reported that application of biochar to acid soils may increase its pH, which is considered a benefit [47, 48]. In alkaline soils such as common to Israel, biochar has not been reported to result in notable soil pH increases. For example, in this research project, no increase in soil pH in the Arava soils was detected (Fig. 57b). Nevertheless, as conservative estimate, we take as a possible cost for increased pH a damage of 6 NIS/dunam for the first year of application only.

**3. Change in soil hydraulic conductivity**

Mixed results have been reported regarding the impact of biochar application on soil physical and hydraulic properties, with most studies showing that biochar addition can have either no effect or positive impacts on soil physical and hydraulic characteristics, by virtue of decreasing soil penetration resistance and bulk density, increasing water holding capacity, and improving saturated hydraulic conductivity [49, 50]. In the current project, biochar was not found to have any impact on either soil hydraulic conductivity or infiltration in the Arava field soils (Fig. 57d,e). Considering these results, we believe the net effect would be zero, but, to be conservative, assign a damage of 3 NIS/dunam/yr.

**4. Reduced pesticide efficacy**

It is possible that biochar may reduce efficacy of soil-applied pest control products due to adsorption [18, 19]. In this project, we found that mainly biochars having high specific surface areas (SSAs) are troublesome, and only at rates of application exceeding 2 tons/dunam. Generally only wood-based biochars produced at high pyrolysis temperatures (>600$^{o}$C) have high SSAs; biochars produced from other wastes, including crop residues, olive pomace, manure, palm fronds, and so on, generally have low SSAs and are not expected to interfere with pest control efficacy. Moreover, 2 tons/dunam is in general our maximal suggested application rate, so that by and large, this is not expected to be a problem. In the Arava field site, we tested a low temperature wood-based biochar; it had no impact on soil-applied pest control efficacy. In event of a problem, the solution for the farmer will be to apply more pest control product. For the sake of argument, we selected a value of 300 NIS per dunam damage in terms of extra needed pest control product, in order to address this point conservatively.

**5. Long-term unknown damage**

Since soil application of biochar to agricultural soils is new, there is not sufficient experience with all its pros and cons. Therefore, the main fear is of cumulative damage from unknown causes. An assessment on the impact of cumulative damage assumes that over the long-term, the main damage will be in reducing soil usefulness for agriculture. This is calculated by considering unlimited income loss, calculated on the basis of standard economic calculations involving capitalization, income and losses over time periods, according to appropriate interest rates.

$$PV = PMT \cdot \left( \frac{1 - \frac{1}{(1+R)^n}}{R} \right)$$

where PV is present value, interest rate is R, PMT is payment, and n is time period

It should be noted that since income and losses are for a given time period, we need to capitalize the income and losses each year, according to the appropriate interest rate of the given year, whereby the discount factor (DF) is:

$$DF = \frac{1}{(1+R)^n}$$

Capitalization (R) of unlimited income loss was calculated according to annual loss of income (IN) divided by the interest rate (RATE).

R= IN/RATE

This loss is divided by the number of applied years in order to obtain an annual loss of income rate depending on the economic formulation above.

PMT (Rate, Year, PV)

Assuming that the application will be for field crops with an annual balance of 200 NIS/dunam, we assume that the risk of permanent damage is 10% (conservatively high estimate), and the interest rate (R) is 5%, giving NIS damages of 400 NIS/dunam

200*0.1/0.05 = 400 NIS/dunam damage
Since the biochar is applied only once per 5 years, the actual yearly payment would be:
49 NIS/dunam = PMT (5, 0.05, 400)

## Conclusions

1. Biochar life cycle: The life cycle of biochar begins and ends with vegetation. Plant residues are the feedstock for making biochar; biochar is added to soil where it improves primary production and creates its own future feedstock.
2. Supply side: There are abundant agricultural feedstocks that can be used for pyrolysis and biochar in Israel. Initial supplies of biochar from these different feedstock sources are estimated at 46,000 ton/yr from agricultural wastes, 15,000 ton/yr from JNF forests, and 55,000 ton/yr from municipal yard waste, all together, 120,000 ton/yr.
3. Demand side: There are many possible uses for biochar: (i) amending soils to improve crop productivity and plant health; (ii) replacing the highly polluting and primitive method of making charcoal used in the West Bank with modern, non-polluting pyrolysis units; (iii) additive to sludges and manures for stabilization and odor reduction; (iv) *in situ* remediation of contaminated soils; (v) precursor to activated carbon; (vi) low cost filters.
4. Market price: Unblended biochar and biochar products blended with other materials are sold in many countries at a wide range of retail prices ranging from $0.08 to $13.48 per kilogram (300 NIS/ton to 50,000 NIS/ton). The average price reported was $2.48 per kilogram (918 NIS/ton).
5. Biochar production costs: The price of pyrolysis units ranges between 10,000 to 1,400,000 NIS, depending on the size and capacity of the unit. Production costs per ton

range from 700 to 1120 NIS/ton biochar, not including income from co-produced energy.

6. Energy generation: Some pyrolysis units generate heat that can be used to heat nearby greenhouses. The energy generated is sufficient to return the investment on the unit within 3 to 5 years.
7. Cost-benefit comparison: The main benefits from the use of biochar are (i) increased yields, ranging from 230 to 1770 NIS/dunam, depending on the crop; (ii) carbon sequestration at 755 NIS per dunam; (iii) soil remediation at 909 NIS/dunam; and (iv) odor abatement at 104 NIS/dunam, with total benefits reaching between 2078 to 3618 NIS/ dunam. On the cost side, the main damages are the risks of reducing pesticide efficacy (300 NIS/dunam) and unknown long term soil damages at 49 NIS per dunam. Total damages could reach 362 NIS/ dunam. The net benefit can range from 1716 to 3256 NIS/dunam. Even without accounting for the potential of biochar use for contaminated lands, and taking into consideration only agricultural benefits and costs, there would still be a net benefit of 807 to 2,347 NIS/dunam.

# Discussion

This research has provided plentiful evidence that different types of plant-based biochars produced from various feedstocks over a range of pyrolysis temperatures can improve plant growth and induce systemic resistance against various foliar fungal pathogens. This is seen not only in pot experiments but in a small-scale field trial. This effect is apparently unrelated to biochar physical or chemical characteristics, and is not due to either nutritional value of the biochar or an effect of biochar on water retention characteristics of the growing medium. This effect, which we have termed “The Biochar Effect”, was documented for the first time over the course of this research project, and we have elaborated on this effect in several publications stemming from this research [28, 38]. We have made a first attempt at discerning the mechanisms responsible for the Biochar Effect. While we still do not have all the answers, we are honing in on the possibility that changes in microbial diversity in the rhizosphere related to the presence of biochar may play an important role. This direction still needs evaluation and development. For example, we saw that biochar may be redox active, which can strongly impact microbial populations. Biochar surface chemistry may also play a role in microbial changes.

There are still many unanswered questions regarding the use of biochar in agriculture in general, and in Israeli agriculture in particular:

1. What is the longevity of the Biochar Effect? We have seen that positive effects on pepper plant performance continued 2 years following the addition of biochar, but we do not know how long this effect may last.
2. Does aging of biochar in the soil environment change its effect?
3. What are the optimal doses of biochar? Should it be added in small doses on a yearly basis or in a single large dose?
4. Can biochar efficacy be improved by creating biochar/fertilizer mixtures?
5. Can biochar addition replace some standard pest control activities? We have seen abundant evidence that biochar can induce plant systemic defenses against diseases caused by foliar fungal pathogens. Is it possible, as a result, to reduce usage of pest control agents?

6. Can biochar replace some fertilizer? To now, we have preliminary indications that adding biochar may substitute for a portion of fertilizer treatment. This needs to be evaluated methodologically in a dedicated study.
7. Is there a difference in biochar performance if the biochar is produced from manure wastes as compared with plant biomass wastes? To now, we have used only biochars produced from plant biomass. Manure-based biochars may have very different qualities and effects.
8. What are the possible negative impacts of biochar in the soil? Biochar lasts for hundreds to thousands of years in the soil, so potential negatives should be carefully examined before advocating its widespread use, particularly in Israel, where arable land is at a premium.
9. Biochars have excellent adsorption capacity for organic compounds, including pesticides; capacity increases with increasing SSA. In laboratory experiments it was found that biochars with very high adsorption capacities may interfere with pest control efficacy. Is this a problem under field conditions? How does biochar aging in the soil change its adsorption ability?
10. Biochars have significant cation exchange capacity; can this impact the bioavailability of important cationic nutrients such as $NH_4$, Zn, and Ca? Does this change over time as biochar ages in the soil?
11. Can biochar be produced economically from agricultural wastes? Is biochar production a good use of wastes? Can it be an economically feasible agricultural tool?
12. Is it possible to isolate microbes having biocontrol and plant stimulation features which have been enhanced under biochar additions? Are there chemicals that are added with biochar that contribute to its impact in soil? Can they be isolated and characterized?
13. Considering the decrease in disease severity evidenced when biochar is added to the potting media, does it have a role to play in organic agriculture, where acceptable plant protection agents are few?
14. Are there contaminants in biochar that may prove problematic when added to the soil?
15. Is biochar protective also against diseases caused by soilborne pathogens and pathogens that are not fungal? What about bacteria, viruses, viroids, pests, and so on?
16. Does addition of biochar to the growing medium result in alterations in plant metabolites, hormones, secondary metabolites? How and why?
17. Which crop systems can most benefit from biochar additions? Which soils are best candidates for biochar amendment?

Being that biochar use in agriculture is such a new topic (only 6 publications in 2007 with the word “biochar” in them), there are many more unknowns than knowns regarding biochar use in agriculture. Ordinarily, if a novel treatment will be short-lived in the soil environment, there is not much downside to testing it. However, the essential feature of biochar is that it has extreme longevity in the soil environment. The effects we have documented and the preliminary economic analysis we have performed are highly encouraging, and are supported by recent findings also from the Ministry of the Environment. As a result, we believe continued intensive study into biochar is well-warranted.

# Papers and patents from this research


Already published

1. Silber, A., Levkovitch, I., Graber, E. R. (2010) pH-dependent mineral release and surface properties of cornstraw biochar: Agronomic implications. Environmental Science & Technology 44: 9318-9323.
2. Elad, Y., Cytryn, E., Meller Harel, Y. Lew, B., Graber, E.R. (2011) The Biochar Effect: Plant resistance to biotic stresses. Phytopathologia Mediterranea, (invited review) 50(3): 335-349.
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8. Elad, Y., Graber, E.R., Lew, B., Yasour, H., Oppenheimer, R. 2013. Influence of biochar added to soil on growth and health of peppers. Yavul Si, Dec. 2013. 80-86 (in Hebrew).
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10. Graber, E.R., Tsechansky, L., Lew, B., Cohen, E. (2014). Reducing capacity of water extracts of biochars and their solubilization of soil Mn and Fe. Eur. J. Soil Science, 65: 162-172. DOI: 10.1111/ejss.12071.
11. Kolton, M., Frenkel, O., Elad, Y., and Cytryn, E. (2014). Potential role of flavobacterial gliding-motility/type IX secretion system complex in root colonization and plant defense. Mol. Plant Microb. Interact. 27:1005-13.

Papers in submission

1. Mehari, Z.H., Elad, Y., Rav-David, D. Graber, E.R., and Harel, Y.M. Induced systemic resistance in tomato (*Solanum lycopersicum*) against *Botrytis cinerea* by biochar amendment involves jasmonic acid signaling. (in revision) Mol. Plant Microb. Interact.

Papers in conference proceedings

1. Meller Harel, Y., Elad, Y., Rav-David, D., Cytryn, E., Borenstein, M., Agra, O., Ben Kalifa, H., Shulchani, R., Tsechansky, L., Silber, A., and Graber, E. R. (2010) Induced systemic resistance to disease in plants by biochar. Annual Meeting in Graz. IOBC/WPRS Bulletin, in press.

2. Kolton, M., Elad, Y., Graber, E.R., Meller-Harel, Y., Pasternak, Z., Cytryn, E. Biochar soil amendment: pinpointing microbial elicitors of induced systemic plant resistance. Annual Meeting in Cordoba, 2011. IOBC/WPRS Bulletin, in press.
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Manuscripts in preparation

1. Kolton, M., Elad, E., Graber, E.R., Cytryn, E. Higher diversity in root associated bacteria is associated with biochar-stimulated plant resistance to pathogens and improved plant growth

List of student theses

1. Cohen, E. M.Sc. (2012) Nutritional elements release from biochar and surface properties of biochar as a function of pH, pyrolysis temperature and feedstock Thesis submitted to The Robert H. Smith Faculty of Agriculture, Food and Environment for the M.Sc. in Soil Sciences, The Hebrew University of Jerusalem
2. Mehari, Z.H. M.Sc. (2012) Characterization of Biochar Induced Resistance against *Botrytis cinerea* in Tomato. Thesis submitted to The Robert H. Smith Faculty of Agriculture, Food and Environment for the M.Sc. in Plant Sciences (Agroecology and Plant Health), The Hebrew University of Jerusalem
3. Kolton, M. Ph.D. Ecology and physiology of plant associated Flavobacteria. Thesis submitted 14/08/2014 to The Robert H. Smith Faculty of Agriculture, Food and Environment for the Ph.D. in Plant Sciences (Agroecology and Plant Health), The Hebrew University of Jerusalem

Patents

1. Gan-Mor, S., Lew, B., Vaknin, Y., Graber, E.R., Kashti, Y. PCT application number PCT/IB2013/056111, filed on Jul 25th, 2013 Machine and method for harvest and the production of liquid fuel, oil, fertilizer and food from agriculture crops

## Summary with Leading Questions

**1. Objectives of the Research for the report period, relating to the research proposal**

There were a number of specific objectives in this research: (i) characterizing the physical and chemical characteristics of biochars made from different waste feedstocks; (ii) examining the content and release of nutrient minerals from different biochars; (iii) examining the impact of biochar additions on soil hydraulic characteristics; (iv) evaluating the impact of biochar additions on crop yield and quality, disease resistance, and microbial populations in pot experiments; (v) determining the impact of biochar on plant sensitivity to disease during the growing season and to post-harvest fruit in a field trial; (vi) examining changes in soil microbial community structure as a result of biochar addition and understanding the connection between these changes and biochar impacts on plant productivity; and (vii) providing a first analysis of the economic potential of pyrolysis/biochar use in Israel.

**2. Major experiments and results obtained over the course of the report period**

1. Production of biochars from a variety of feedstocks under different pyrolysis conditions, giving biochar yields under different conditions.
2. Physical and chemical characterization of various biochars, documenting, among other things, that biochar cation exchange capacity is pH-dependent and a function of surface acid groups, that biochar is redox active, and that it is an excellent adsorbent for pesticides and may compromise pesticide efficacy under certain circumstances.
3. Pot experiments testing biochar impact on growth and health of basil, wheat, and tomato, demonstrating that biochar promotes plant growth and health.
4. Field experiment evaluating biochar impacts on pepper production and health under commercial conditions, demonstrating that biochar promotes pepper plant growth, improves yield, and positively influences its health.
5. Microbial community structure, functioning and diversity as impacted by biochar addition, showing that biochar increases rhizosphere microbial diversity, which in turn improved plant performance.
6. Impacts of biochar addition on soil hydraulic conductivity, showing that addition of biochar at agronomic levels has minimal effects on soil hydraulic properties.
7. Preliminary evaluation of pyrolysis/biochar economic sustainability for Israeli farmers, showing that there is significant potential which needs further development of efficient and inexpensive pyrolysis technologies.

**Scientific conclusions and implications for application of the research and its continuation. Were the objectives met?**

*The objectives were not only met in full, but greatly exceeded.*

This research has provided plentiful evidence that different types of plant-based biochars produced from various feedstocks over a range of pyrolysis temperatures can improve plant growth and induce systemic resistance against various foliar fungal pathogens. This is seen not only in pot experiments but in a small-scale field trial. This effect is apparently unrelated to biochar physical or chemical characteristics, and is not due to either nutritional value of the biochar or an effect of biochar on water retention characteristics of the growing medium. This effect, which we have termed "The Biochar Effect", was documented for the first time over the course of this research project. We have made a first attempt at discerning the mechanisms responsible for the Biochar Effect. While we still do not have all the answers, we are honing in on the possibility that changes in microbial diversity in the rhizosphere related to the presence of biochar may play an important role. This direction still needs evaluation and development. For example, we saw that biochar may be redox active, which can strongly impact microbial populations.

There are still many unanswered questions regarding the use of biochar in agriculture in general, and in Israeli agriculture in particular, these are elaborated in the Discussion section of the report.

Being that biochar use in agriculture is such a new topic, there are many more unknowns than knowns regarding biochar use in agriculture. An essential feature of biochar is that it has extreme longevity in the soil environment. The effects we have documented and the preliminary economic analysis we have performed are highly encouraging. As a result, we believe continued intensive study into biochar is well-warranted.

**Has publication of the results of the research already begun?**
*Yes*

**Publications resulting from the research**


1. Silber, A., Levkovitch, I., Graber, E. R. (2010) pH-dependent mineral release and surface properties of cornstraw biochar: Agronomic implications. Environmental Science & Technology 44: 9318-9323.
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