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Impact of biochar on soil hydrodynamics properties, water economy and tomato (S*olanum lycopersicum* l.) yield in a context of climate change, in semi-arid zone, Senegal.

A thesis, in the Rural Polytechnic Institute of Training and Applied Research (IPR/IFRA) in partnership with the West African Science Service Centre on Climate Change and Adapted Land use (WASCAL), submitted in partial fulfilment of the requirements for the Doctor of Philosophy in Climate Change and Agriculture of the University of Sciences, Techniques and Technologies of Bamako (USTTB)

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IMPACT OF BIOCHAR ON SOIL HYDRODYNAMICS PROPERTIES, WATER ECONOMY AND TOMATO (S*OLANUM LYCOPERSICUM* L.) YIELD IN A CONTEXT OF CLIMATE CHANGE, IN SEMI-ARID ZONE, SENEGAL.

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Dedication

This work is dedicated to my family, especially my parents, Edouard DIEDHIOU, Marguerite DIATTA and Isabelle NGANDOUL, for giving me the opportunity to be educated, to my wife Marie Noelle DIEDHIOU and daughter Marguerite Adiou-Baala Innocence Siabo DIEDHIOU for the understanding and the support.

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ANOVA: Analysis of Variance

BD: Bulk Density

CEC: Cation Exchange Capacity

ENSA: Ecole Nationale Superieure d'Agriculture

FAO: Food and Agriculture Organization

FAOSTAT: Food and Agriculture Organization Statistics

IBI: International Biochar Initiative

IPCC: Intergovernmental Panel on Climate Change

IWUE: Irrigation Water Use Efficiency

LCA: Life Cycle Assessment

LSD: Least Significant Difference

MF: Mychorrhizal Fungi

NE: Norme Européenne

NF: Norme Française

USDA: United States Department of Agriculture

SA: Surface Area

WHC: Water Holding Capacity

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Abstract

In Senegal, the long period of the dry season, the insufficient amount of water in the rainy season, the water pollution, and the increase in population led to a decrease in freshwater resources and put it under pressure and competition among the users. Inadequate agricultural water management combined with the weak capacity of most Senegalese soils to hold water will lead to more inefficient irrigation water use. This study aims to assess the impact of biochar on tomato yield, growth, and irrigation water use efficiency (IWUE) in sandy-loam soil in West Africa-Senegal. A two growing seasons factorial experiment was conducted with a combination deficit irrigation-biochar from February 2021 to February 2023 with three irrigation levels, i.e. full irrigation (recommended-W0=40L.day^{-1}), 75% of full irrigation (W1=30L.day^{-1}), and 50% of full irrigation (W2=20L.day^{-1}), and three amount of biochar, i.e. 3kg.m^{-2} (B2), 50%B2 (B1=1.5kg.m^{-2}), and 0%B2 (B0=0 kg.m^{-2}) (control). The application of the irrigation treatment and the measurement of different parameters started 10 days after transplantation. The results showed that the use of biochar over two years of experiment had improved soil bulk density, porosity, and moisture content at field capacity. The growth parameters of tomatoes evolved during the two years of the experiment, going from disparate results in season one to clear significant ($P<0.01$ and $P<0.05$) impacts in the second season. The evolution of the yield of tomatoes from growing season one to growing season two was up to 71.5%. Furthermore, our results suggest that biochar treatment, regardless of the amount of irrigated water level, presents a better IWUE than full irrigation without biochar (W0B0). The combination biochar's lowest irrigation water level (W2B1 or W2B2) can allow water economy up to 50% of full irrigation without compromising the yield.

Key words: Biochar; Deficit-irrigation; Water use efficiency; Sandy loam soil; Tomato yield

Résumé

Au Sénégal, la longue période de saison sèche, la quantité insuffisante d'eau pendant la saison des pluies, la pollution de l'eau et l'augmentation de la population ont entraîné une diminution des ressources en eau douce et ont créé une pression et une concurrence entre les utilisateurs. Une gestion inadéquate de l'eau agricole combinée à la faible capacité de la plupart des sols sénégalais à retenir l'eau conduira à une utilisation plus inefficace de l'eau d'irrigation. Cette étude vise à évaluer l'impact du biochar sur le rendement et la croissance des tomates, ainsi que sur l'efficacité de l'utilisation de l'eau d'irrigation (IWUE) dans un sol sablo-limoneux d'Afrique de l'Ouest-Sénégal. Une expérience factorielle de deux saisons a été menée avec une combinaison d'irrigation déficitaire et de biochar de février 2021 à février 2023, avec trois niveaux d'irrigation : irrigation complète (recommandée - W0=40L.jour^{-1}), 75% de l'irrigation complète (W1=30 L. jour^{-1}), et 50% de l'irrigation complète (W2=20 L. jour^{-1}), et trois quantités de biochar : 3kg.m^{-2} (B2), 50%B2 (B1=1.5 kg.m^{-2}), et 0%B2 (B0=0 kg.m^{-2}) (témoin). L'application des traitements d'irrigation et la mesure des différents paramètres ont commencé 10 jours après le repiquage de la tomate. Les résultats ont montré que l'utilisation de biochar pendant les deux années d'expérimentation a amélioré la densité apparente du sol, la porosité et la teneur en eau à la capacité du champ. Les paramètres de croissance de la tomate ont évolué au cours des deux années d'expérimentation, passant de résultats disparates la première saison à des impacts significatifs ($P<0,01$ et $P<0,05$) clairs la deuxième saison. L'évolution du rendement de la tomate de la première à la deuxième saison a été de 71,5 %. En outre, nos résultats suggèrent que les traitements avec biochar, quel que soit leur niveau d'irrigation, présentent une meilleure efficience de l'utilisation de l'eau (EUE)que le traitement combinant irrigation complète sans biochar (W0B0). La combinaison du biochar avec le niveau d'eau d'irrigation le plus bas (W2B1 ou W2B2) peut permettre une économie d'eau jusqu'à 50 % de la quantité d'eau utilisée en irrigation complète, sans compromettre le rendement.

Mots clés : Biochar, Irrigation réduite; Efficience de l'utilisation de l'eau; Sol sablo-limoneux; rendement de la tomate

Chapter I: Introduction

I. Problem and justification

Currently, climate change occurs in terms of increments in temperature and winds, erratic rainfall patterns, and more violent extreme events (Vermeulen et al., 2012). Due to its influence, the world faces increased natural disasters that hurt local and national livelihoods and economies (FAO, 2017). The food systems around the world will also be affected by climate change. Delgado et al. (2011) argue that feeding a growing population is one of the significant challenges the world will have to face in the context of climate change. The combination of population growth and climate change will amplify the state of resource degradation such as water depletion, desertification, deforestation, etc., which is already underway (Delgado et al., 2011). In terms of food demand by 2050, increasing global crop production to meet the needs of this population is mandatory (FAO, 2016). At the same time, there is also a need to adapt agricultural practices to meet the requirements of sustainable agriculture in the context of climate change (Sudarkodi & Sathyabama, 2011). Climate change and agriculture are closely linked and influence each other (Wani et al., 2010). Thus, to address its adverse effects on agriculture, mitigation and adaptation must also be considered (Koundinya et al., 2018). Though, because of its importance in food security, agriculture must first focus on adaptation. Failure to do so the efforts to eradicate hunger, malnutrition and poverty will be annihilated (FAO, 2016).). Climate fluctuations, sometimes reaching the most extreme levels, are the causes of the recent increases in food insecurity and hunger worldwide (FAO, 2019). According to Muller et al. (2011), predictions show that food insecurity and malnutrition will be severe challenges in the future. Climate change will adversely affect many crops in many regions worldwide by reducing yields by affecting water supply in rainfall and irrigated systems. If the effects worsen, conditions will no longer meet the environmental requirements (temperature and precipitation) necessary for good crop growth (FAO, 2016). The fact that agriculture is highly dependent on water resources, which are likely to continue to be affected by climate change, increases its vulnerability. As a result, people in developing countries, whose livelihoods and economic activities depend on agriculture, will face more difficult living conditions (Calzadilla et al., 2013).

Climate change has become one of the biggest concerns because of the significant uncertainty it has created for agriculture and food security, which is highly related to an increasingly scarce water resource (Iglesias et al., 2011). Water and food security are two of the most vulnerable sectors regarding climate change. These two themes should receive more attention in climate change adaptation plans and perspectives for developing countries (Daba et al., 2018). Of all the available freshwater for human activities, agriculture uses 70%. The crop water demand for irrigation is likely to increase due to climate change (Calzadilla et al., 2013; Kakumanu et al., 2017).

On the contrary, the sources of fresh water are going to decrease. Of the 2.5% of existing freshwater in the world, only 0.3% is of easy access; the rest is not accessible or needs a supplementary energy supply to maid it available. Furthermore, this available part is likely to decrease because of variability in precipitation, evaporative demand, and warm temperatures. Water availability is highly related to temperature variations (Daba et al., 2018). Even if the predictions on the water are highly uncertain, one of the impacts of climate could be crop water demand requirement. Projections indicate that climate change will decrease rainfall and soil moisture in dry regions by the end of the 21st century (IPCC, 2013). Climate change will reduce water sources such as renewable surface water and groundwater in most dry subtropical regions. Thus, accessibility of water becomes a significant issue, given the place of water in the life of every living being. This weak water accessibility will increase competition for water between different sectors (IPCC, 2014).

In Africa, for instance, climate change is affecting and will continue to profoundly affect the agricultural production of smallholder farmers due to their low adaptive capacity (Müller et al., 2011). African countries are highly vulnerable to climate change because their economies depend on natural resources and rain-fed agriculture, which are very sensitive to erratic rainfall patterns (Asafu-Adjaye, 2013). Across Africa, drought continues to challenge agricultural systems. As a result, crop productivity in agriculture will decline due to erratic rainfall and unpredictable high temperatures (Ramjan et al., 2011). The yield of rain-fed crops will decrease due to irregular rainfall and rising temperatures.

In sub-Saharan Africa, the heavy dependence of more than 70% of the population on dry land farming and grazing systems increases their vulnerability to climate shocks. Around 97% of all cropland in Sub-Saharan Africa is used for rainfed agriculture, which exposes the region's agricultural production to considerable seasonal rainfall fluctuation (Calzadilla et al., 2013).

Senegal is predicted to be negatively affected by the climate change in terms of food production. In fact, most of the Senegalese agricultural system rely on rainfed (Faye et al., 2022). In addition, in Senegal, as in most West African countries, the availability of fresh water to meet the population's domestic water and agricultural irrigation needs is a major concern, as groundwater levels are often declining due to severe pressure on resources (Tall et al., 2017).

II. State of knowledge

Soil fertility depletion has been identified as the most significant constraint to West African food security (Bationo et al., 2007). Furthermore, Zougmoré et al. (2014) indicated that improving the soil water holding capacity in the Sahel zone is important. Bright et al., (2021) showed that an increase in particulate and total organic matter, and extractable nutrients could positively affect the soil's water status. Their findings remind us of the important role of soil fertility management in improving soil water-holding capacity. Soil water availability is highly sensitive to climate change, and severe water-stress conditions will affect crop productivity, particularly vegetables (Spaldon & Samnotra, 2015).

Much research was carried out to address these two critical issues in West Africa, namely the soil fertility and water holding capacity. Different researchers proposed different types of soil remediation processes. Two main types of research for soil fertility status improvement can be distinguished: the research that focuses on the cropping systems and land uses (Mahe et al., 2005; McClintock & Diop, 2005; Mason et al., 2015; Bright et al., 2021), and the ones treating the issue in the angle of soil organic carbon improvement through application of compost, crop residues incorporation, biochar application (Ouédraogo et al., 2001; Bationo et al., 2007; Häring et al., 2017; Faye et al., 2021).

Biochar has consistently been proposed as a way of improving soil fertility by increasing nutrient and soil water availability (Roussel et al., 2001; Spokas et al., 2012; Mulcahy et al., 2013; Cao et al., 2014; Scott et al., 2014; Ulyett et al., 2014). For presenting several benefits of sustainable agriculture, the amendment of biochar is being increasingly discussed as a fertility enhancer. In the last decade, there are tremendous increase in the number of publications using a variety of biochars as an amendment. William & Qureshi (2015) concluded through their research that biochar could be used as a fertiliser to improve plant nutrient availability. Knowing the importance of the feedstock on the final biochar, some authors have assessed the impact of biochar on soil nutrient status relative to the feedstock type. For instance, El-Naggar et al. (2018) have confirmed that biochar made from amur silver grass residue (AB), paddy straw (PB), and umbrella tree (UB) have respectively increased the soil cation exchange capacity (CEC), respectively up to 906%, 180%, and 130%. For Ghorbani et al. (2019), in addition to the feedstock type, it is important to consider the soil type and the amount of applied biochar. Thus, they demonstrate that the CEC increases by 20% and 30% when applied in loamy sand soil against 9% and 19% in clay soil at 1% and 3% respectively.

The effect of biochar on alleviating soil water-holding capacity is also of interest to many researchers. Researchers are interested in different aspects of biochar's effect on soil water holding capacity in this particular topic. Werdin et al. (2020) investigate the effect of feedstock's wood content on biochar on soil water holding capacity. They found that low-density eucalyptus feedstock has a 35% higher water-holding capacity and 45% more water available to plants than biochar made from high-density eucalyptus. In their research, Mao et al. (2019) have linked the ability of biochar to increase soil water holding capacity to its hydrophobicity. Thus, they give a better understanding of how biochar is effective on soil hydraulic properties. Some works were specifically focused on a particular point of soil hydraulic properties, such as hydraulic conductivity. Jačka et al. (2018) conducted research that shows that saturated hydraulic conductivity is drastically reduced by biochar application on soil through its swelling property.

Furthermore, the performance of biochar was also evaluated, in combination with saline water, on tomato growth (She et al., 2018). Most of the studies on the application of Biochar to improve the soil water holding capacity for tomato growing were conducted in the temperate zone and a lab or greenhouse (Patanè et al., 2011; Cao et al., 2014; Agbna et al., 2017; Liu et al., 2021; Zhang et al., 2020). Some studies (Paneque et al., 2016), quantified the use of biochar to improve the water holding capacity in the field, but not on tomatoes, in terms of water economy in sandy loam soil and semi-arid zone through the combination biochar-deficit irrigation. Studies on the combination between biochar and deficit irrigation exist, and Liu et al. (2021) worked on that combination with a focus on tobacco yield. Faloye et al., (2019) worked on the same theme of biochar-deficit irrigation but observations targeted the yield and the water use efficiency of maise. On tomatoes, the research is either on deficit irrigation only (Patanè et al., 2011; Savić et al., 2008) or on biochar, but the combination of the two is rare. Although, Zhang et al. (2020) carried out a research on the effect of the combination of biochar and different irrigation regimes on greenhouse tomatoes.

Biochar has been proposed to boost different crop performance regarding yield and growth parameters. Researchers explored several categories of plants. Adekiya et al., (2019) have explored the effect of biochar application on the yield of radishes, while Carter et al. (2013) concentrated their attention on the growth of lettuce and cabbage. Apart from vegetables, research has been set up to observe the root behaviour of sugarcane seedlings under biochar amendment (Yang et al., 2015).

In West Africa, where the soil conditions, the weather and the practices are different from elsewhere, the studies on biochar as an enhancer of soil water holding capacity are limited. Such studies on the water-holding capacity of applied soil biochar can be very important, knowing that many West African countries will have to overcome the challenges of multi-usage of the same water source. Also, it can help farmers to make a better profit from their farming activities knowing that most of the time, in many places, Senegal, for instance, water used for irrigation generally has a cost (150FCFA/m^3, 200FCFA/m^3, 300FCFA/m^3…) which could be consider as expensive according to the area. However, researchers are trying to understand better the relation between biochar, soil fertility status and water holding capacity. In that regard, Dugan et al., (2010) evaluated the effect of biochar from sawdust, maize straw and charcoal on three types of soil in Ghana. In Senegal, Faye et al. (2021) assessed the long-term effect of biochar on increased fertilizer efficiency, C Sequestration, and pH in sandy soil. After observing the positive effect of biochar on water use efficiency, the authors suggested further research with the combination of biochar-deficit irrigation as an approach to increase crop water use efficiency. Nevertheless, to our knowledge, no study in West Africa, particularly in Senegal, has been carried out on the combination biochar-deficit irrigation on tomatoes. This research's primary purpose is to understand further the impact of biochar and deficit irrigation on soil hydrodynamics properties on sandy loam soil in Thies in Senegal.

The research question of this study is: How does biochar application on soil under deficit irrigation enhance the efficient use of water without compromising the yield of tomatoes?

Specific research questions are:

- Does the amount of biochar influence the soil water content?
- How does the application of biochar allow the economy of water in an irrigation system?
- Which combination biochar-Irrigation improves the yield of tomatoes?
- What is the efficiency of irrigation under biochar application?

III. Research hypothesis

It is hypothesised that:

- The application of biochar improves the hydrodynamic properties of the soil
- Biochar in the soil reduces the amount of water used in irrigation
- Biochar application into the soil improves the yield of the tomato
- The use of Biochar improves water productivity

IV. Objectives

IV.1 General objective

This research aims to understand the mechanism of soil fertility improvement and water economy by biochar application.

IV.2 Specific objectives

1. Determined the effect of biochar on soil hydrodynamic properties.
2. Determined the tomato growth and yield under different biochar application rates at different irrigation regimes.
3. Describe the influence of biochar on the water use efficiency of tomatoes in an irrigation system.

Chapter 2: Literature review

I. Tomato

I.1 Importance of tomato production

I.1.1 Tomato around the world

Lycopersicum esculentum was the former name of the tomato plant before it changed, thanks to the research, to *Solanum lycopersicum* (Pavan et al., 2009). Although that former scientific name is still in use and accepted by the scientific community (Ghorbani et al., 2008; Martínez et al., 2013; Mueller et al., 2009; Van Eck et al., 2006; Yilangai et al., 2014). Before it spread away worldwide, and because it belonged to the same family as the nightshade, Solanaceae, the tomato was seen as too dangerous for consumption (Rick, 2017). Before the 1500s, the fruit was only consumed where it originated, "in the area extending from Ecuador to Chile in the western coastal plain of South America." In the rest of the world, tomato is not advisable for consumption; they represent a risk (Kelley & Boyhan, 2014). The mid-1500s marks the introduction of tomatoes in European countries (Kelley & Boyhan, 2014a). This introduction of tomatoes in Europe did not include consumption because the tomato was only grown as ornamental plants for decoration. People in Europe only started to accept tomatoes as food around 1840 (Arah et al., 2015) for human consumption. Thanks to its health benefit, its diverse form of consumption (raw or cocked), and its use in a range of food and diet, the tomato has awakened the interest of many researchers from different domains (Arah et al., 2015; Tahir , Shah, and Sharif, 2012). Much research on tomatoes goes from genetic to agronomy, passing by economics, chemistry, environment, physiology, and hydrology (Arah et al., 2015; Creamer et al., 1996; Houshyar et al., 2015; Kim et al., 2017; Pék et al., 2010; Tahir, Shah, and Sharif, 2012). Van Eck et al. (2006) indicate that no less than 4000 varieties have different characteristics depending on production goals and environment. However, despite this, science continues to seek to improve the quality of tomatoes. The research on the crop facilitated its current wide use in almost all countries, giving it status at the same time as a cash crop and staple crop according to the cultivation region.

Furthermore, the health benefits of tomatoes establish the need for their use in a healthy diet and are encouraged in the area of low nutrient consumption (Arah et al., 2015). Tomato, thanks to research, can be eaten to prevent "cancer, cardio-vascular and neuro-degenerative diseases" et restore the body's equilibrium (Dorais et al., 2008). In addition, its beautiful colour has aroused the curiosity and desire of consumers to taste it, thus spreading widely. (Saad et al., 2014).

From a poisonous plant status, the tomato (*Solanum lycopersicum*), a member of the family of the *Solanaceae*, has become one of the most-grown vegetables in the world (Naika et al., 2005; Rick, 2017). Nicolas et al. (2009) stated that tomato is the second most consumed vegetable in the world after potato. FAOSTAT data (fig.1) from 2021 shows that between 1999 and 2019, the worldwide tomato harvest area increased from 3,965,596 hectares to 5,030,545 hectares, respectively, an increase of 26.85% in just 20 years. In the same period, the global world production grew to 65.93%, moving from 108,942,310t to 180,766,329t. Among the continents, in 2019, Asia was the leader in tomato production with 112,104,020t, followed by America (23,786,872t), Europe (22,803,866t), Africa (21,664,774t), and finally, Oceania (406,797t). Asia produces then 62.01% of the total world production of tomatoes. This position of Asia is mainly due to China's (62,869,502t) production, which represents 56.08% of Asia's production. In 2019, China was ranked first in the world before India (19,007,000t) (FAOSTAT, 2021).

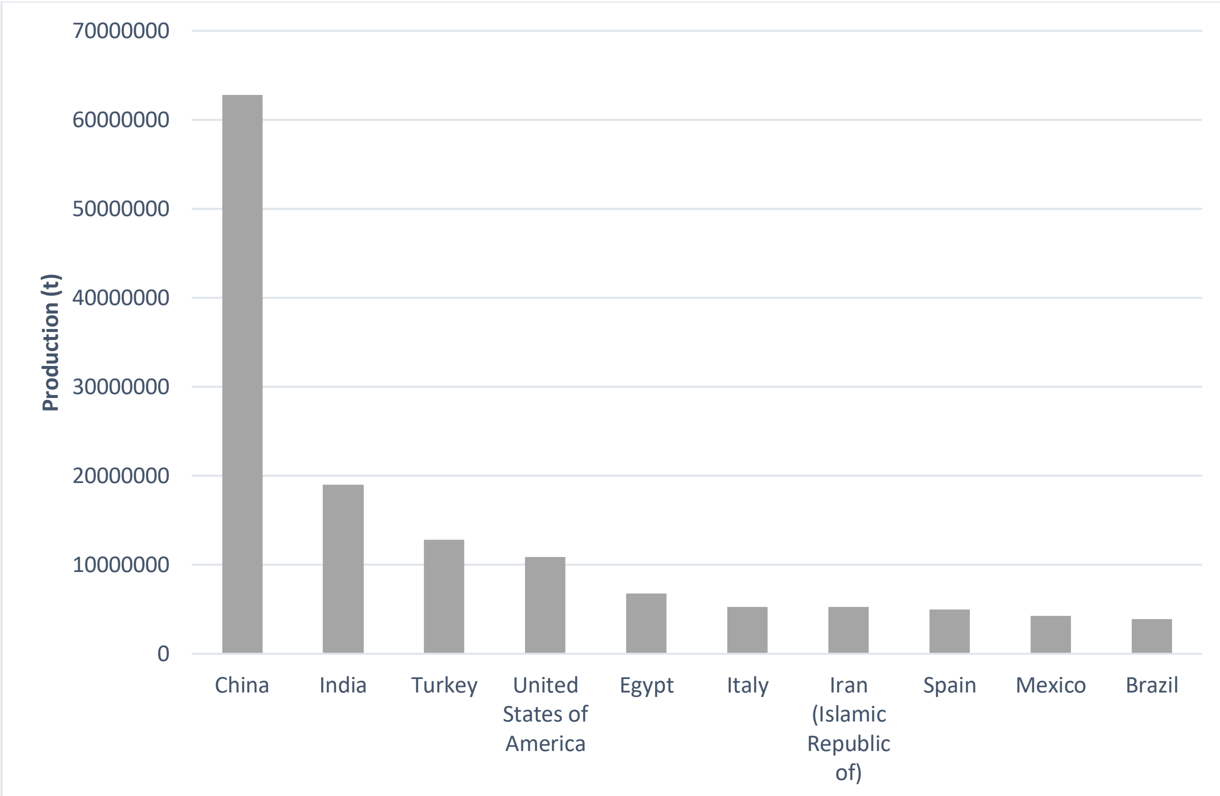

Figure 1: Top 10 country production of tomatoes in 2019 (Adapted from FAOSTAT 2021)

The use and value of tomatoes have increased due to their high demand worldwide, thanks to their broad and diversified consumption pattern (Tahir, Shah, and Sharif, 2012).

I.1.2 Tomato in West Africa

The FAOSTAT (2022) data show that West African countries still need to be among the top 10 countries regarding tomato consumption (fig.1). Nevertheless, the same data indicate that from the 2000s to 2021, production has globally increased reaching 65.2% (Fig.2). Thus, tomato production is gaining more and more place in West African agriculture (Fig.3). This progression is due to the usage of tomatoes in daily dishes in some West African countries (Adegbola et al., 2018), like Nigeria, Ghana, and Benin (Figure 3), and the fact that some farmers see tomatoes as a cash crop. It is an excellent source of income diversification for smallholders with low incomes. Among horticultural crops in Africa, tomatoes are in the top 10 for yield (Amuji et al., 2020).

In the context of climate change, a decrease in water resources is one of the main challenges, especially in West Africa (Arouna et al., 2018). Due to its reliance on rain-fed agriculture, threatened by climate change, West Africa is one of the region's most vulnerable to water scarcity (FAO, 2019).

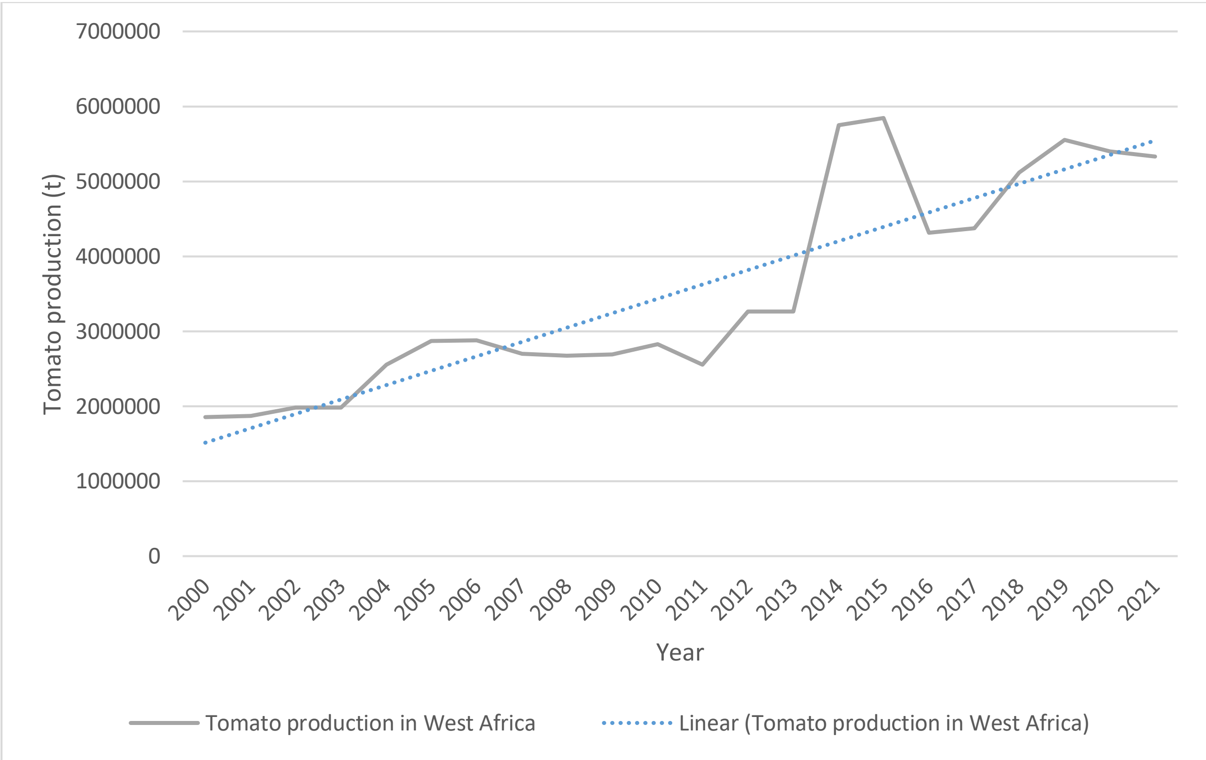

Figure 2: Evolution of tomato production in West Africa from 2000 to 2020 (Adapted from FAOSTAT 2022)

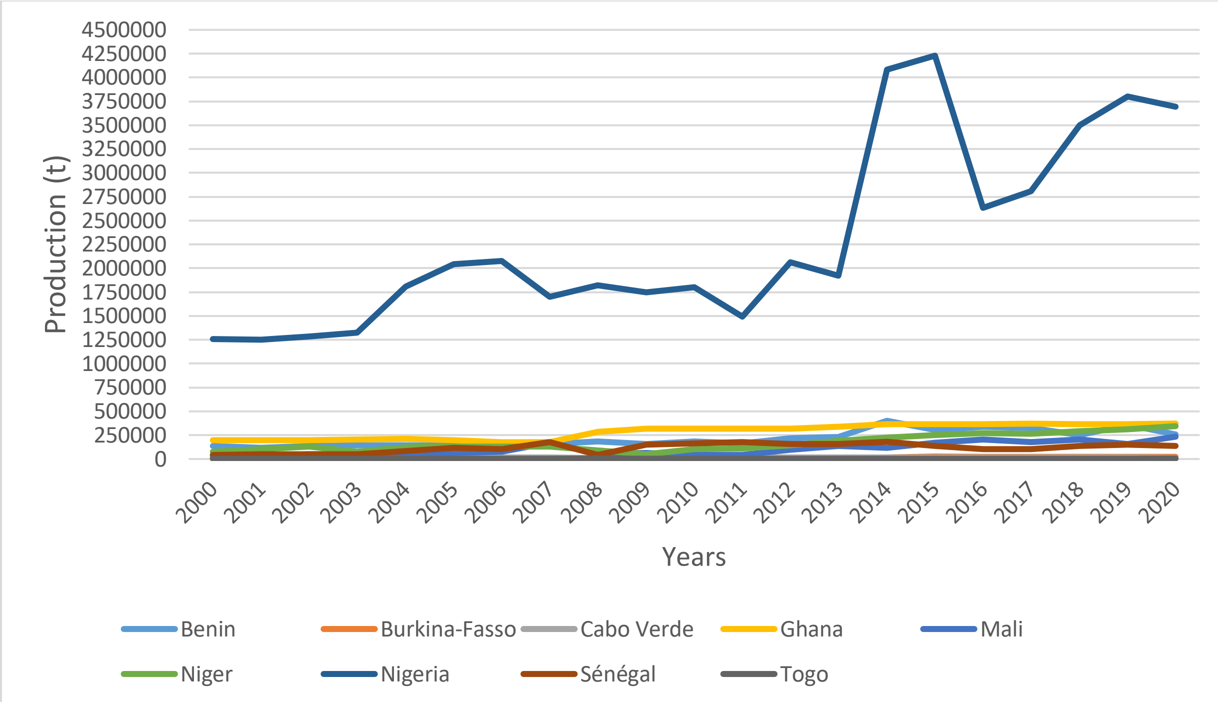

Figure 3: Tomato production per Country in West Africa from 2000 to 2020 (Adapted from FAOSTAT 2022)

I.1.3 Tomato in Senegal

Tomato is one of the major crops in vegetable production in Senegal in terms of the cultivated area and total production. According to FAOSTAT (2022), from 2010 to 2020, the harvested surface of tomatoes in the country and the entire production have irregularly evaluated with periods of decrease and increase (Figure 4 & Figure 5). Globally, however, tomatoes are the country's second most important crop, after onions, with about 20% of the total cultivated area (Fall et al., 2009). In 2019, the production trend in the primary Senegal market was, in terms of size, 14,652 hectares of onions, 6,867 hectares of tomatoes, and 6,031 hectares of potatoes. Those areas gave respectively in the same year 444,871 tons, 148,000 tons, and 140,000 tons for onion, tomato, and potatoes. Thus, if we suspend only the surface area aspect, tomato is the second largest water consumer in Senegal market gardening, after the onion. Drought conditions drastically reduce vegetable productivity. Water requirements for vegetable crops such as radishes and tomatoes range from 152.4mm to 609.6mm per season, respectively (Spaldon & Samnotra, 2015).

Furthermore, knowing that it is produced under irrigation most of the time, it represents a great source of competition for human water consumption (Fall et al., 2001).

In Senegal, tomato production's main challenges are reduced water availability (Faye & Msangi, 2018), poor soil water retention, and mineral content (Fall et al., 2001). Although for excellent and sustainable tomato production, it is necessary to have sufficient water, optimum soil water retention, and an adequate and sufficient nutrient supply (Naika et al., 2005).

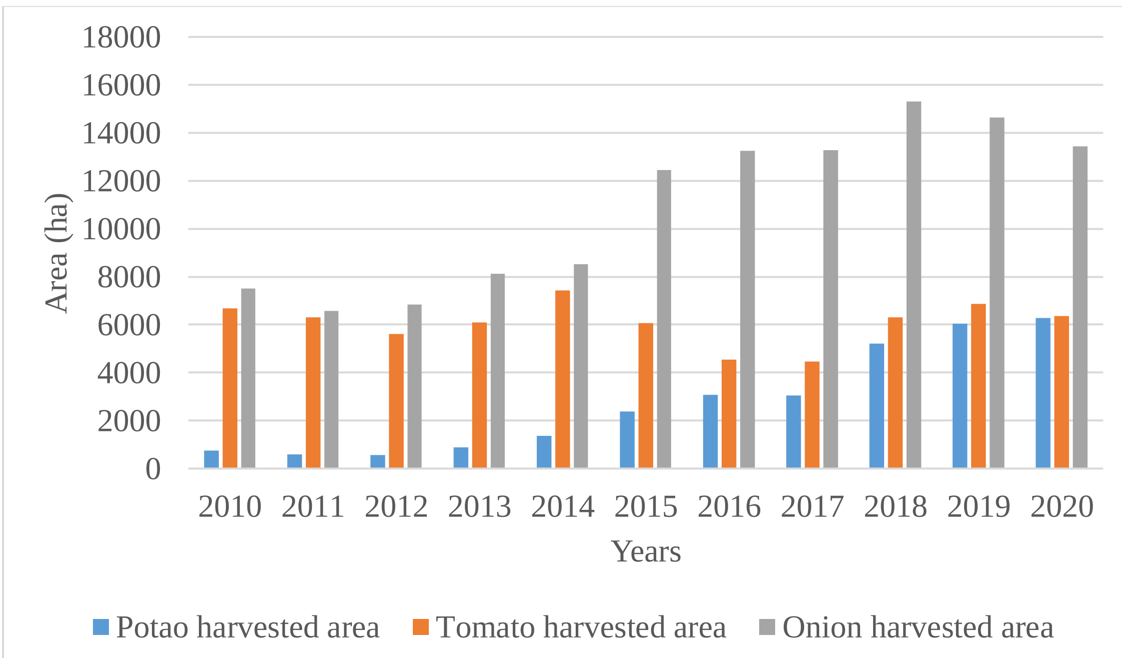

Figure 4: Harvested area of Potato, Tomato, and Onion from 2010 to 2020 in Senegal (Adapted from FAOSTAT 2022)

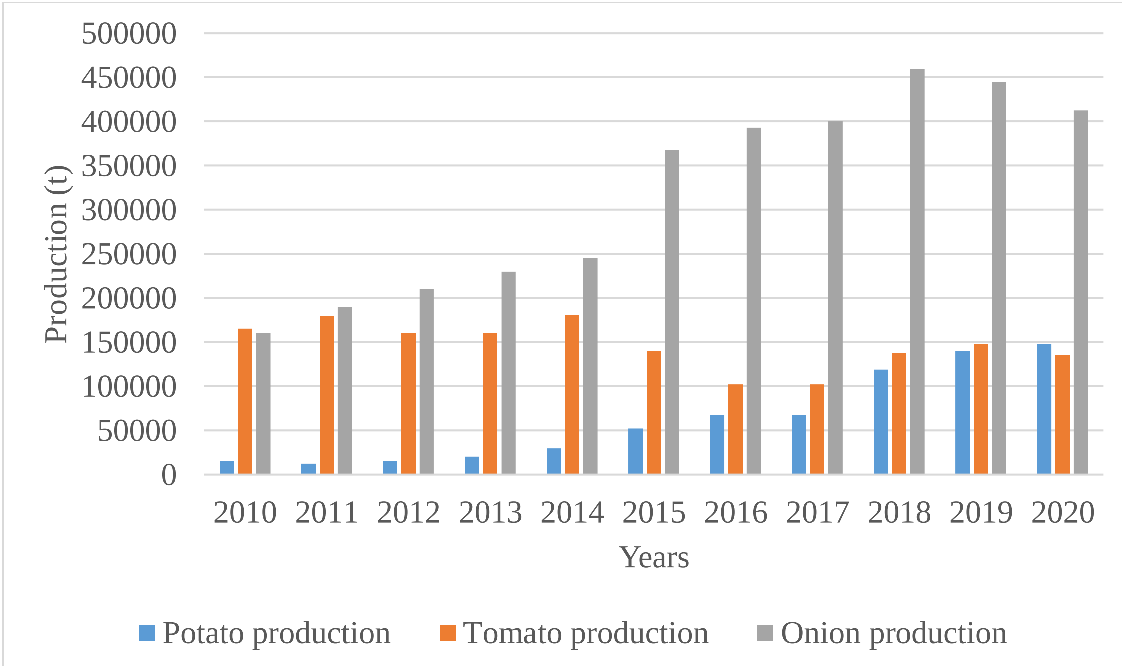

Figure 5: Productions of Potato, Tomato, and Onion from 2010 to 2020 in Senegal (Adapted from FAOSTAT 2022)

I.2 Requirements for tomato production

Tomato can be grown in many environments and locations, going from the tropics to a certain extent in the Arctic. However, it is simultaneously subject to various abiotic stresses (Golam et al., 2012).

I.2.1 Temperature

The climate is a crucial driver of agriculture and determines the kind of production suitable in a given region (Tshiala & Olwoch, 2010). Most vegetables grow better in moderate to cooler temperatures. The tomato requires a relatively cool and dry climate to produce a large, high-quality crop. However, the plant has adapted to various climatic conditions, from temperate to hot and humid tropical climates. The optimum temperature for most varieties is between 21 and 24°C. The plants can overcome a specific temperature range, but their tissues are damaged below 10 °C and above 38°C. The tomato reacts to temperature variations during the growth cycle. Pollen production gets reduced when cold or hot periods persist during flowering. Less pollen production will indeed affect fruit formation. Light intensity affects leaf colour, fruit set, and colour (sNaika et al., 2005). In arid regions like Sub-Saharan Africa, the yield of tomatoes is significantly affected by high temperatures and low moisture levels in the soil (de la Peña & Hughes, 2007).

As with many crops, one of the significant issues that tomato production faces nowadays are the increased temperature level (Golam et al., 2012). High temperatures can harm tomatoes, but both high and low temperatures affect tomato growth and production. Fruit size and quality can also be affected by variations in temperature (Prasad & Chakravorty, 2015). Tomatoes are not only sensitive to global average temperature. Thus, not only is the variation substantial but the moment when the variation occurs should be considered, i.e., day or night (Ayankojo & Morgan, 2020). The temperature impacts are differentiated depending on whether the stress happens in the daytime or at night (Van Der Ploeg & Heuvelink, 2005). The increase of the day or night temperatures, or both of them beyond a certain threshold, leads to much damage to tomato crops; however, the main ones are flowers dropping and low fruit set (Ayankojo & Morgan, 2020). Although up to date, there are no particular day and night temperatures for optimum tomato production. It is range sometimes between 20 and 30°C (Abdel, 2006), 20 and 27°C for Nicolas et al. (2009), or again 20°C and 25-30°C for Vijayakumar & Beena (2020), respectively for night and day temperatures. The day and night temperatures can have different effects according to the stage of development, and each part of the plant can be affected differently. Various features and components of the tomato fruit can be affected by specific temperatures (Van Der Ploeg & Heuvelink, 2005; Ayyogari et al., 2014). They later reported that the maximum temperatures in lycopene pigment production in tomatoes are between 25 to 30°C and destroyed at 40°C. The same authors also indicate that the reduction in pollination happens at high temperatures. Tomato growth and yield are also affected by the difference between the day and the night temperature. Vijayakumar & Beena (2020) indicate that the optimum daily temperature for tomato production ranges between 25 and 30°C and 20°C at night. According to the same authors, beyond that threshold and when exposed for an extended period, the impact on tomato growth and yield is negative and irreversible. The effect of global average temperature and the variation of day and night temperature goes beyond plant growth and quantitative yield. It can also affect the quality of the fruit (Bertin & Génard, 2018).

High temperatures and low temperatures can affect tomato production. Van Der Ploeg & Heuvelink (2005) showed that low night temperatures below 12°C negatively impact tomato flowering.

Besides the intrinsic parameters of the tomato, temperature also affects the duration of the production. According to De Koning (2000), the number of days of fruit growth period increased up to 31 days when the temperature of production increased from 17 to 26°C.

I.2.2 Water availability

Water is one of the most critical environmental factors affecting fruit development and tomato yield (Kuşçu et al., 2014). Tomatoes are one of the most water-intensive vegetables, varying from 500 mm to 600 mm during the season(Giuliani et al., 2016; Klunklin & Savage, 2017). Any water restrictions negatively impact tomato development because they are water-dependent horticulture crops.

Water scarcity restricts photosynthesis, plant development, and fruit production. In contrast, excessive irrigation results in anaerobic soil conditions, which harm greenhouse tomatoes by causing root death, delayed flowering, and strange fruit (Chand et al., 2021). Mould and fruit rot are more pronounced when it rains heavily, with high humidity, than in reduced rain quantity. Cloudy weather slows the ripening of tomatoes (Naika et al., 2005). Therefore, using irrigation management practices without creating the best soil-water-plant connections may result in poor crop quality and a loss of valuable water resources. Indeed, Water management practices such as the timing of application, frequency of irrigation, and amount of irrigation water significantly impact tomato yield and quality (Chand et al., 2021).

Prolonged periods of drought and lack of water stress plants, causing fruit to snap and buds to drop. Cloudy weather slows the ripening of tomatoes (Naika et al., 2005). The increasing population demand and the nutritional value of tomatoes raise their demand, leading to a need to increase the total production (Agbna et al., 2017; Jiang et al., 2019). As a great agricultural water consumer, the rising demand for tomatoes will enhance agricultural water use. Thus the competition for freshwater is already dominated by agriculture (Grindle et al., 2015; Nikolaou et al., 2020). Therefore, it is imperative to find an alternative that can maximise water optimisation applied to tomato production without affecting yield (Sousa et al., 2022). Deficit irrigation (DI) is among the leading solutions for reducing water use in irrigation and optimising tomato yield (Kuşçu et al., 2014; Agbna et al., 2017; Ouda et al., 2020). The reduction of water use in irrigation and the optimisation of tomato yield can also be achieved by improving the soil moisture status, mainly in the root zone (Agbna et al., 2017; Duc et al., 2018; Ahmed & Fahmy, 2019; Horváth et al., 2020).

I.2.3 Soil and tomato nutrition

Tomato can thrive in various types of soil. Most mineral soils with good water-holding capacity, good aeration, and no salinity are suitable for growing tomatoes. Tomatoes prefer deep loamy soils with good drainage (Shankara Naika et al., 2005). They thrive in medium-textured, fertile, well-drained soils with a deep sandy loam or loamy texture. The soil profile influences the extent to which the tomato root system grows. Hard bread, compacted layers, and heavy loam zones all limit root growth. Tomatoes are profound root crops. Some roots can extend as far as 10 feet when the conditions are ideal. However, most roots grow in the upper 304.8mm to 609.6 mm of soil (Kelley & Boyhan, 2014b). Naika et al.(2005) suggested that the top layer of soil should be permeable.

Tomatoes tolerate varying acidity (pH levels) but thrive in soils with a pH between 5.5 and 6.8, provided the plant has adequate nutrition (Naika et al., 2005). While Sainju et al. (2003) indicated a soil pH of 5.5 to 7.0, Sideman (2016) suggested 6.2 to 6.8. Therefore, the soil for tomato production can be slightly acidic but cannot be below 5.5.

Adding organic matter generally promotes healthy growth. Peat soils and other organically rich soils are less suitable as they contain more water and need more nutrients. An excess of nitrogen will cause the plant to produce very little fruit but will have green and healthy (Sideman, 2016). For healthy growth and reproduction, tomatoes need twelve nutrients, or "essential components." Nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), boron (B), iron (Fe), manganese (Mn), copper (Cu), zinc (Zn), and molybdenum (Mo) are among them. Since they have a high concentration in tomatoes compared to other nutrients, N, P, K, Ca, Mg, and S are referred to as macronutrients because the plant needs them in substantial amounts for optimum production. A small dose of micronutrients, including B, Fe, Mn, Cu, Zn, and Mo, are also required. The amount of N, P, and K in the soil must be increased for high tomato growth and production. As a result, these nutrients are added to the soil as additives through manures and fertilisers (Zuba et al., 2011).

On the other hand, the soil typically provides micronutrients at sufficient levels unless a plant is deficient in them (Sainju et al., 2003). According to Hinman et al. (2012), the most necessary nutrients for optimum tomato growth are potassium (K) and calcium (Ca) for the macronutrients, as well as the micronutrients iron (Fe), manganese (Mn) and zinc (Zn). The same authors stated that the fruits would only have the appropriate soluble solids content if there is a sufficient supply of both K and Ca for plant uptake and utilisation. Their susceptibility to physiological disturbances like blossom end rot will increase. According to Sainju et al. (2003), fertilisation timing and method can impact tomato growth.

I.3 Climate change and tomato production

I.3.1 Contribution of tomato to climate change

Tomato production can generate consumption of a significant quantity of energy depending on the agricultural practices in a given area (Çetin & Vardar, 2008). Jadidi et al. (2012) demonstrate, in Iran, that fertilisers consume the more significant part (50%) of the energy input in tomato production. Continued population growth, scarcity of arable land, and the demand for generally higher living standards contribute to the increasing energy demand for agriculture. As a result, there is a growing need for energy input to increase yields, streamline labour-intensive operations, or both (Ozkan et al., 2011). The increase in energy needs for tomato production represents a threat to the activity's sustainability. It is a source of environmental problems that, in the long term, exacerbate the impact of climate change (Çetin & Vardar, 2008; Jadidi et al., 2012).

A significant part of tomato greenhouse gas emissions comes from fertiliser, at least 50%, but the total amount of emission depends on the value chain characteristics and the agricultural management practices (Jones et al., 2012; Tongwane et al., 2016). Fresh tomatoes may not have the same Carbone footprint than process tomatoes, and locally produced and consumed tomatoes may emit less CO_2 than exported tomatoes (Theurl et al., 2014).

I.3.2 Impact of climate change on tomato production

Climate change will disproportionately impact crop yields, which is predicted to have more detrimental and beneficial effects in most regions, particularly those already warmer, like Africa and Latin America (Bezner Kerr et al., 2022). The significant barriers to maintaining and raising crop output include rising temperatures, declining irrigation water availability, flooding, and salinity (de la Peña & Hughes, 2007). Drought stress and high temperatures can considerably impact vegetable production (Massimi, 2021). According to the same author, high temperatures can cause drought stress. Temperature is likely to rise to 1.5°C in the near future, even with the effort to reduce greenhouse gases (Pörtner et al., 2022).

Like many vegetables, tomato is affected by extreme events, as it is highly susceptible to variations in temperatures and rainfall. Temperatures above 28°C and water stress in tomatoes inhibited flowering in various cultivars by 30–45%. Extreme weather events like floods and droughts negatively impact tomato output (Akramzoi et al., 2021). The severity of the impact of drought stress on tomatoes depends on the moment it happens. When it occurs in the vegetative stage, the impact is less severe than in the flowering and fruiting stages. Different aspects like yield, fruit firmness, fruit shape, fruit weight, and fruit quality are affected differently depending on the stress stage (Cui et al., 2020).

The impact of climate change on tomatoes and most vegetables is not only in terms of the direct effects of temperature and rainfall. The increase in temperatures is favourable to pest and pest disease development. Climate has a significant impact on the global distribution of species. Climate, namely temperature and precipitation, are essential in disease development and the interactions of vectors, crops, and diseases because climate changes can affect the circumstances for infectious disease organisms, plant hosts, and vectors (Ramos et al., 2019).

Drought can cause direct crop damage. Drought can also have an indirect impact on crops through the positive effect that it has on insect spreading. Ximénez-Embún et al. (2016) demonstrate that the population of *Tetranychus evansi* grows and develops better when the pest feed on drought-stressed tomatoes than in non-stress tomatoes.

I.3.3 Adaptation strategies

In this work we consider mainly the context of climate change impact on water resources. According to Pörtner et al. (2022), drought is a significant risk in the cropping system. It can cause substantial economic loss and can affect the food system. Drought combined with high temperature, variability in the rainfall pattern, and the increased CO_2 in the atmosphere will lead to losses in crop yields, mostly in tropical regions. The actual rainfall and temperature trends may lead to severe water stress for crops, especially vegetables like tomatoes, which are most sensitive to drought (Akramzoi et al., 2021). The IPCC's (2022) sixth report recommended adaptation measures for cropping systems, by using new cultivars, irrigation to overcome drought, and promoting agroecology technics.

Adapting vegetables to climate change involves many strategies, from simple technics on the ground to genetic transformation according to the means at disposal. Farmers in tropical developing countries need ways to adapt to and mitigate the negative impacts of climate change on agricultural production, especially vegetable production, quality, and yield. Current and emerging methods of plant stress physiology research may help adapt to the effects of climate change on vegetable production. On the other hand, farmers in developing countries tend to be small farmers, with fewer opportunities and relying on resources available in their area (de la Peña & Hughes, 2007).

There is, therefore, a need to use simple, affordable, and accessible technologies to improve the resilience of farms in developing countries. Genetic improvement is generally a preparation for a future climate. Thus, different characteristics of the climate are considered in the plant gene to allow it to be more resistant to the adverse effects of the climate (Koundinya et al., 2018). The same authors proposed grafting, mulching, protected cultivation, post-harvest technology, organic farming, and irrigation management to address climate change. For instance, in Afghanistan, farmers of tomato cultivation use new cultivars, adjust their cropping season and use some agroecological technics like mulching to reduce moisture losses to adapt to climate change (Akramzoi et al., 2021).

Recently smart agriculture has been promoted as an excellent way to adapt to climate change. The concept in vegetable production involves a set of technology that can improve the productivity of the crops with less impact on the environment and the atmosphere and better adaptation (Gaire & Dahal, 2021).

II. Biochar

II.1 Definition

Biochar results from organic materials' "thermal combustion" under limited oxygen and various temperatures (Wang & Wang, 2019; Joseph et al., 2010). According to Jeyasubramanian et al. (2021), Biochar is a product with high carbon content from organic materials' "thermochemical or mechanochemical" processing. For some authors, it is essential to precise the role of biochar in soil status improvement (Mukherjee & Lal, 2013). In addition to the fact that it results from organic materials processing, Blanco-Canqui, 2017, stated that it is a slow process. The definition of biochar is not unique; it varies and evolves from one author to another. However, the international biochar initiative (IBI), trying to standardise the definition of biochar, defined it as "material obtained from the thermochemical conversion of biomass under an oxygen-limited condition" (IBI, 2013). Hence, all the definitions converge on one point: the high carbon content of biochar. It has also been named differently by different authors, and one of its names is black carbon (Spokas et al., 2012; Lorenz & Lal, 2018) or pyrogenic carbon (Bird et al., 2015), or charcoal (Kinney et al., 2012).

II.2 Biochar production

II.2.1 Biochar feedstock

Biochar can be produced from different carbonaceous feedstock (Hagemann et al., 2018; Shaaban et al., 2018; Jeyasubramanian et al., 2021; Haider et al., 2022). Thus the feedstock comprises animals (Uzoma et al., 2011; Gavili et al., 2018; Rehman et al., 2020) and plants (Ghorbani et al., 2019; Elias et al., 2020; Feng et al., 2021) organic matter. The feedstock is one of the significant factors to consider regarding the final biochar product (Ippolito et al., 2015). According to Li et al. (2019), the kind of feedstock and pyrolysis temperatures impact various parameters, including CEC, pH, and the C and N content of the biochar produced. The same authors continued asserting that "animal wastes and biosolids"-made biochar are less efficient in mitigating greenhouse gases (N_2O, CO_2 emissions...). Their findings were confirmed by (Ippolito et al., 2020), who stated that if the target of biochar is used in plant nutrition, the one made from manure can perform better. Still, if the objective is to reduce CO_2 emissions, it is preferable to use wood-made biochar. The choice of the raw material and its intended usage are closely related. That is why, before biochar production, one must know the "initial feedstock properties" (Ippolito et al., 2020). The yield of the biochar production in terms of mass is a function of the feedstock water content, and the more water content, the less the outcome (Weber & Quicker, 2018), and it also depends on the lignin content of the biomass (Xie et al., 2014). In addition, Tomczyk et al. (2020) demonstrate that lignin, cellulose, and hemicellulose are the essential elements in the biomass that can positively influence the surface area and pore size distribution of the produced biochar via the degradation of their structures. Gabhane et al. (2020) reveal that the high cellulose content of feedstock produces the best quality biochar. The output of the biochar production process is independent of the feedstock. The production temperature is involved primarily for more predictable biochar properties (Hassan et al., 2020). The intended application of biochar can serve as a valuable indicator of the kind of feedstock required for its production (Sun et al., 2013; Yaashikaa et al., 2020). Temperature and feedstock, the two necessary elements for controlling the final biochar product, can influence each other. On the one hand, the feedstock available can dictate the production process, mainly the temperature (Li et al., 2019). On the other hand, different production temperatures applied on the same feedstock can lead to different biochar properties (Li et al., 2019; Hassan et al., 2020; Ippolito et al., 2020).

II.2.2 Temperature of production

According to Abukari & Duwiejuah, 2019, production temperatures vary from 300°C to 600°C. However, the production temperature can exceed 600°C (Shaaban et al., 2018; Asadi et al., 2021). As a by-product of the pyrolysis of organic material biochar, its use determines the choice of production temperature. Biochar is a multipurpose carbonaceous material (Garcia et al., 2022). If the purpose of biochar production is for soil amendment, then it must satisfy the specific nutrient requirements of the target soil (Dume et al., 2015). For instance, in the soil where the objective is to enhance nutrient concentration, except for N, (Gaskin et al., 2008) suggested a high pyrolysis temperature to have rich biochar in such elements. Nevertheless, according to Dume et al. (2015), biochar can increase nutrient exchange capacity and availability if produced at low temperatures. The CEC of biochar decrease when the production is at high temperature because of the removal of some functional groups such as -OH, C-O, and C=O (Dume et al., 2015; Tomczyk et al., 2020). The removed groups are also responsible for increasing the surface area (Dume et al., 2015).

The hydrologic properties, such as soil's field capacity, are sensitive to biochar made at high temperatures (Kinney et al., 2012). High temperatures modify the surface area and the pore size distribution of biochar (Tomczyk et al., 2020), which could, in turn, alter the soil pores statute and thus increase the soil’s water retention capacity (Kinney et al., 2012). Shafie et al. (2012) stated that in sandy soils mixed with biochar, biochar has a greater surface area than soil, and smaller pore size can improve its ability to hold water. The water-holding capacity of a given biochar is also a function of the duration time of the production. Hien et al. (2020) noted that total pore volume increase with the temperature and the production duration. However, the same authors have drawn attention to the fact that at a specific temperature (greater than 600°C), the process results in low H/C and O/C ratios, leading to a low water holding capacity.

II.2.3 Biochar technology and type of production

The production of biochar is not a recent activity. It started over 2500 years ago (Gabhane et al., 2020). The same authors continued and stated that the production process is constantly evolving, leading to the quality of the product while reducing the labour's hardness and production. According to carbonisation technology, the pyrolysis of biomass, animal products, or sewage sludge can result in different outcomes (Zhou et al., 2021). The most popular thermochemical methods for biochar production are pyrolysis, torrefaction, and carbonisation. They can produce biochar, syngas, and bio-oil (Yaashikaa et al., 2020; Zhou et al., 2021). The mean available, the targeted yield (biochar, bio-oil, or syngas), and the production scale typically influence the choice of the method. (Gabhane et al., 2020). Pyrolysis and gasification are the most often employed techniques in the material's thermochemical conversion (Suárez-Hernández et al., 2017).

Pyrolysis: The heating process of biomass, animal products, industrial wastes, domestic wastes etc., at low or absence of oxygen and temperatures ranging roughly from 250°C to 900°C is called pyrolysis (Gabhane et al., 2020; Kumar & Bhattacharya, 2020; Shafie et al., 2012; Zhou et al., 2021). The pyrolysis process can be split into two categories: slow and fast, depending on the production temperature, heating rate, and production time (Gabhane et al., 2020; Zhou et al., 2021). It is generally the method that gives better biochar yield. Thus it has become the most widely used method for biochar production (Zhou et al., 2021).

-Slow pyrolysis is, as indicated by the name, a slow process that can last from some hours to a day due to a low heating rate going from 5°C to 10°C per minute. Production temperature ranges from 290°C to 700°C (Gabhane et al., 2020; Yaashikaa et al., 2020). The biochar yield in terms of the percentage of biomass converted into biochar is higher in slow pyrolysis (Shafie et al., 2012; Yaashikaa et al., 2020) and can be estimated to be around 35% to 45% (Gabhane et al., 2020; Malyan et al., 2021). Nevertheless, Shafie et al. (2012) find when transforming empty fruit bunch into biochar in slow pyrolysis, the low temperature (up to 300°C) gives a better yield than the high one (≥400°C), which reduces the output on every increment. For the other products, such as bio-oil and syngas, Gabhane et al. (2020) reported that they yield 25% to 35% and 20% to 30%, respectively.

-Fast pyrolysis occurs when the heating rate and the residence time are drastically reduced, and the production temperature is greater than or equal to 500°C and can reach 1000°C (Zhou et al., 2021). However, the most determining factors, according to the literature, are the residence time and the heating rate knowing that the temperature of production can sometimes be the same that the use one slow pyrolysis (Dume et al., 2015; Yaashikaa et al., 2020; Zhou et al., 2021). The heating rate in this process can evolve from 10°C/s to 1000°C /s. That indicates a residence time ranging from a second to some minutes. The yields of fast biomass pyrolysis are about 15 to 30% of biochar, 50 to 70% of bio-oil, and 15 to 20% of syngas (Kumar et al., 2020). Bio-oil is then the main product obtained in fast pyrolysis, although, increasing the percentage of biochar involves a reduction in the heating temperature (Gabhane et al., 2020).

Gasification is one of the thermochemical methods of biomass conversion (Yaashikaa et al., 2020). It is an incomplete combustion of biomass at usually high temperatures between 700°C and 1500°C (Boateng et al., 2015; Wang et al., 2020). Cha et al. (2016) state that producing biochar through gasification involves several steps, including drying, pyrolysis, oxidation, and combustion. In this process, biochar is the by-product, and the main product is syngas (Wang et al., 2020). In contrast to biochar's yield, syngas increase with increasing temperature (Yaashikaa et al., 2020). The characteristics of gasification are high ash content (60%), smaller specific surface area and pore volumes due to the process per see. The number of carbon ranges between 20 to 60% for gasification against 50 to 80% for pyrolysis (You et al., 2017). The description of the yield of different products in gasification is 0-5%, 5-20%, and 85-95%, respectively, for bio-oil, biochar, and syngas (Boateng et al., 2015; You et al., 2017).

II.3 Field of application of biochar

Because of its high porosity, wider surface area, long-term stability, high cation exchange capacity, and other properties, biochar is widely used in various fields. Agriculture, removal of heavy metals such as Chrome (Cr), Mercury (Hg), and Arsenic (As) from effluent, reduction of organic and inorganic pollutions, catalytic activity, energy production, and reduction of greenhouse gas emissions are some of the fields where biochar is used (Shaaban et al., 2018; Abukari & Duwiejuah, 2019; Jeyasubramanian et al., 2021).

II.3.1 Biochar as a soil amendment

Biochar application has different impacts on soil parameters. It can affect both physical and chemical properties. Biochar's physical and chemical properties are critical for understanding its efficiency and mechanisms for enhancing soil fertility (Ding et al., 2016).

II.3.1.1 Biochar effect on soil physical properties

Compared to chemical properties, biochar's effect on soil physical properties has generally drawn less attention from researchers (Aslam et al., 2014; Blanco-Canqui, 2017; Asadi et al., 2021). However, adding biochar to the soil can positively alter some interesting physical properties, such as soil bulk density and porosity (Blanco-Canqui, 2017). These parameters are critical in agriculture since they determine the movement of microorganisms, water, and air into the soil. Soil physical properties can be impacted by biochar application through a change in soil water and nutrient holding capacity, enhancement of the aeration, and improvement in permeability. Important properties include high surface area (SA) and the presence of micro-pores. This surface area contributes to the adsorption properties of biochar. It can modify pore size distribution (PSD), bulk density (BD) and variation soil SA, water holding capacity (WHC) and penetration resistance (PR) (Mukherjee & Lal, 2013). The mechanism through which biochar can modify the soil's physical properties for agriculture is mainly through a reduction of soil bulk density which is a result of the increase of soil porosity through an improvement of soil aggregate (Asadi et al., 2021). For Aslam et al. (2014), biochar application reduces soil porosity due to biochar dust obstructing soil pores. Indeed, soil bulk density reduction leads to more water-holding capacity and aeration.

The effectiveness of the effect of biochar on these soil parameters depends on the soil type, the nature of the feedstock, the temperature of pyrolysis, and the production methodology (Jeyasubramanian et al., 2021). Like so, it is essential to choose the feedstock and the production methodology according to the type of soil involved. Aside from the feedstock, the methodology, and the soil type, the amount and the particle size of biochar applied have also been reported to affect the soil's physical properties (Verheijen et al., 2019). Their experiment found the effect of small-size biochar to be more effective on sandy soil than on sandy loam soil. In addition, Burrell et al. (2016) found that the longer the period biochar lasts in the soil, the better its effect on bulk density. Their research shows a 13%, 10.3%, and 9.9% decrease in bulk density respectively on Planosol, Chernozem, and Cambisol after three years of woodchip biochar application.

The addition of biochar can indirectly affect the soil's physical properties. Burrell et al. (2016) have related that biochar is a perfect ecological niche for soil microorganisms thanks to its good interaction with organic matter. Some microorganisms that might be present within the biochar as habitat can produce a polysaccharide that favours the adherence of soil colloid particles and, thus, the formation of soil aggregate (Aslam et al., 2014). They continue by stating that biochar in the soil is favourable to good soil exploration by the roots since it stimulates growth. Root growth also indirectly affects the soil structure and might improve crop yield.

II.3.1.2 Biochar effect on soil chemical properties

The main effect of biochar on soil chemical properties is the improvement of soil fertility status and boosts crop productivity. As for the soil's physical properties, the effect of the incorporation of biochar into the soil on chemical properties depends upon the feedstock's nature, fabrication technology, and application soil (Jeyasubramanian et al., 2021). That means it is essential to know the type of soil to which biochar will be added for more efficient production.

Soil pH is one of the most important parameters controlling numerous biochemical and physical processes in soil. Accordingly, one of the essential chemical effects biochar can have on the soil is the improvement of the soil pH. Soil pH affects soil quality, crop production, and pollution by controlling the solubility and bioavailability of soil chemicals (Asadi et al., 2021). Abukari & Duwiejuah (2019) indicate that the effect of biochar on the soil pH is tightly linked to the nature of the feedstock. However, it is also a function of the amount of biochar applied. The effect of biochar application on soil pH could be more precise. While many studies show an improvement, others showed no or even a negative effect on soil pH (Asadi et al., 2021). However, its impact has been reported to be more efficient on acidic soils and is a solution. Four main factors have been ascribed to be the source of biochar acidic soil alleviation: 1) alkalinity of biochar, 2) high pH buffering capability, 3) functional group effects and 4) Silicium (Si) effects.

The cation exchange capacity (CEC) is another factor that could be shifted in the soil when mixed with biochar. Biochar, through its high specific surface area and the number of carboxylic groups, is essential in improving the soil's CEC. Thus it enhances soil fertility through better retention of nutrients for plants (Ding et al., 2016). According to Vaccari et al. (2015), the increased cation exchange site on the surface of biochar is the origin of the greater CEC. A greater CEC leads to better crop availability of K, P, and Na. Biochar can increase the soil CEC by 4 to 31% (Ding et al., 2016). Some studies have also reported no or slight increase of CEC on soil with biochar application (Spokas et al., 2012).

Biochar has been described as a natural healer for the soil since much research has shown its effect on soil biota and pollution reduction. The physicochemical properties of biochar can change microbial biomass and activity, soil enzymatic activity, bacteria–fungi relationships, and microbial community structure and diversity. In some cases, adding biochar does not modify microbial activity and biomass but significantly changes microbial community structure in the soil (Haider et al., 2022).

Biochar can alleviate degraded soil regarding fertility status and enhance crop productivity. Nevertheless, its action to relevant for soil fertility rely on different factors such as the soil type, the purpose of adding it into the soil, the amount added, the nature of the feedstock and the method of production (mainly temperature of production and retention time) (Haider et al., 2022). One must take care of all these parameters before starting the biochar production process to avoid the adverse effect of its application on the soil. Spokas et al. (2012) indicate that biochar did not have only positive impacts. When added to the soil, it can also reduce yield in some cases. The compilation of different studies by the same authors on biochar showed a 50% increment in output or growth, 30% no significant impact, and 20% negative effect.

Biochar has also been promoted as a material for pest management. It has been stated that incorporating biochar into the soil can induce changes in the metabolism pathway of crops., It has, for; example, reduced fungal diseases in tomatoes and pepper caused by *Botrytis cinerea L*. in Switzerland and Fusarium root rot infection by 50% in *Asparagus officinalis L.*, relative to the soil without biochar addition (Haider et al., 2022)

II.3.2 Biochar effect on soil water holding capacity

Regarding climate change, drought is the primary threat to crops in agriculture. Developing countries in the tropics will be the first to suffer from it and water scarcity (IPCC, 2022). Drought inhibits plant growth and biomass accumulation and slows photosynthesis by reducing leaf expansion rate and stomatal conductivity (Ali et al., 2017). Enhancing the water-holding capacity of soils in that part of the world will be an efficient adaptive strategy for their communities. A substantial body of knowledge has reported that Biochar improves soil water-holding capacity (Mulcahy et al., 2013; Shaaban et al., 2018; Abukari & Duwiejuah, 2019; Yu et al., 2019; Jeyasubramanian et al., 2021).

Using biochar as an amendment can be of more outstanding help for drought adaptation. However, the mechanism through which biochar is capable of helping soils, mostly sandy ones, of holding more water must be known. Some conditions must be considered for more biochar efficiency to help the soil retain water. Thus, many researchers have tried discovering how biochar makes more water for crops. A review conducted by Ali et al. (2017) has concluded that the efficiency of biochar on soil water holding capacity is probably linked to the type of soil, the kind of biochar (feedstock and process), and the cultivated crop. They have relieved the positive effect of biochar made of Wood pellets, the biomass of *Lantana*, and Woodchip sieving, regarding soil water holding capacity, on tomato, okra, and maise, respectively, on sandy loam, sandy loam, and sandy soils. They also noticed that biochar, combined with other amendments, might be more effective relative to soil water holding capacity than biochar solely applied.

Indeed, biochar added into the soil creates pores inside (intra-pores) and between soils' pores (inter-pores), creating additional pores that change soil inter-pores characteristics like size, shape, connectivity, and volume—this increase in soil porosity results from the highly porous nature of biochar. Thus, using biochar increases the overall porosity of the soil. However, the increased porosity depends on the type of biochar used and the soil to which it was applied (Aslam et al., 2014). It is clear that the increase in soil water holding capacity as a result of biochar amendment is not only dependent on biochar particle size but is a result of the combined effect of the biochar particle size, shape and pores structure (Liu et al., 2017). The relative contribution of the three types of pores (macro, meso and micro-pores) to the overall increase in soil porosity varies between biochar and soil types (Aslam et al., 2014). It profoundly affects the water movement and storage in the soil. Intra-pores control water retention at lower soil water potential values, increasing field capacity, permanent wilting point, and plant-accessible water in medium and coarse biochar-sand combinations.

Conversely, inter-pores regulate water retention at higher soil water potential values for fine biochar-sand combinations (Liu et al., 2017b). This study reveals the significance of biochar's particle size on soil water-holding capacity. Therefore, mixt particle size of biochar might be an excellent tool to regulate water flows in the soils' pores. The biochar particle sizes, pore size and distribution, are dictated by the type of feedstock used in the production. Werdin et al. (2020) have determined that low-density wood biochar is more efficient than high-density wood biochar in increasing available plant water in the soil. Another study has affected the biochar's capability to help the soil hold more water to its swelling property. The study explains that the interaction between water molecules and biochar surface forms strong bonds that create intensive swelling, which causes a decrease increases bulk density and thus increases soil water holding capacity (Jačka et al., 2018).

Before working on the biochar particle size, one must consider different elements. Dai et al. (2020) have reported that the effectiveness of biochar particle size on soil water-holding capacity is a function of the type of soil, arguing that some research has shown a more significant effect on low-silt/sand soils than clay soils. The amount of applied biochar also affects soil water-holding capacity. De Melo Carvalho et al. (2014) have observed a proportional increase in soil water-holding capacity in sandy soil. However, this observation is controversial since Dugan et al. (2010) have observed that in the same type of soil, in Ghana, an increment of soil field capacity is independent of the amount of biochar applied. These two different results might be due to the difference in the rate of biochar applied. While De Melo Carvalho et al. (2014) applied 0, 8, 16 and $32 t.ha^{-1}$ (Dugan et al., 2010) used a rate of 5, 10 and $15 t.ha^{-1}$. Comparing these two studies showed that the increase in soil water holding capacity as a function of biochar rate seems effective for biochar amounts greater than $15 t.ha^{-1}$.

II.4 Biochar versus organic matter and fertilisers

Increasing soil organic matter with the necessary inputs to improve soil quality and increase productivity remains a significant challenge. The nature of the input in the soil to improve its quality and productivity must take into account several elements, among which the increment of C input into it and the decrease of losses from managed agroecosystems (Lal, 2009). Biochar is far more effective than other organic matter at retaining and releasing plant nutrients. The large biochar's surface area and intricate pore structure attract bacteria and fungi, which plants require to take nutrients from the soil. Furthermore, biochar is a more stable source of nutrients than compost or manure (Zheng, 2010).

These recent years, biochar has drawn the attention of the research community in agriculture. It might be because of its effects when incorporated into the soil as an amendment. Biochar improves the soil quality while at the same time sequestering more carbon into it. It reduces CO_2, N_2O, and CH_4 emissions from the soil (Zheng, 2010). In addition, in most parts of the world, the use of organic matter as an amendment for the soil is limited by its availability. Organic matter is mainly constituted by agricultural residues primarily split into soil amendment and animal feeding. Thus the weak organic restitution of soil year after year results in a drastic soil fertility reduction (Faye et al., 2021).

One specific attribute of biochar that other organic matters are not reported to have is its capability to reduce groundwater pollution by heavy metals through their immobilisation (Rehman et al., 2020). Applying biochar into soil reduces heavy metals' bioavailability by forming mostly an ion complex with metals and sorption. These mechanisms prevent heavy metals from leaching deep down into the groundwater. Biochar reduces organic and inorganic pollution (Shaaban et al., 2018).

Biochar is preferred as fertiliser against inorganic nitrogen fertilisers because of the detrimental effect of N in the soil. The overuse of N fertiliser can lead to soil acidification through the increment of H^+ and Al^{3+} and thus negatively affecting the soil biota and the biochemical processes. Evidence shows that biochar has inherent alkalinity and alkaline components that give it the property to increase soil pH. It can then restore acidic soils and reduce N_2O emission by stimulating nitrification, denitrification, and decreasing NH_3 volatilisation.

Nitrogen leaching is nowadays a serious environmental problem. Organic matter used to improve the soil status must consider the alleviation of N leaching that causes pollution in groundwater. Using biochar without compost can reduce the N leaching compared to the sole application of compost (Asadi et al., 2021). Thus, biochar reduces N leaching and improves crop availability (Wang et al., 2017).

Combining biochar and other amendment types is very productive for crop performance. Indeed, specific organic matter like poultry manure can act as an accelerator of the surface oxidation of biochar through an elevation of the temperature, especially at the beginning of the process (Adekiya et al., 2019). The same authors have confirmed that biochar associated with poultry manure could enhance the efficiency in the utilisation of nutrients. Combined with compost, it helps reduce the N leaching from the compost (Ghorbani et al., 2019). Thus, on the one hand, biochar, in addition to its inherent properties to improve soil status, can be used as a complement for more efficiency of other fertilisers. On the other hand, organic matter increases the capacity of biochar to improve soil properties such as soil bulk density, porosity, aggregate stability, water-holding capacity, infiltration rate, and hydraulic conductivity. However, the combination has to consider a set of parameters, biochar feedstock, type of soil, pyrolysis method, and the amount of biochar (Adekiya et al., 2019; Sharma et al., 2021).

This multipurpose use of biochar makes it an efficient tool for combating climate without spending tremendous amounts of money. Additionally, the long term effect of biochar when incorporate into the soil makes it a powerful to sustain world agriculture productivity (Wei et al., 2016).

II.5 Biochar and climate change

Climate change will strain food production and availability, particularly in vulnerable areas, jeopardising food security and nutrition. Increases in the frequency, duration, and severity of droughts, floods, heat waves, and continuous sea level rise will elevate food security risks from moderate to severe between 1.5°C and 2°C global warming levels, with no or low levels of adaptation. Food security threats from climate change will be more severe in the mid-term if the global temperature exceeds 2°C, resulting in malnutrition and micronutrient deficiencies concentrated in Sub-Saharan Africa, South Asia, Central and South America, and Small Islands. Global warming will gradually deteriorate soil health and ecological services (IPCC, 2022).

The most critical factor driving climate change is the progressive increase of atmospheric greenhouse gases. The primary greenhouse gases in the atmosphere are, in ascending order, nitrous oxide (N_2O), methane (CH_4), carbon dioxide (CO_2), and water vapour. These gases are nowadays largely emitted by world agricultural lands due to intensification to feed the world population growing fast (Stavi & Lal, 2013). Numerous propositions such as agroforestry, crop residue incorporation into the soil, and conservation agriculture have been made to reduce greenhouse gas emissions from agriculture. However, it has been noted that those solutions could have been more efficient in mitigating climate (Bis et al., 2018). Suppose vast areas of agricultural land are impacted by climate change or converted to C-sink forestry. In that case, significant increases in food production may only become possible if new technologies and sustainable practices are swiftly implemented (Singh et al., 2011). Thus in this recent years, the option of using biochar to reduce greenhouse gas emissions has grown up because of it a triple advantage in combating climate change: low cost, efficiency in reducing greenhouse gas emissions, and improvement in soil physical and chemical properties (Lorenz & Lal, 2014; Koide et al., 2015; Bis et al., 2018). Thus, biochar can be used both for mitigation and adaptation purposes.

II.6 Biochar and greenhouse gases mitigation

Based on past civilisations' management methods, scientists have been interested in sequestering carbon in soil by adding biochar to decrease global warming through soil carbon sequestration (Nair et al., 2017). Carbon sequestration has been defined as the process through which C is captured and stored to prevent it from being emitted into the atmosphere. One of the means to decrease C emission into the atmosphere is to take from an active to a passive form, which is more stable or inert (Qambrani et al., 2017). According to the same authors, even a tiny fraction of the carbon circulating between the atmosphere and plants would significantly impact atmospheric CO_2 concentration if it were shifted to the much slower biochar cycle. Biochar can store 20% of total carbon biomass as stable carbon material, indicating that conversion to biochar can capture approximately 20% of total carbon biomass (Arif et al., 2020).

Biochar will eventually decompose considerably more slowly as an organic carbon source than other organic materials. The chemical recalcitrance of biochar, caused by the presence of aromatic groups, accounts for its high stability (Arif et al., 2020). The CO_2 fixed by different crops will take more time to return to the atmosphere when the crop residues are transformed into biochar and incorporated into the soil (Woolf et al., 2010)

Although biochar contains a part of labile carbon that decomposes quickly, most biochar is formed of recalcitrant carbon that takes hundreds to thousands of years to disintegrate in soil and even longer under marine conditions (Arif et al., 2020). This long decomposition time is a real advantage regarding carbon sequestration in the soil. Thus, biochar may provide adequate long-term soil carbon storage, offering a viable abatement option for anthropogenic carbon emissions (Shackley et al., 2013). Indeed, a life cycle assessment (LCA) on rice amended with biochar showed at least a constant decrease in rice footprint over eight years through the reduction of CO_2 and CH_4 emissions (Mohammadi et al., 2016).

The primary greenhouse gases from agriculture are N_2O and CH_4, respectively 298 and 25 times greater warming potential than CO_2 (Arif et al., 2020). Biochar applied in agricultural soils can help alleviate the emission of these two gases (Bracmort, 2011). Rittl et al. (2021) observed that biochar could reduce N_2O when applied at 25t.ha^{-1}, at 40°C compared to the same rate applied at 20°C. This result suggests that biochar can play a crucial role in decreasing global warming, predicted to increase over the years since its effect of reducing N_2O emission might increase with the temperature. The mechanism through which biochar reduces N_2O emission from the soil is indirect. Nitrification, which produces N_2O as a by-product through an aerobic process, and denitrification, in which N_2O is an intermediate product, is known as the primary source of N_2O from the soil with a contribution of 70%. Biochar reduces N_2O emissions by shifting the soil pH and changing the N_2O-to-N_2 in the denitrification process. Furthermore, biochar modifies microorganisms' abundance, increases NH^+_4 or NO_3^- adsorption, and improves soil's aeration and porosity, thus influencing soil water dynamics which decreases nitrification rates (Brassard et al., 2016).

The emission of CH_4 from the soil is mainly linked to microorganisms' activities in anaerobic conditions. The effect of biochar on reducing CH_4 emissions from the soil is then attributed to the improvement of soil aeration after biochar application (Qambrani et al., 2017). However, some studies have concluded that the emission of CH_4 from the soil has increased after biochar application. Furthermore, a straightforward process through which biochar application in the soil can help to alleviate the emission of CH_4 from the soil has yet to be discovered (Mohammadi et al., 2016; Qambrani et al., 2017).

As many of its effects on the soil, the role of biochar in mitigating climate change depends on several of its inherent properties, which are a function of the feedstock components and the production process, and the amount of application. The characteristics of the soils in which biochar has been applied is also an important parameter to consider for having a good effect out of its use.

II.7 Biochar and climate change adaptation

The agricultural sector is one of the most vulnerable sectors to the effect of climate change. Different components of soil properties are adversely affected by climate change (Fahmuddin and Husnain, 2015). Thus a vast portion of agricultural land will be or is already negatively impacted by climate change (Singh et al., 2011). If the world wants to maintain or increase the productivity of agricultural lands to ensure food security in line with the sustainable development goals (SDG) 2 (Zero hunger), adaptation is compulsory. These adaptation efforts necessitate modifications in land management and cropping patterns to build resilience and adapt to extreme climate conditions (Fahmuddin and Husnain, 2015). More agricultural lands are needed to produce enough to feed the world's constantly growing population. However, it is not sufficient to have ample land; instead, more healthy lands are necessary. According to IPCC (2022), climate change will affect soil health in terms of loss of soil organic matter. Thus, practices that build soil organic matter, such as carbon sequestration, constitute an excellent strategy to improve crop and livestock productivity sustainably.

Many strategies are proposed in the literature to remedy or improve soil organic matter status. Among different solutions, biochar has been identified as one of the most suitable for a positive impact on decreasing soil organic matter. Due to its organic nature (60-80% C) and highly active surface area and functionality, biochar can improve soil quality (Yu et al., 2019). Nair et al. (2017) stated that biochar could protect and stabilise soil organic matter by increasing the C storage inside the soil macro aggregates.

The role of biochar in adapting agriculture to climate change goes beyond its impact on soil organic matter. It is also related that biochar can facilitate symbiotic association between mycorrhizal fungi (MF) and terrestrial plant roots that might significantly affect water and nutrient uptake (Singh et al., 2011).

Biochar's role is also essential to reduce N leaching, which can lead to groundwater pollution. Indeed, adding biochar to the soil implies a low mineralisation rate, reduction in N leaching, and better plant-nutrient availability (Nair et al., 2017). Following the application of rice husk biochar, Asadi et al. (2021) have noticed a general increase in available P, K, and total N.

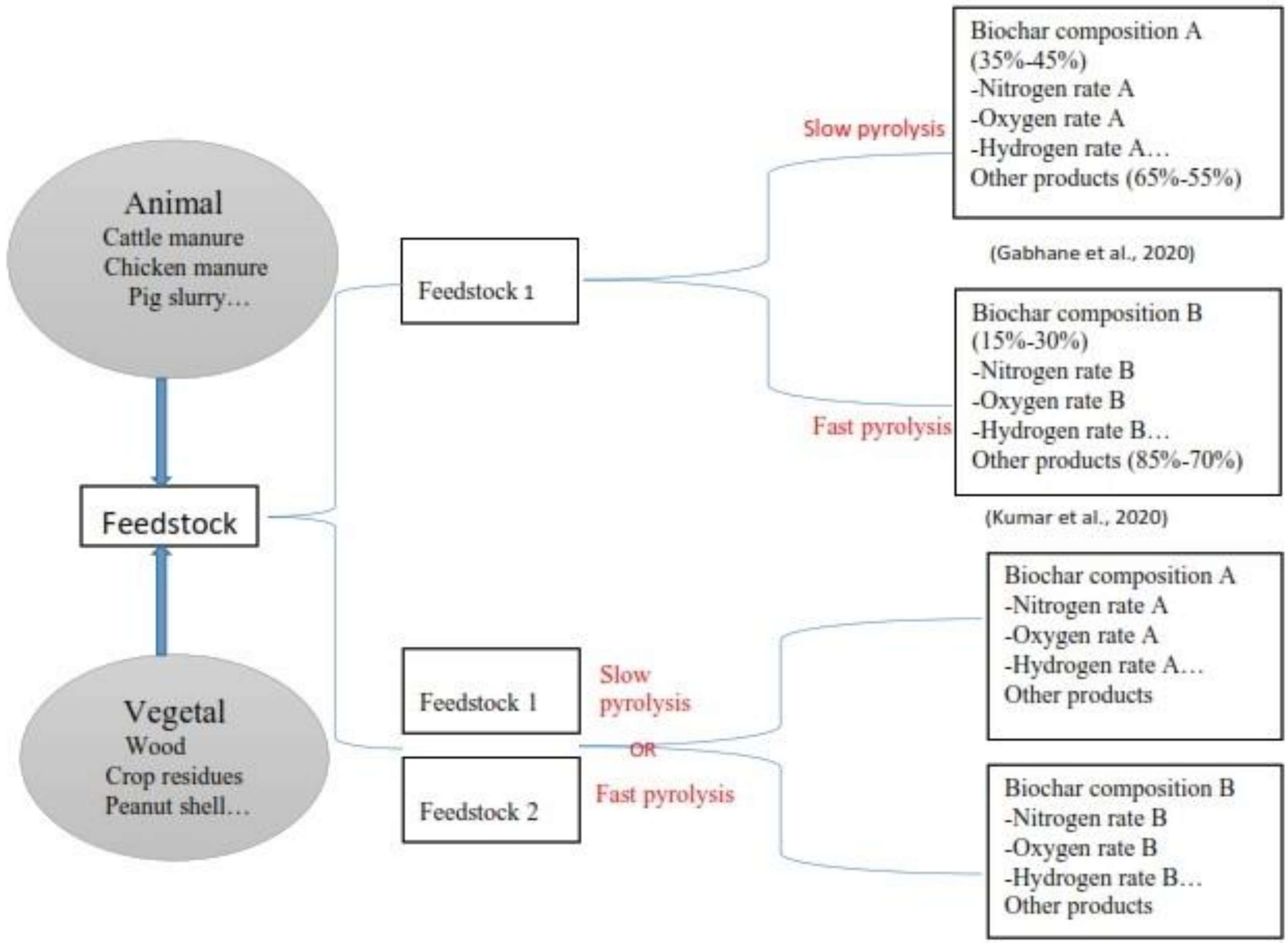

Figure 6: Overview of biochar composition according to the feedstock type and the production method

Chapter III: Research methodology

I. Study area

I.1 Location

The fieldwork was located in Thies (fig. 7), one of the 14 administrative regions of Senegal, located in the western part of the country, 70km from the capital Dakar (Ndour et al., 2020). The work was conducted in semi-real conditions at the experimental site of the Agricultural Technology Application Centre (ATAC/CATA in French) of the National School of Agriculture (14°45'50"N;16°53'24" W).

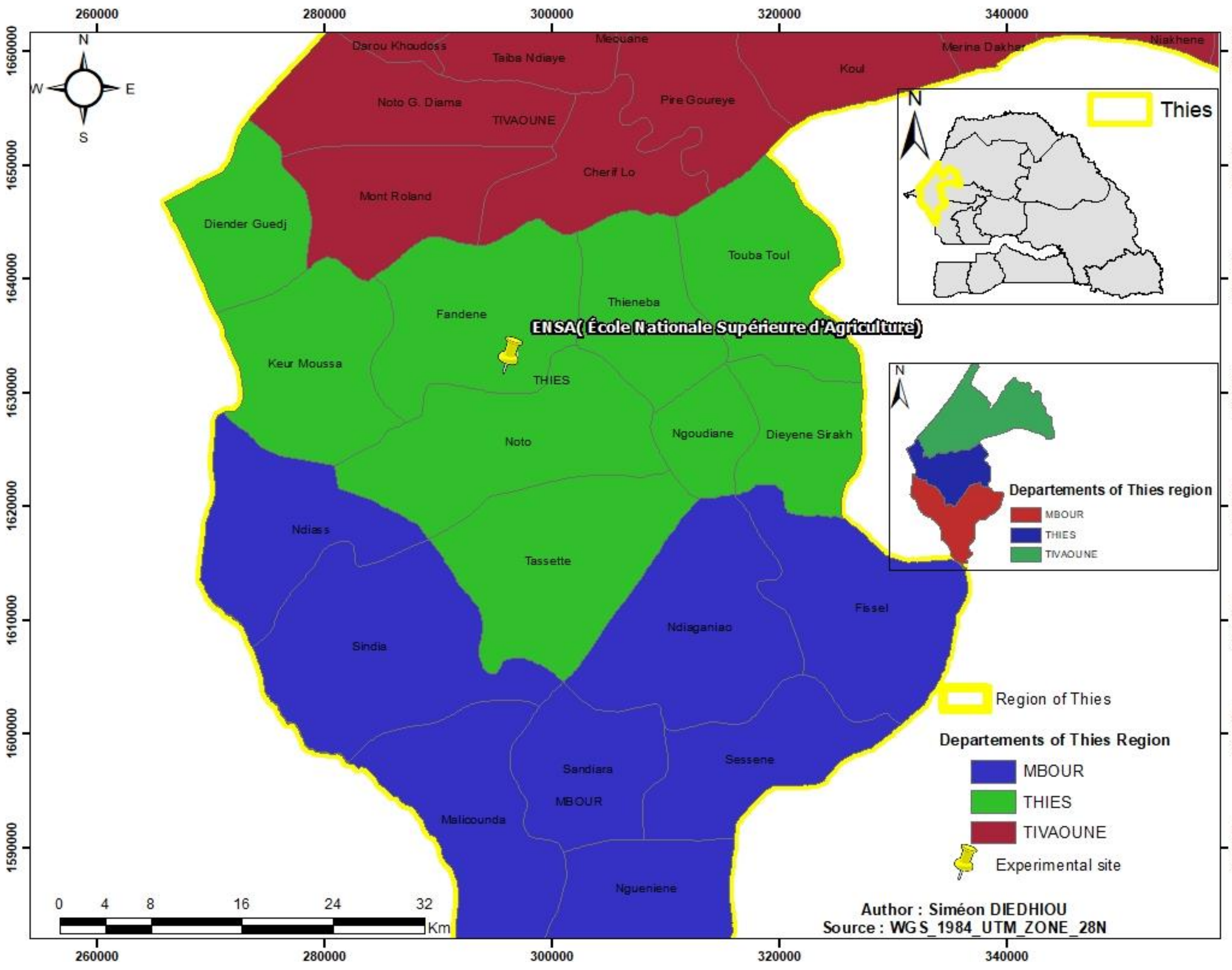

Figure 7: Localisation of the study area

I.2 Temperature, rainfall, relative humidity

The study area has a semi-arid climate, with an average annual precipitation of 400mm to 600mm and an average annual temperature of 27°C (Centre de Suivi Ecologique, 2015; Lufafa et al., 2008). The temperature of the air varies greatly throughout the day and year. The rainy season lasts from July to October and is typically characterised by scattered, high-intensity, episodic drought and short-duration showers (Kizito et al., 2006). The dry season for its part last from November to June and is split into a cool, dry season (November to February) and a hot, dry season (March to June) (Centre de Suivi ecologique, 2013; Julia & Dingkuhn, 2013). The relative humidity of the study region is, on average, 75% (Zoclanclounon et al., 2019).

I.3 Vegetation

As vegetation development over the years follows the rainfall patterns, the vegetation in Thies is characteristic of the Sahelian one. It is an open vegetation dominated by *Acacia raddiana, Acacia senegal, Acacia seyal, Balanites aegyptiaca, Commiphora africana* and annual grasses, forming more or less continuous carpets (Centre de Suivi ecologique, 2013). The leguminous is very representative of the zone and are of great importance for soil fertility and sustainability (Hirai, 2005).

II. Plant Material

In this experiment, tomato (*Solanum lycopersicum L*) was used as plant material. Specifically, the variety F1 MONA (Appendix 1), which is meant for moist heat conditions, was used. F1 MONA is among the new varieties developed by TropicaSem. It is a determinate growth variety with an earliness of 65 to 70 days after transplanting. This variety is tolerant to nematodes.

III. Biochar production

The biochar was produced in the country’s south at the University Assane Seck of Ziguinchor (UASZ) (12°32'52"N; 16°17'12" W). The process of production was artisanal. It was necessary to produce handmaid biochar since the technology has to be replicated in rural areas where it should be easily accessible in terms of cost and technology. The objective was also to use organic material that can be found easily in rural areas. That is more or less not a source of competition because of its multiple uses. In addition, the organic material was chosen for the purpose of post-harvest waste management. Thus, after prospecting the agricultural system in Senegal, the extent of peanut production, the easy access to peanut shell wastes, and the weak competition for its uses, we choose peanut shells as feedstock for our biochar production. The production of locally made biochar involves several steps, which can be summarised in four main points (Appendix 2).

III.1 Container preparation

The device consists of a 200 L open-head still barrel with a 57.15cm diameter and 83.82cm height. The lid is topped by a chimney (fig. 8) of 10cm in diameter, and it can be closed more or less tightly on the sides. The diameter of the chimney is important because it is the main element that determines the time of pyrolysis and how best the biochar will be cocked. The bottom of the barrel was perforated with several small holes (fig. 9) to allow air to enter. The connection of the air entering from the perforations at the bottom of the barrel and the opening of the chimney is the key driver of the process. The second step can begin when all this work on the container is done.

Figure 8: Barrel topped with a chimney

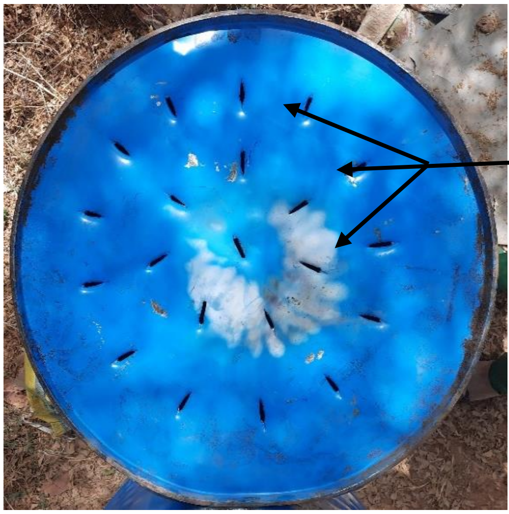

Figure 9: Openings at the bottom of the barrel

III.2 Preparation and beginning of the pyrolysis

The empty barrel is placed up to 15 to 20 cm from the ground on stones in circular disposal to bear the base of the barrel. The barrel-stone assembly is then sealed with wet sand. Four holes are opened on the damp sand to allow air to enter and the combustion to be drawn down through the air interaction between the openings at the base of the barrel and the chimney. After setting the device, the peanut shells are carefully poured into the barrel in such a way as to avoid disturbance of the layout of the barrel and to avoid air leaks in different places that were not intended for this purpose. The barrel is filled to the last upper line, and the shell is soundly levelled. Then with easily flammable materials (dry grass, paper), the fire was lit on the surface of the groundnut shell. The chimney lid was only closed when the fire had spread to the entire upper surface of the groundnut shell.

III.3 Pyrolysis monitoring

A probe linked to a thermometer (fig.10) capable of taking temperatures up to 1000°C was inserted into the barrel through a tiny hole created at the surface of the barrel to monitor the pyrolysis temperature (fig. 11). In this study, the pyrolysis temperatures have reached 800°C.

Figure 10: Digital Thermometer displaying the temperature during the pyrolysis process

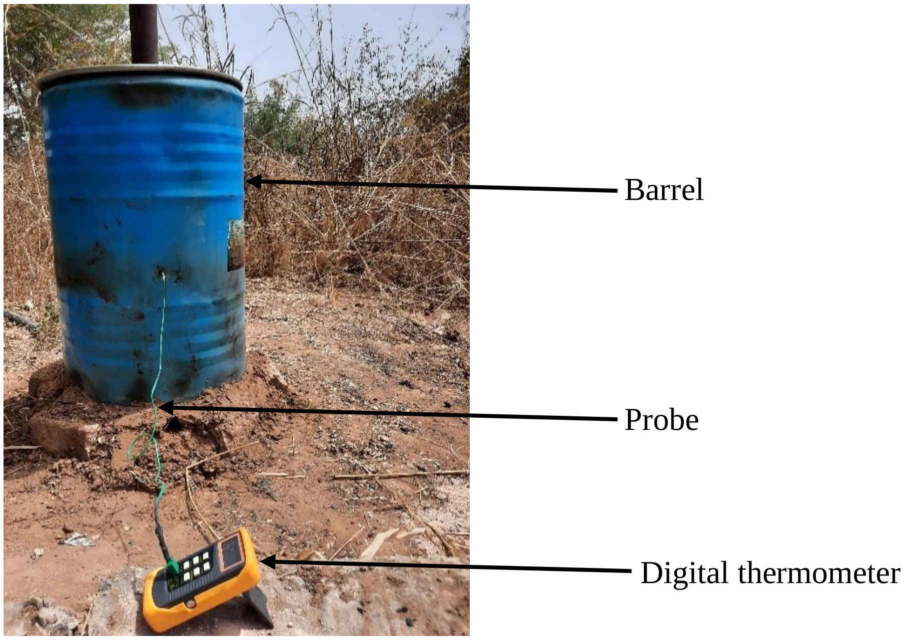

Figure 11: Feature of the temperature monitoring

To obtain the 225kg of biochar used in the study, 25 bags of 29kg average each were pyrolysed, yielding 31% per bag of groundnut shell. The yield was calculated by the formula below:

$$Y_b = \frac{Wf}{Wb} \times 100$$

Where: Y_b is the yield of biochar production; Wf is the weight of the peanut shell; and Wb is the weight of biochar.

The duration of the pyrolysis process was monitored, and the average time was 1h30min. The level of completion of the pyrolysis was monitored through the colour of the smoke. There was a significant dense brownish smoke at the beginning of the pyrolysis. In the middle of the pyrolysis, it became blue, less dense, and scarce. When pyrolysis is complete, the smoke is entirely light blue and very little in terms of quantity.

III.4 Cooling process

When the pyrolysis was complete, the biochar was poured into a new barrel which did not have neither opening at the bottom nor a chimney. The final biochar is hermetically sealed into the new barrel, knowing that the contact between the hot fresh biochar and the air can turn it into hash through complete combustion. Thus, the average duration for the cooling down of the biochar was two hours and a half. After this time, the biochar can be spread out in the open air at ambient temperature for 30min before being ground in a mortar. Hence, for one production, the whole process can last four hours and a half. In this regard, it was possible to do only 02 biochar production per day.

III.5 Biochar analysis

Biochar analysis was performed at the Laboratory of Chemistry and Physics of Materials of the University Assane Seck of Ziguinchor (12°32'52"N; 16°17'12" W). The details of the further analysis are given in the table below:

Table 1: Different biochar parameters analysis

Biochar parameter	Immediate analysis on a dry basis (%)	Elemental analysis on a dry basis (%)	Method of analysis
Moisture content (MC)	8.5	-	NF EN 1860-2
Volatile Matter (VM)	9.75	-	NF EN 1860-2
Ash content (AC)	7.75	-	NF EN 1860-2
Carbon (C)	-	83.49	Nhuchhen, 2016
Hydrogen (H)	-	2.44	Nhuchhen, 2016
Nitrogen (N)	-	0.78	Nhuchhen, 2016
Oxygen (O)	-	5.54	Nhuchhen, 2016
Biochar particle sizes			
Size (mm)		Size in final biochar (%)	
0.05		6.5	
0.2		19	
2		46.5	
>2		28	

IV. Experimental design

The dedicated space for the experiment was split into three blocks of 7.5mx6m, that is, 45m^2. Each block was divided into 09 subplots of 2.5mx2m (5m^2) representing the different treatments. A total of 27 subplots were followed up. Blocks were separated from one another by an alley of 2m, while the distance between subplots was 1m. It was a factorial experiment where water irrigation rate and biochar amount were the studied factors comprising three levels each (Table 2). The experimental design (fig. 12) was a split plot where the main plot is the irrigation rate, and the subplot is the amount of biochar mixed in the soil at 0-20cm depth. The subplots were randomly set inside the main plot. Biochar was incorporated into the soil at a depth comprised between 0cm and 20cm. There was no incubation of the biochar since it was applied in the soil right after the production and two days before transplanting the tomatoes. In addition, before the transplantation, each subplot was abundantly irrigated for a whole week. Tomatoes were planted in the subplot with a spacing of 0.5m between the crops in the rows, and between the rows. Thus, 20 plants were planted in each subplot of $5m^2$ (fig.13). Tomatoes were irrigated every day.

Table 2: Treatment composition of the experiment

Water level	Biochar amount	Treatment
W0	B0	W0B0
W0	B1	W0B1
W0	B2	W0B2
W1	B0	W1B0
W1	B1	W1B1
W1	B2	W1B2
W2	B0	W2B0
W2	B1	W2B1
W2	B2	W2B2

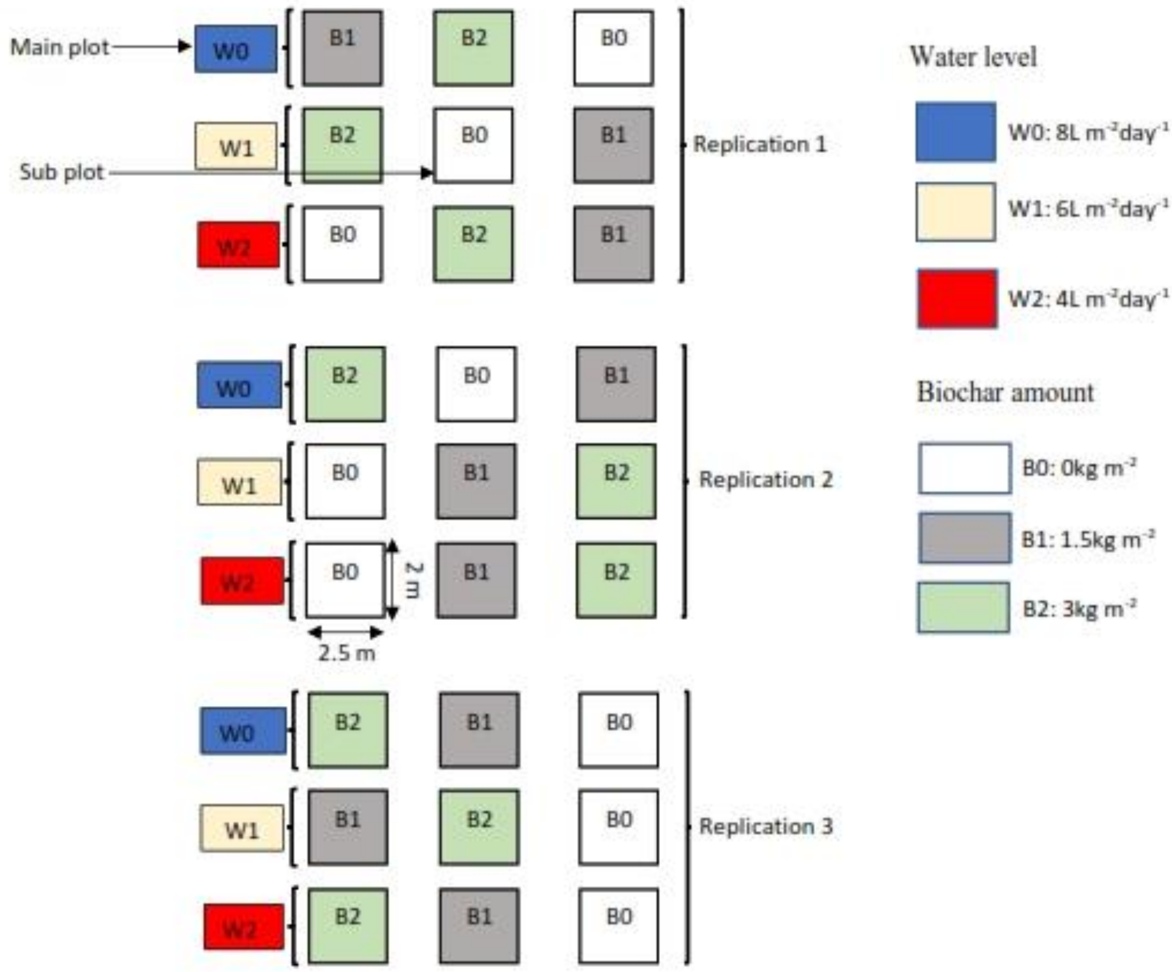

Figure 12: Experimental design split plot

Figure 13: Plant layout in a sub-plot

V. Data collection and analysis

V.1 Soil

V.1.1 Data collection

Before setting the experiment and after designing blocks and subplots, soil samples were collected (25/02/2021) at 0-20cm depth in each subplot for baseline analysis. After soil sampling, biochar was mixed in the subplots two days before tomato transplantation. The results of the soil analysis in the experimental site are shown in table 3. The soil analysis results indicate that the experiment was performed in sandy loam soil (USDA, 2023).

Table 3: Experimental site soil composition

Mineral composition	Unit	Value
Sand	%	64.576
Silt	%	24.67
Clay	%	10.754
Chemical composition		
pH		6.65
CE 1/10	µs/cm	59.34
Carbon	%	0.478
Organic matter	%	0.824
Nitrogen	%	0.041
Calcium	meq/100g	6.447
Magnesium	meq/100g	1.036
Sodium	meq/100g	0.152
Potassium	meq/100g	0.008
Total Phosphorus	ppm	77.417
Sulfur	meq/100g	7.633
Cation exchange Capacity	meq/100g	12.225

V.1.2 Soil sampling

Soil samples were collected in each treatment, at 20cm depth, three times during the two seasons. The samples were taken in the lab for analysis to determine the soil composition in the experimental site. After the sampling, a quantity of 200g of soil is air-dried and sieved at 2mm before it is taken to the lab for analysis.

V.1.3 Soil analysis

The particle size analysis was performed using Robinson's pipette method (NEN5357 and ISO 11277). The pH/H_2O of soils is determined by the potentiometric method using a pH meter in an aqueous extract with a soil/water ratio of 1/2.5. The organic matter content was assessed according to the modified Anne method (Spectrophotometry). A mixture of potassium dichromate and sulphuric acid oxidises carbon in the soil. The carbon content is read using a spectrophotometer at a wavelength of 600 nm. The method of phosphorus determination used in our study is the one of

Bray & Kurtz (1945). The soil has been mineralised by boiling concentrated sulphuric acid in the presence of a catalyst to assess its nitrogen content. Thus, the nitrogen contained inorganicc matter is transformed into ammonium sulphate. The mineralisation is done by a mixture of sulphuric acid and salicylic acid. The ammonium was measured with an SP 320 UV spectrometer at a wavelength of 660 nm. Exchangeable bases were determined by atomic absorption spectrophotometry.

V.1.4 Physical soil parameters measurements

-Bulk density: The bulk density was determined with the cylinder method at the end of each season. Undisturbed soil samples were collected from each subplot with a known volume cylinder (98.17m^3). Two samples were collected per subplot and gently transferred into a container where the empty weight was determined. The containers with the soil samples were taken to the lab for oven drying for 24h at 105°C. The bulk density was calculated by the formula below:

$$\rho_d = \frac{Ms}{V_T}$$

Where: ρ_d is the bulk density of soil, Ms is the mass of dry soil, and V_T is the volume of the cylinder

-Field capacity: The field method was used to determine the field capacity of our field experiment. Undisturbed samples were collected through a cylinder of 100cm^3, 48h after the rainfall and taken into the lab for fresh weight, oven drying (105°C for 24h), and dry weight measurements. The field soil field capacity was determined by the difference between the soil's fresh and dry weights.

-Permeability: This parameter was determined in the lab. A quantity of 100ml of distilled water was allowed to pass through 50g of soil, sieved at 2mm, and collected from each treatment. The time was taken between the first drop of water traversing the soil and the last drop. The permeability was calculated via the formula below:

$$\mu = \frac{V_1 - V_2}{T}$$

Where μ=Soil permeability; V_1=the total volume of water poured in the 50g of soil; V_2=the volume of the collected water after passing through the soil; T_0=the time taken to collect V_2.

-Porosity: It was determined through the relation between the soil bulk density and the particle density (ρ_s), which was assumed to be constant and equal to 2.65g.cm^{-3} in soils where the organic matter is less than 5% (Blake, 2008; Schjønning et al., 2017). The relation between the soil bulk density and the particle density for total porosity determination is shown below:

$$\Phi = 1 - \frac{\rho_d}{\rho_s}$$

Where Φ correspond to the porosity; ρ_d is the bulk density of soil in g.cm^{-3}; and ρ_s the particle density of the soil in g.cm^{-3}.

V.2 Crop

As indicated in the topic of this work, the experiment was performed under tomato cultivation. The measurement of different parameters was taken in the field and the lab.

V.2.1 Plant height

The measurement of plant growth started 10 days after tomato transplantation. It was a field measurement with a decameter measuring the plant height from the collar to the insertion of the last leaf. In this study, the measurement occurs for both seasons (2021-2022; 2022-2023) at 30 days, 60 days, and 80 days after transplantation. These targeted days correspond to the stages of vegetative, flowering and fruit formation (Shamshiri et al., 2018). The measurement was taken weekly in each treatment. Six plants in the middle of each plot were regularly followed up (fig 14)

V.2.2 Plant stem diameter

The measurement of the tomato stem diameter started simultaneously and concerned the same targeted plant as that of tomato height. The measurements were also taken at the vegetative, flowering, and fruit formation stages, as in the plant height measurements. We use a digital calliper to perform the different measurements 10cm above the collar. The 10 days were chosen to allow a good recovery of the tomato plant and reduce losses after transplantation before plants monitoring.

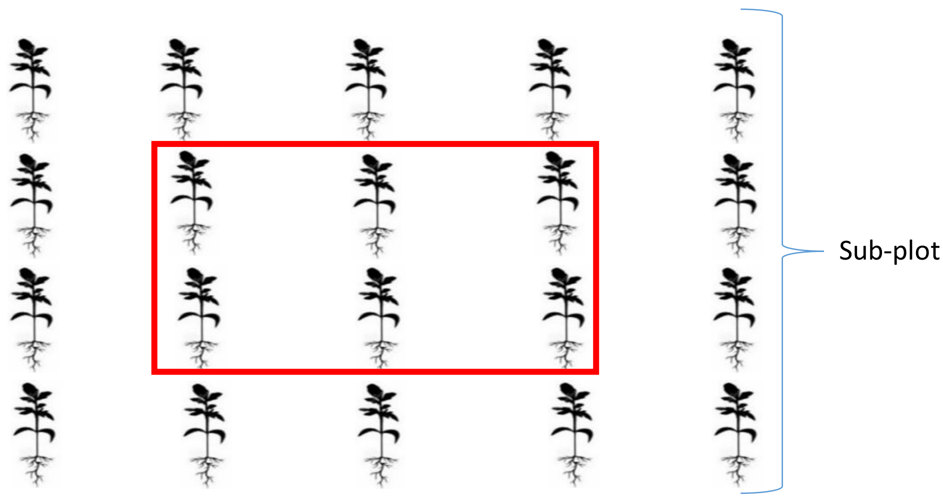

Figure 14: Targeted crops for plant height and stem diameter measurement

V.2.3 Above-ground and root biomasses

All the above-ground and root biomass of the 27 subplots were harvested for dry weight determination. The different biomass was oven dried at 80°C for 48h before it was weight according to the different subplots.

V.2.4 Fruit parameter measurement

-Fruit size: At each harvest, the fruit size was taken in terms of diameter according to the FAO Codex Stan 293-2008 (Codex Alimentarius, 2008). The fruit size determination permits us to determine the average fruit size at the end of the season.

-Fruit weight and yield: Every single fruit harvested was weighed on the field with an electronic scale of 0.1g precision. For yield, every single fruit was weighted after harvesting and at the end of each season, the total yield for each treatment was calculated.

The weight of the 100 fruits was used in each treatment to determine the fruit's average weight.

-The total number of fruits: The number of consumable fruits was directly counted at the moment of harvest.

V.2.5 Irrigation water use efficiency

This parameter was calculated through the fruit yield and the above-ground biomass. It was obtained by dividing the fruit yield or the above-ground biomass by the total amount of irrigation water applied during the whole season of production (Bright et al., 2021). The irrigation water use efficiency was determined for both seasons.

V.3 Statistical analysis

Statistical analyses were performed with R Studio version 4.2.0. The split plot function was used to analyse the data collected in the split plot design. A two-way split plot ANOVA was used to analyse different crops and soil parameters at a significant difference at $P \leq 0.05$. Means separation analysis was done with the LSD (Least Significant Difference) to assess the differences among treatments and between treatments.

Chapter IV: Results and discussion

I. Results

I.1 Effect of biochar on soil physical properties and water movement

I.1.1 Porosity

The soil response to biochar application is reported here for two growing seasons, 2021-2022 and 2022-2023. These results express the total porosity of the soil at 0 to 20cm depth. The application of Biochar at 30t/ha (B2) and 15t/ha (B1) significantly ($P<5\%$) increased the porosity of the soil compared to the control during the first growing season (fig.15). B2 showed a higher increase in porosity, with half of the data comprised between 40.8% and 41.5% compared to the control, which has a maximum porosity of 37.6%. In the second growing season, a global increase in porosity was observed in all the treatments, including the control. However, the biochar treatments showed a significant ($P<5\%$) increase of the porosity relative to the control (B0=39.1%) only on the greater dose (B2=44.8%) of biochar (fig 16). The porosity evolution from one growing season to another showed no significant difference among the treatments. Generally, treatment B2 seems to be more effective in modifying soil porosity.

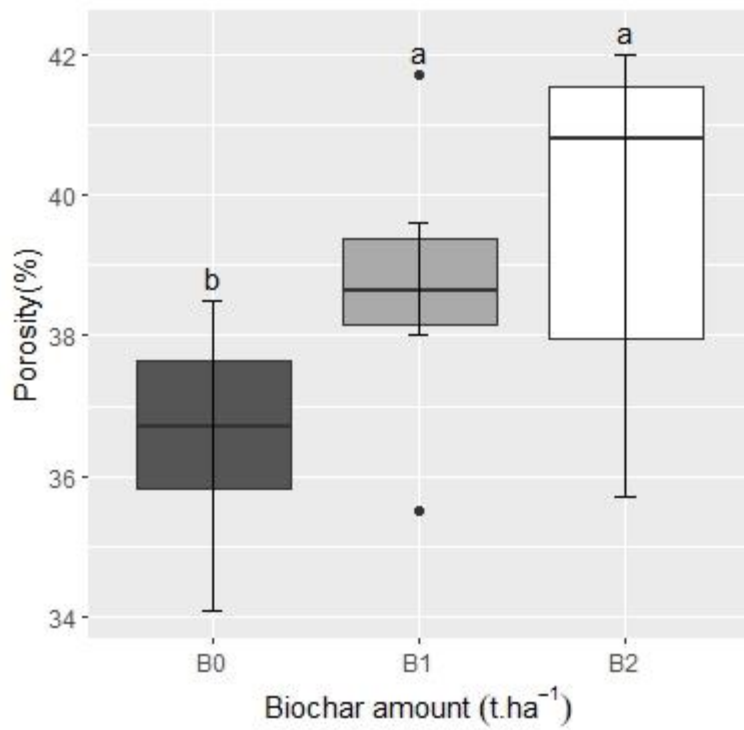

Figure 15: Effect of biochar on the soil porosity in first growing season (2021-2022)

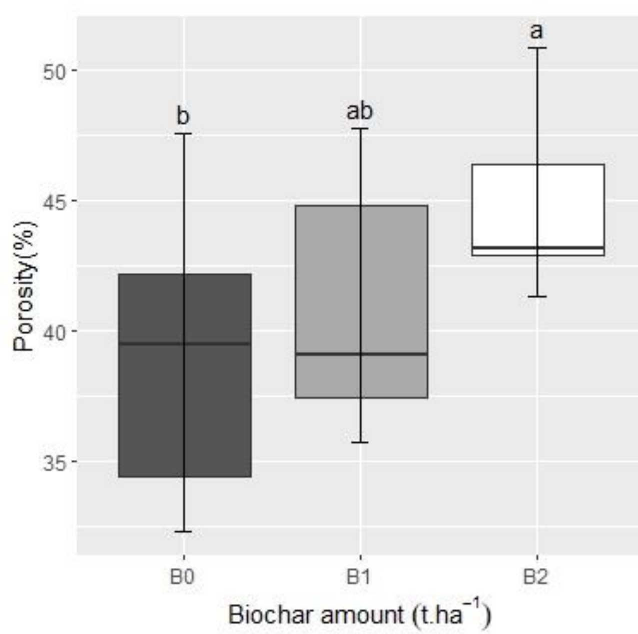

Figure 16: Effect of biochar on soil porosity in the second growing season (2022-2023)

I.1.2 Bulk density

The bulk density is one of the most important parameters for soil compactness assessment. It is an important determinant of infiltration, water availability, and soil porosity. It also influences the root movement in the soil, soil biota activity, and the nutrient state of the soil (Indoria et al., 2020). Biochar immediately affected the bulk density in the first growing season (fig 17) of the experiment (2021). The bulk density was reduced in both biochar treatments by 3% and 5%, respectively, for B1 and B2, compared to the control at a significant level of 5%. In the second growing season (fig 18), a general decrease was observed in all treatments relative to the first growing season. However, this decrease was not significantly different (P< 5%) from the bulk density measured in the first growing season. Furthermore, the 30t.ha^{-1} application rate was the only treatment in the second growing season of an experiment showing a significant decrease in bulk density regarding the control.

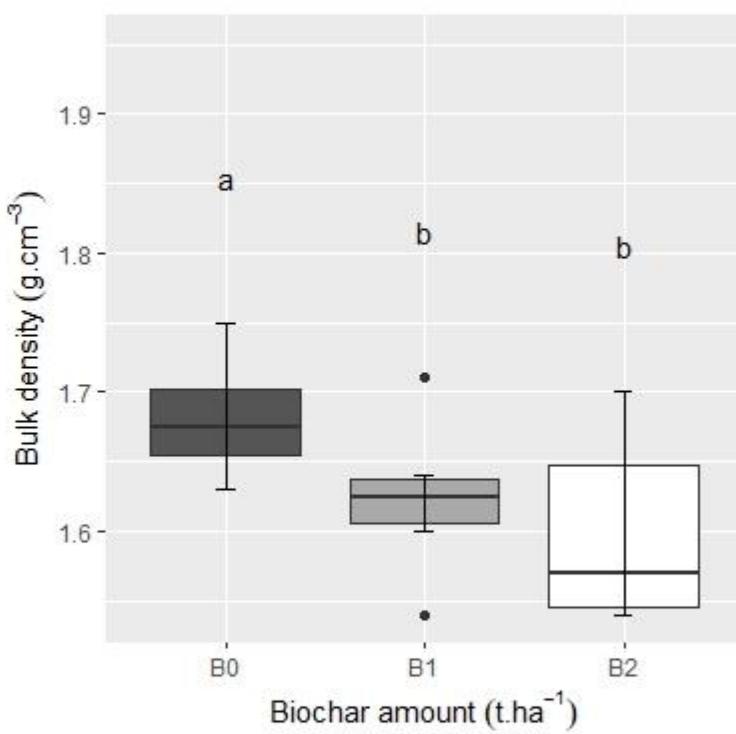

Figure 17: Biochar effect on soil bulk density in the first growing season (2021-2022)

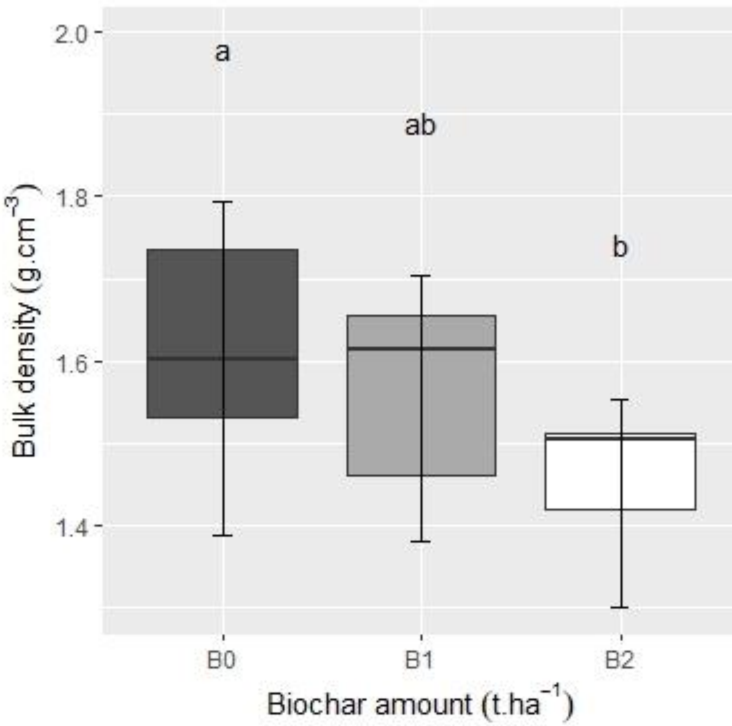

Figure 18: Biochar effect on soil bulk density in the second growing season (2022-2023)

I.1.3 Filed capacity

The results suggest (fig. 19), at a significant rate of 1%, that all the biochar treatments can hold more water than the control at field capacity, regardless of the applied amount of water irrigation. Compared to the control, B1 and B2 can hold 16.4% and 13.4% additional water. Although even if among the biochar treatments there is no significant difference, the results indicate that B1 can be more efficient than B2.

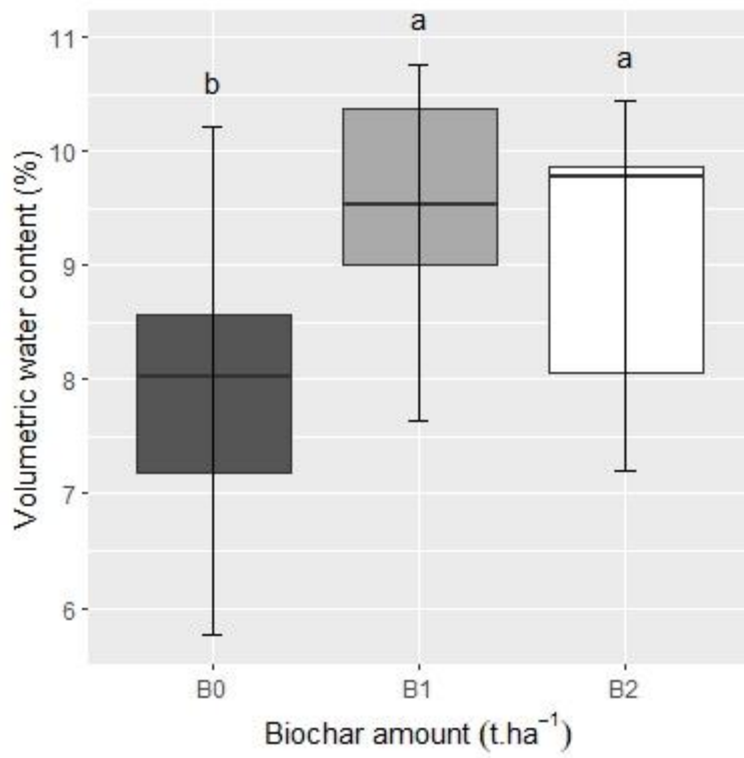

Figure 19: Effect of biochar on soil moisture content at field capacity

I.2 Effect of biochar and water treatment on tomato growth parameters and yield

I.2.1 Plant height and plant stem diameter

Tables 4 and 5 represent the results of the analysis of the impact of different applied treatments on tomato height and stem diameter at 30 days after transplantation (DAT), 60 DAT, and 80 DAT. These days respectively stand for the vegetative stage, flowering stage, and fruit formation stage of our tomato variety. Table 4, which stand for the first growing season, indicates that the irrigation water level started to significantly (P<5%) influence the tomato growth at the fruiting stage. The full-water irrigation (W0) showed the highest tomato height compared to the reduced irrigation (W1 and W2). The results indicated a growth of W0 up to 16% compared to W1 and 23%

compared to B2. The growth of the tomato stem diameter was significant (P<1%) and solely impacted by biochar treatment from the flowering stage.

Furthermore, the table suggested that at 60 DAT, only B1 is statistically different (1%) from B0. However, at 80 DAT, all biochar treatments were significantly different, compared to the control regardless of the amount. In the second growing season, table 5 indicated a disappearance of the water irrigation effect on tomato height and stem diameter. Only biochar influenced the tomato height and stem diameter. Its influence on stem diameter was highly effective (P<0.1%) at the first stage of the development of the tomato after transplantation which is the vegetative stage (30 DAT). Both biochar treatments (B1 and B2) were greater than B0 at all stages regarding the stem diameter. The significance of the effect of Biochar on plant height was noticed from 60 DAT (P<5%), with an increase of up to 11% for B1, while B2 was not significant. At 80 DAT and 1% significance level, the two amounts of Biochar applied showed a difference in tomato growth up to 13.3% and 8.4% for B1 and B2, respectively. The interaction between biochar amount-water level did not influence tomato stem diameter. These two parameters did not show any difference over the two seasons.

Table 4: Impact of different treatments on plant height and plant stem diameter in the first growing season (2021-2022)

	DF	30 DAT		60 DAT		80 DAT	
		Height	Stem diameter	Height	Stem diameter	Height	Stem diameter
Water level	2	11.847 ns	0.011 ns	104.901 ns	1.236 ns	2543.86*	1.2 ns
Biochar amount	2	11.79 ns	0.009 ns	5.793 ns	0.205**	246.02 ns	0.268**
Waterlevel:Biochar amount	4	7.51 ns	0.013 ns	22.71 ns	0.038 ns	77.92 ns	0.014 ns

	30 DAT		60 DAT		80 DAT	
Treatment	Height	Stem diameter	Height	Stem diameter	Height	Stem diameter
Water level						
W0	8.014 a	0.350 a	23.657 a	0.940 a	56.385 a	1.144 a
W1	7.650 a	0.322 a	23.014 a	0.675 a	47.398 b	0.998 a
W2	8.579 a	0.344 a	20.987 a	0.681 a	42.905 b	0.846 a
Biohar amount						
B0	8.620 a	0.324 a	22.485 a	0.700 b	46.475 a	0.914 b
B1	7.835 a	0.348 a	22.909 a	0.822 a	49.703 a	1.037 a
B2	7.788 a	0.344 a	22.264 a	0.775 ab	50.509 a	1.037 a
Combination Biochar_deficit irrigation						
W0B0	7.733 b	0.300 c	22.622 ab	0.827 bc	53.577 ab	1.050 bc
W0B1	8.111 b	0.372 ab	24.266 a	1.050 a	57.583 a	1.200 a
W0B2	8.200 b	0.377 a	24.083 a	0.944 ab	57.994 a	1.183 ab
W1B0	8.416 ab	0.333 abc	22.527 ab	0.627 d	43.611 d	0.900 de
W1B1	7.222 b	0.322 abc	23.405 a	0.694 cd	47.244 cd	1.027 cd
W1B2	7.311 b	0.311 bc	23.111 ab	0.705 cd	51.338 bc	1.066 abc
W2B0	9.711 a	0.338 abc	22.305 ab	0.644 d	42.238 d	0.794 e
W2B1	8.172 b	0.350 abc	21.055 ab	0.722 cd	44.283 d	0.883 e
W2B2	7.855 b	0.344 abc	19.600 b	0.677 d	42.194 d	0.861 e
R^2	0.298	0.185	0.197	0.522	0.401	0.536

Table 5: Impact of different treatments on plant height and plant stem diameter in the second growing season (2022-2023)

Treatments	DF	30 DAT Height	30 DAT Stem diameter	60 DAT Height	60 DAT Stem diameter	80 DAT Height	80 DAT Stem diameter
Water level	2	44.535 ns	0.016 ns	133.785 ns	0.035 ns	104.95 ns	0.024 ns
Biochar amount	2	37.821 ns	0.071***	69.363*	0.071**	127.47**	0.060***
Water level: Biochar amount	4	20.927 ns	0.004 ns	16.637 ns	0.002 ns	6.59 ns	0.001 ns

Treatment	30 DAT Height	30 DAT Stem diameter	60 DAT Height	60 DAT Stem diameter	80 DAT Height	80 DAT Stem_diameter
Water level						
W0	38.741 a	0.846 a	52.323 a	1.038 a	56.684 a	1.141 a
W1	34.371 a	0.767 a	45.352 a	0.927 a	50.296 a	1.047 a
W2	37.278 a	0.834 a	45.983 a	0.932 a	51.397 a	1.054 a
Biohar amount						
B0	34.945 a	0.715 b	44.961 b	0.866 b	48.795 b	0.986 b
B1	39.000 a	0.883 a	50.484 a	1.038 a	56.267 a	1.132 a
B2	36.445 a	0.850 a	48.213 ab	0.993 a	53.315 a	1.124 a
Combination Biochar_deficit irrigation						
W0B0	38.11 ab	0.723 cd	51.470 ab	0.933 bc	52.610 bc	1.026 cde
W0B1	42.946 a	0.946 a	55.833 a	1.133 a	61.693 a	1.213 a
W0B2	35.166 ab	0.870 ab	49.666 ab	1.050 ab	55.750 ab	1.1833 ab
W1B0	32.056 b	0.696 d	42.000 c	0.823 c	47.166 c	0.956 e
W1B1	36.500 ab	0.833 abc	47.276 bc	1.016 ab	52.583 bc	1.083 bcd
W1B2	34.556 ab	0.773 bcd	46.780 bc	0.943 bc	51.140 bc	1.103 abc
W2B0	34.670 ab	0.726 cd	41.413 c	0.843 c	46.610 c	0.976 de
W2B1	37.553 ab	0.870 ab	48.343 bc	0.966 bc	54.526 b	1.100 abc
W2B2	39.613 ab	0.906 a	48.193 bc	0.986 abc	53.056 bc	1.086 bcd
R^2	0.741	0.901	0.862	0.891	0.898	0.935

‡Values within a column followed by the same upper-case letter are not significantly different at P <0.05 (*) or P<0.01 (**); ns=not significant

I.2.2 Root biomass

Root biomass is an important parameter to evaluate how the crop has explored the soil to accomplish its need in terms of water and nutrients. The development of the root biomass is an indicator of the useful depth of the soil. For the first growing season of our experiment, the root biomass did not show a significant difference at a 5% significant level among all treatments. The second growing season showed a highly significant difference (P<1%) between biochar treatments and the control. B1 and B2 are respectively higher than the control for 26.4% and 21.5%.

Furthermore, most biochar treatments registered a quantity of root biomass greater than or equal to 100kg/ha (fig 20). No interaction between the amount of biochar and the water irrigation level was relevant to root biomass in both seasons. Among biochar treatments, the difference was not significant. A seasonal growing effect in terms of total growing season biomass indicated a significant effect at 5% between the two growing seasons of the experiment (fig 21). This difference between seasons is probably the effect of the distribution of the total biomasses of biochar treatments which half recorded more than 100kg/ha in season 2.

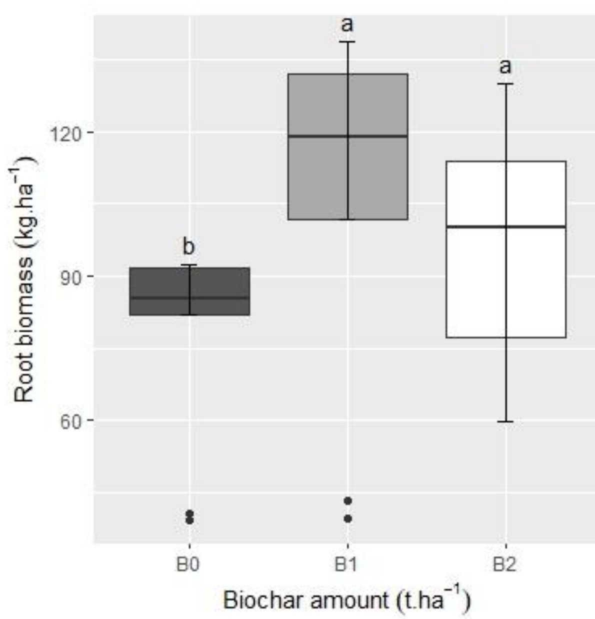

Figure 20: Biochar effect on tomato root biomass development in the second growing season experiment (2022-2023)

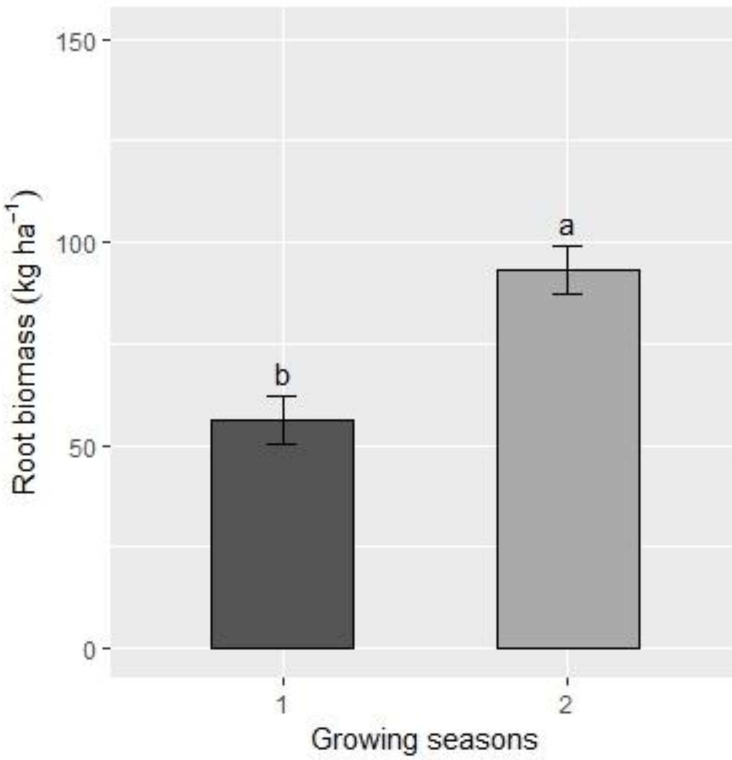

Figure 21: Tomato root biomass over growing seasons (2021-2022; 2022-2023)

I.2.3 Above-ground biomass

The above-ground biomass in the first growing season experiment did not indicate any significant difference among biochar treatments or between biochar amount and water level. In this growing season, the development of above-ground biomass was probably due to the sole irrigation water level, as shown in figure 22. Indeed, at P<5%, W0 ($8L.m^{-2}.day^{-1}$) shows a significant difference compared to the reduced irrigation W1 (75%W0) and W2 (50%W0). Figure 22 indicates that the above ground in W0 (1114. $27kg.ha^{-1}$) is more than twice greater than the combined above ground produced in the sum W1+W2 (860. $3kg.ha^{-1}$). Biochar started to influence the development of the above-ground biomass in the second growing season with a significant difference (P<1%) between biochar treatments and the control, independent of the amount of water irrigation applied (fig 23). B1 and B2 showed 37% and 30.5% greater above-ground biomass than the control. The results of the second growing season indicate a progressive effect of biochar over time. While moving from growing season one to growing season two, figure 24 shows that the effect of water irrigation level solely on influencing the above-ground biomass has been reduced regarding the full irrigation. However, for the reduced irrigations, a significant difference was observed while moving from growing season one to growing season two. This situation has led to a balance between the water level treatments.

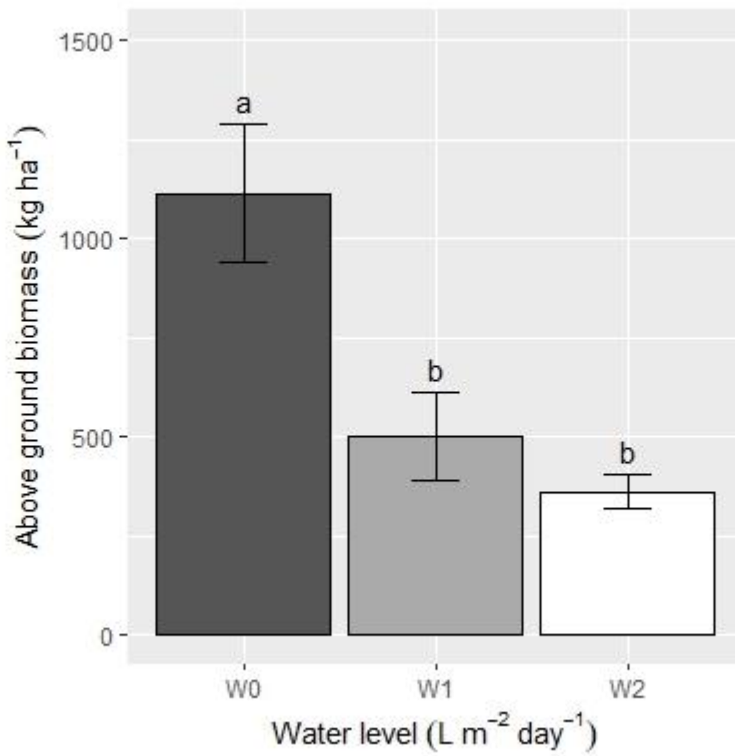

Figure 22: Effect of irrigation water level on tomato above-ground biomass in the first growing season (2021-2022)

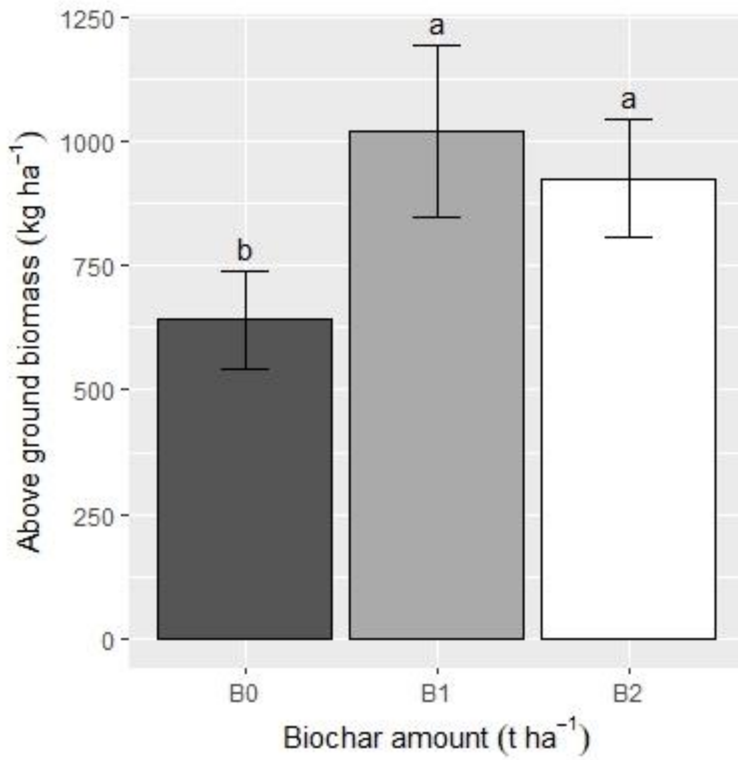

Figure 23: Effect of biochar on tomato above-ground biomass in the second growing season (2022-2023)

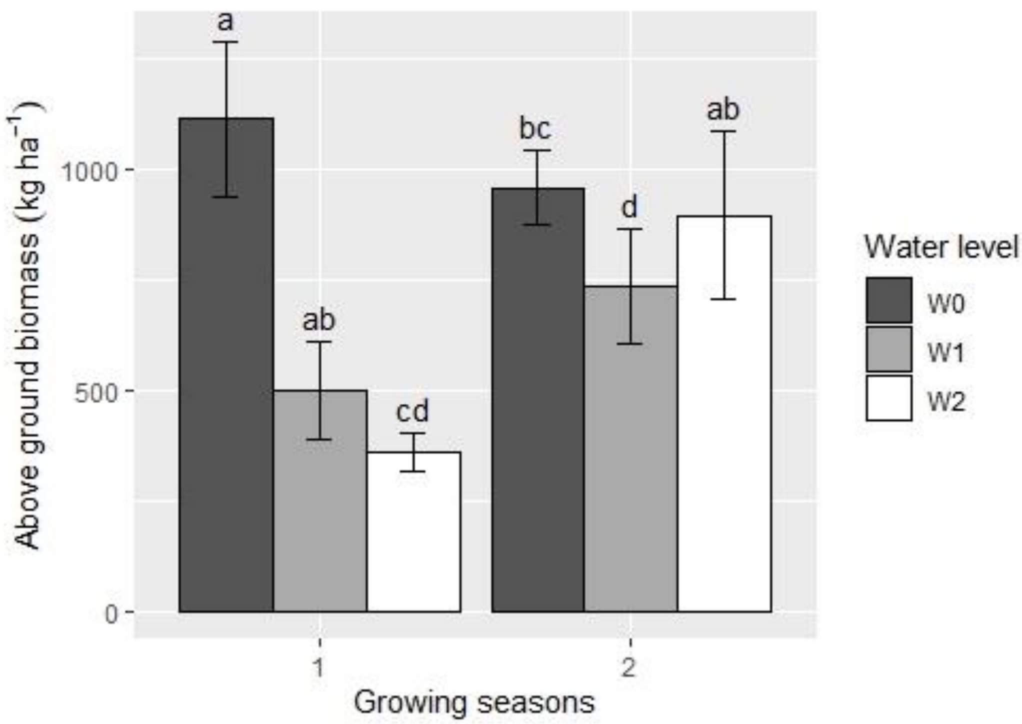

Figure 24: Water level effect on tomato above-ground biomass over the growing seasons

I.2.4 Fruit yield

Tomatoes are water and mineral demanding plants. However, in irrigation, the quantity of water to apply to grow tomatoes in good conditions should be optimum, not too much to avoid certain diseases such as fungal diseases, but not small to help the crop to grow with less water stress. In the first growing season of our study, the yield of tomatoes was dependent on irrigation water and biochar application, as shown in figure 25. The figure points out three tendencies. The first is that the variations in the yield could be explained by the amount of water applied to irrigate the crop. The highest yields were observed under W0 (B1=7.3t ha^{-1}, B2=6.02t ha^{-1}, B0=5.71t ha^{-1}), followed by W1 (B2=3.9t ha^{-1}, B0=2.2t ha^{-1}, B1=1.7t ha^{-1}). The second one is that in every water treatment, the influence of biochar is a function of its amount. That means the same amount of biochar can provide different results according to the water irrigation amount. B1 performed better in W0, but in W1, B2 showed a greater yield. The third and last tendency indicates that the amount of biochar accommodates the quantity of water supplied to irrigate tomatoes.

Thus, at a 5% significant level, the graph suggests that the quantity of 15t ha^{-1} (B1) fits better to the high quantity of water while the amount of 30t ha^{-1} (B2) performs better when the quantity of water is average. Below, the biochar treatments showed no significant difference compared to the control. However, in the second growing season (fig. 26), the performance of biochar was higher than that of the quantity of water supplied. In fact, the figure indicates at a 1% level of significance that all biochar treatments produced greater yields respectively for B1 and B2, 35.15% and 34.43% more than the control. The results of the two seasons of experiment trend to indicate that the influence of biochar on the yield of tomatoes is divided into two phases: the phase of hydrodynamic regulation seen in the first season and the phase of nutrient and water combined effect on the yield highlighted in the graph (fig. 26) of season two. On a seasonal growing basis, only biochar, regardless of the applied amount, indicated a difference between the two growing seasons. Irrigation water level did not show any significant variation over the growing seasons. The influence of biochar on the yield of the second growing season was significantly (P<5%) greater than that of the first growing season (fig. 27). The effect of biochar on the yield might be increasing upon its duration in the soil if mixed.

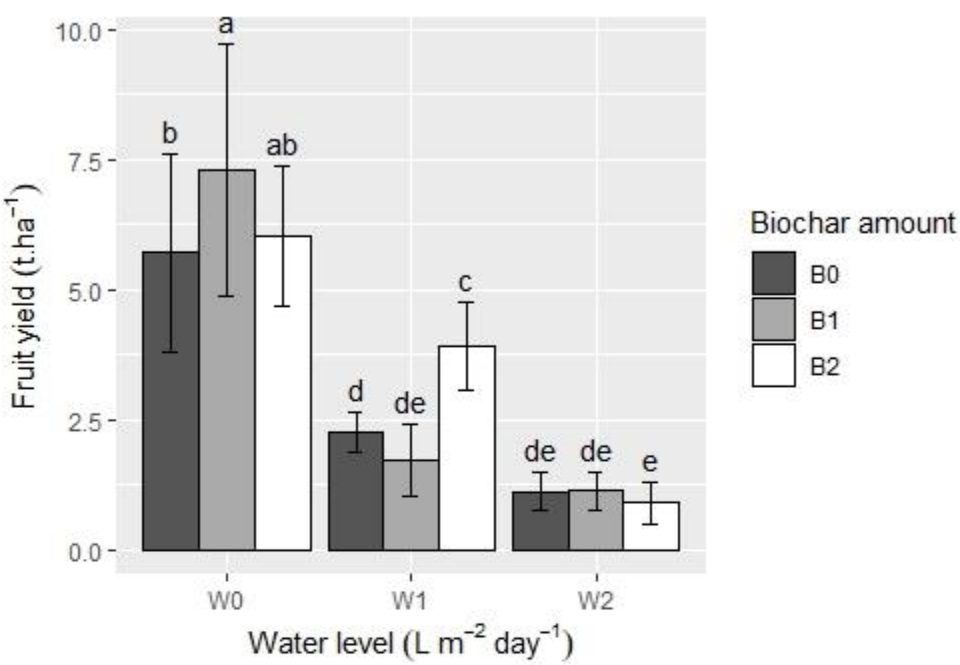

Figure 25: Effect of the combination biochar amount- irrigation water level on tomato yield during the first growing season (2021-2022)

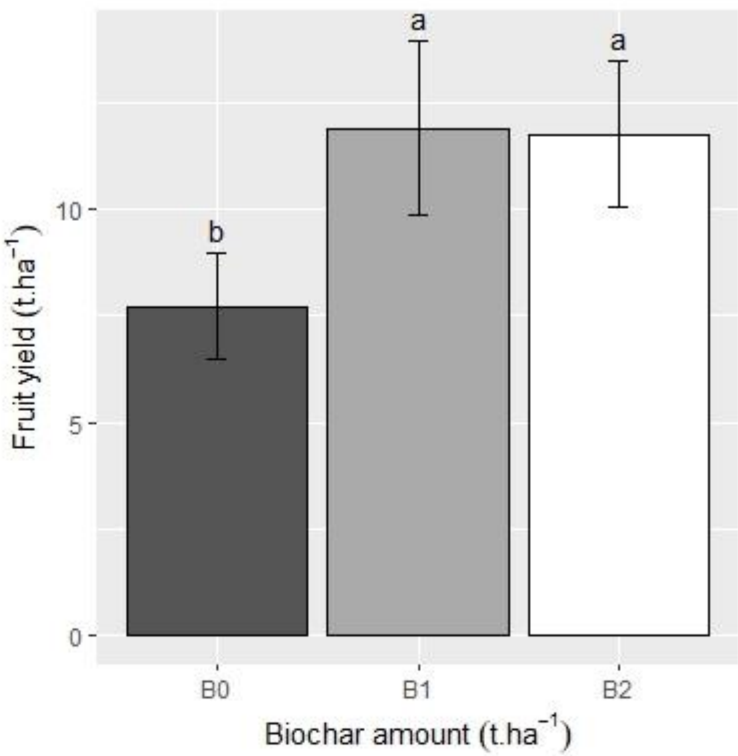

Figure 26: Influence of biochar on tomato yield in the second growing season experiment (2022-2023)

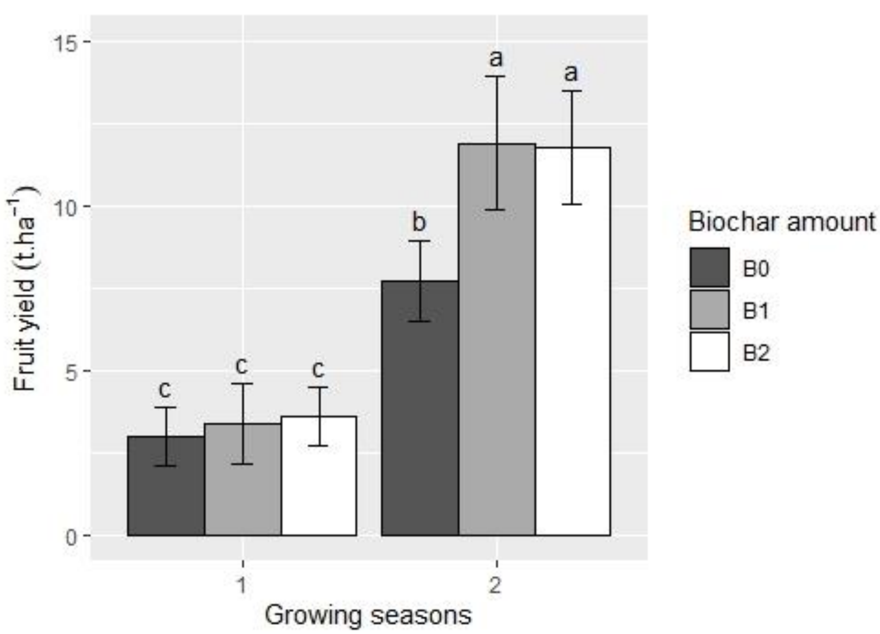

Figure 27: Tomato yield variation over growing seasons upon biochar amendment

I.2.5 Number of fruits per treatment

The number of fruits per treatment was typically linked to the quantity of water applied to the crops. Hence, figure 28 points out a significant difference at 1% significance among the various levels of irrigation. The full irrigation recorded more fruit than the reduced irrigation combined together. The reduced irrigation treatments did show any significant difference between them. In the first growing season, biochar could be considered a water flow regulator. In the second growing season (fig. 29), the number of fruits per plot was influenced by biochar application and was highly significant, at 0.1% in both treatments regarding the control. Globally (fig. 30), the first growing season of water irrigation showed a significant difference in comparison to the second growing season in full water irrigation treatment. In reduced irrigation, the growing season two presented a significant difference relative to the growing season one, only on W2 representing 50% reduced irrigation.

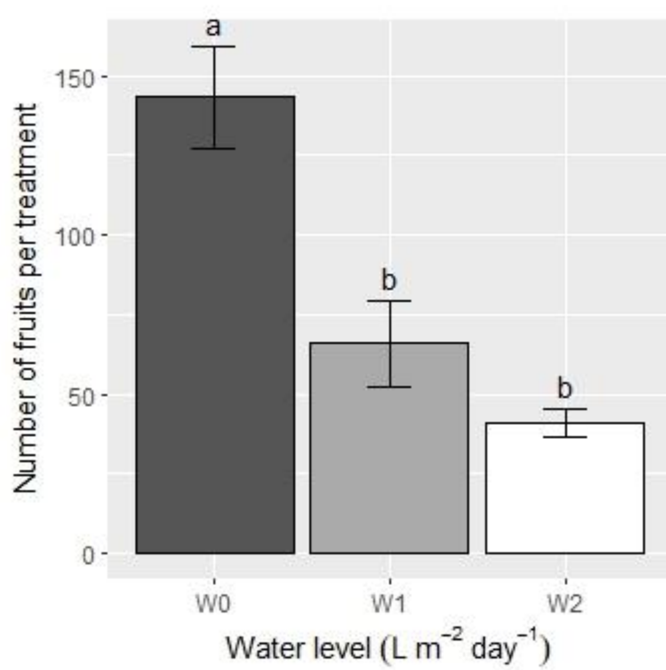

Figure 28: Influence of water supply on the total number of fruits harvested in the first growing season (2021-2022)

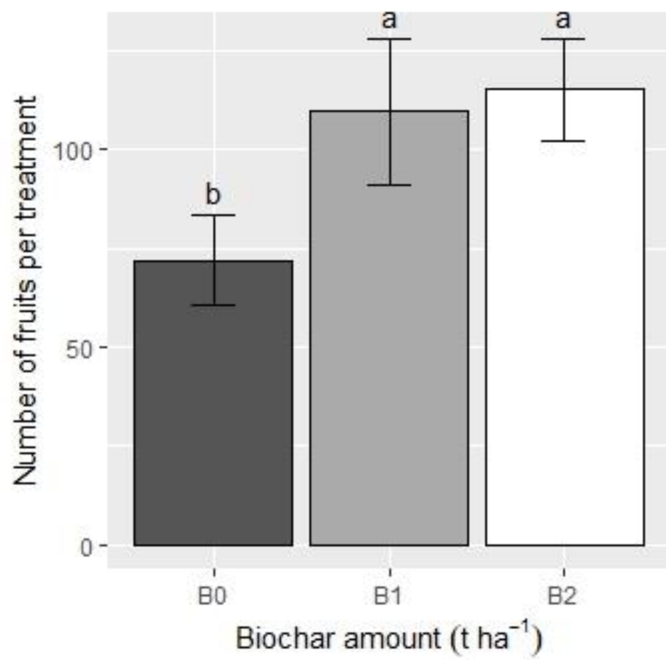

Figure 29: Influence of biochar on the total number of fruits harvested in the second growing season (2022-2023)

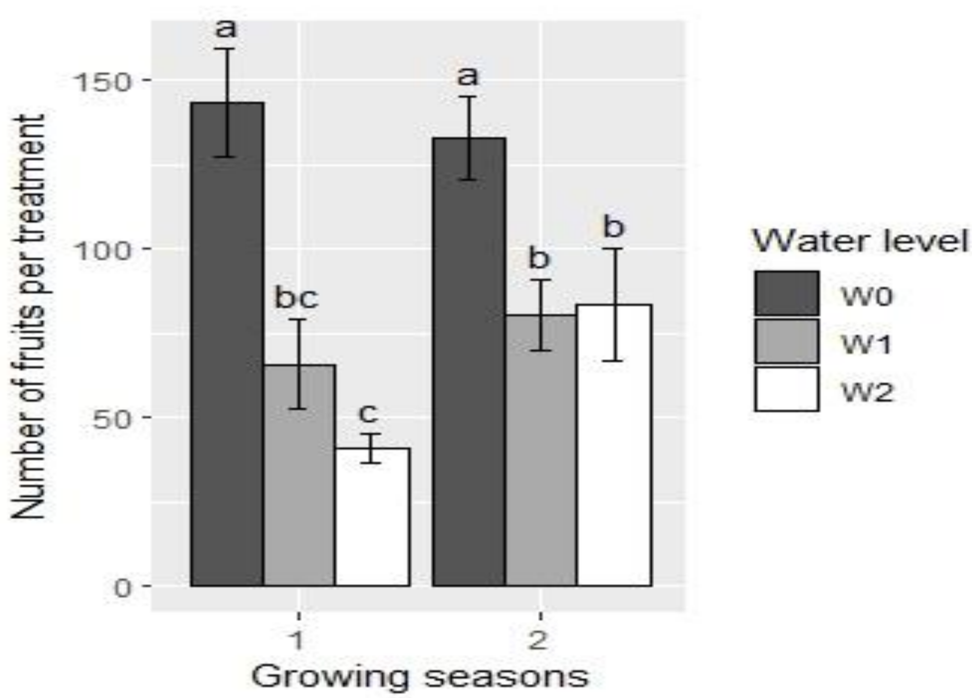

Figure 30: Water effect on tomato fruits number per treatment between the two growing seasons

I.2.6 Fruit average weight

Tomatoes' weights differed according to the variation in water level and biochar amount inside the water level treatments (fig. 31). The impact of the interaction biochar amount-water level on fruit weight was higher W0, followed by W1 at a significant level of 5%. Furthermore, the difference between biochar treatment under water irrigation treatment and the control was significant for B1 and B2, respectively, under W1 and W1. Figure 32, which presents the biochar effect on fruit weight in the second growing season, showed heavier fruits on all biochar treatments at a 5% significant level.

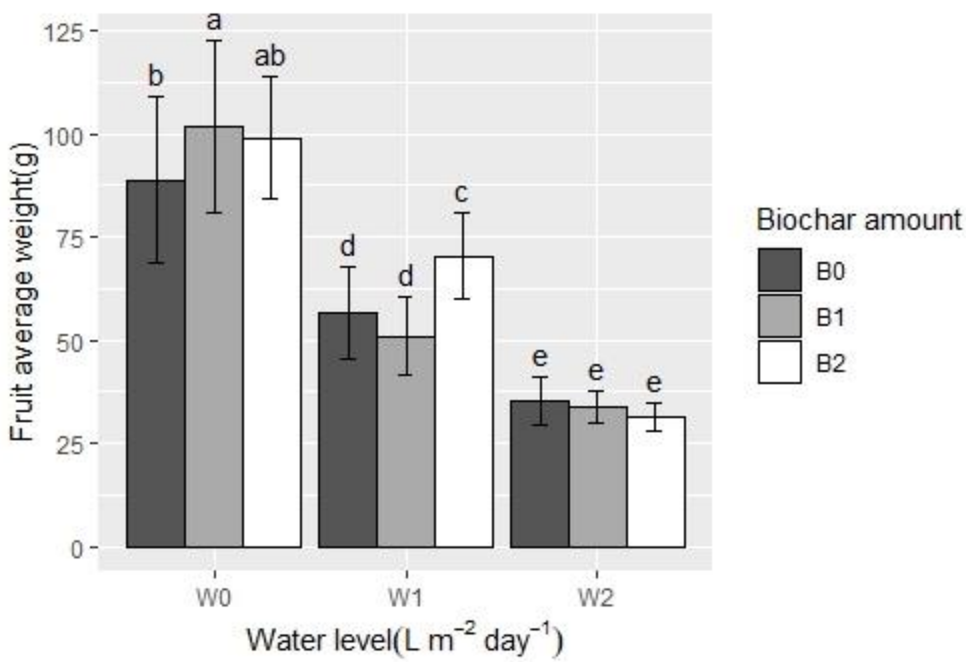

Figure 31: Impact of biochar on tomatoes' average weight in the first growing season (2021-2022)

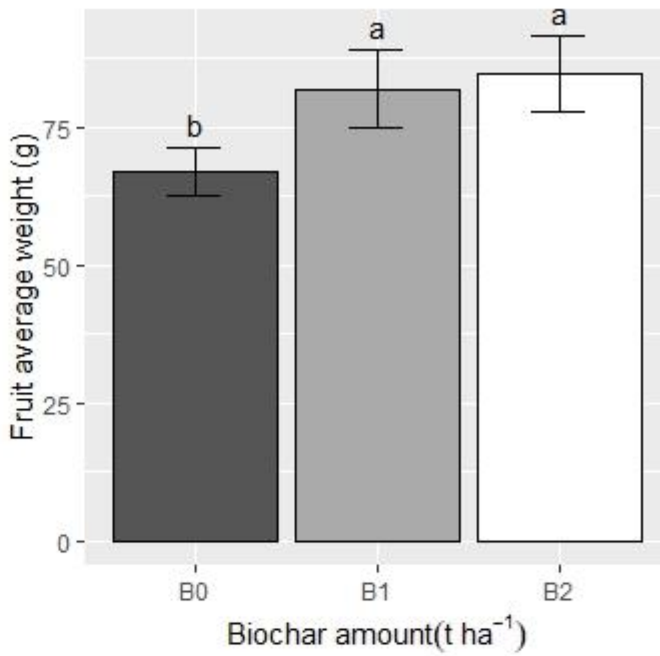

Figure 32: Impact of biochar on tomatoes' average weight in the second growing season (2022-2023)

Over the two growing seasons (fig. 33), it can be seen that water influences most of the fruit's average weight. Furthermore, all the water levels in growing season 2 showed a significant difference at 5% compared to W2 in growing season 1. However, only W0 in growing season indicates a significant difference relative to W1 in growing season 1. In addition, the fruit average weight under W0 in growing season 1 is significantly heavier compared to W1 and W2 in growing season 2.

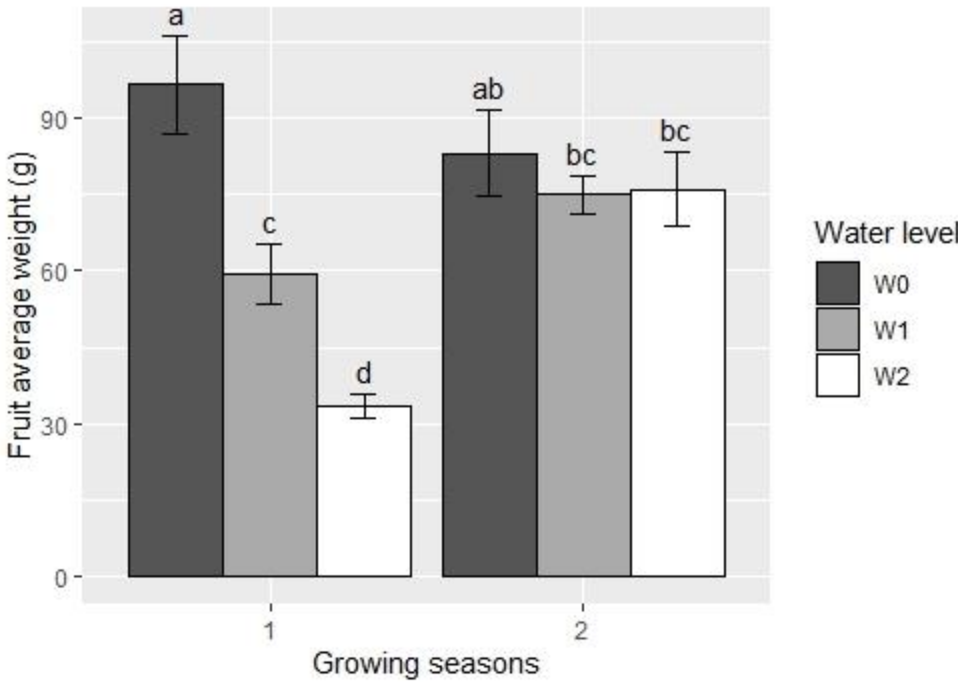

Figure 33: Impact of water irrigation level on tomatoes' average weight over the two growing seasons

I.3 Effect of biochar amount and water level on Irrigation water use efficiency

The irrigation water use efficiency is calculated in this study by dividing the grain yield or the above-ground biomass by the total supplied water for irrigation.

The water use efficiency through the tomato above-ground biomass did not show any difference at a 5% significance level in the first growing season of the experiment. In the second growing season (fig. 34), biochar treatments indicated a greater water use efficiency at P-values less than 5%. B1 and B2 were respectively more water efficient than the control for 38.1% and 30.8%.

The irrigation water use efficiency calculated using the tomato fruit yield indicates that the best results were obtained through the interaction of biochar and water in the first season. Figure 35 suggests that when water is sufficient for irrigation, water use efficiency is hardly effective. However, all the treatments under W0 are significantly more efficient in water use efficiency

(P<5%) than all the biochar treatments under reduced irrigation, except for B2 under W1. In fact, only B1 under W0 has a significantly greater water use efficiency than B2 under W1. Thus, the combination of B2 and W1 can be the most sustainable measure in terms of optimising water use in irrigation using biochar. The second growing season has confirmed the effect of Biochar on improving water use efficiency. Figure 36 showed a significant difference (P<1%) between biochar treatments and the control, with respectively 37.25% and 35.69% greater IWUE for B1 and B2. Furthermore, when comparing the two growing seasons, the results point out a highly significant difference (P<1%) between the first and the second growing season regarding the biochar treatments (fig. 37). The use of biochar can then contribute to optimising the water use in irrigating tomatoes in arid or semi-arid regions.

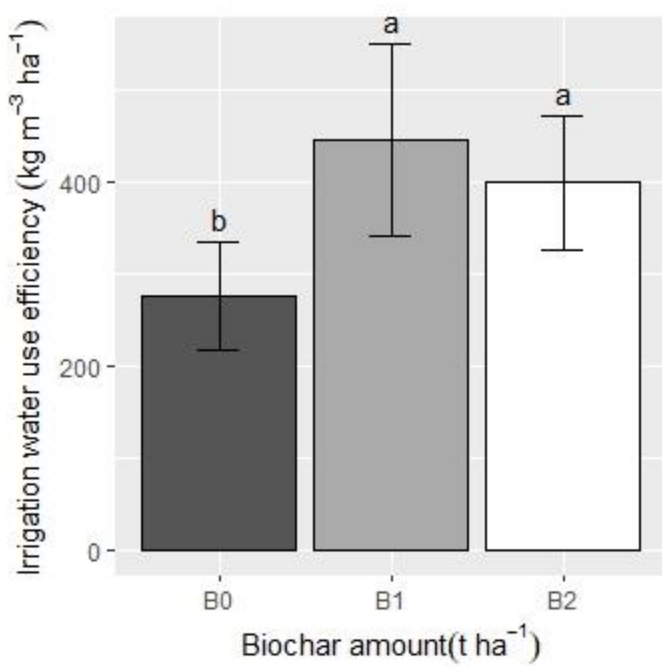

Figure 34: Biochar effect on irrigation water use efficiency calculated through the above-ground biomass

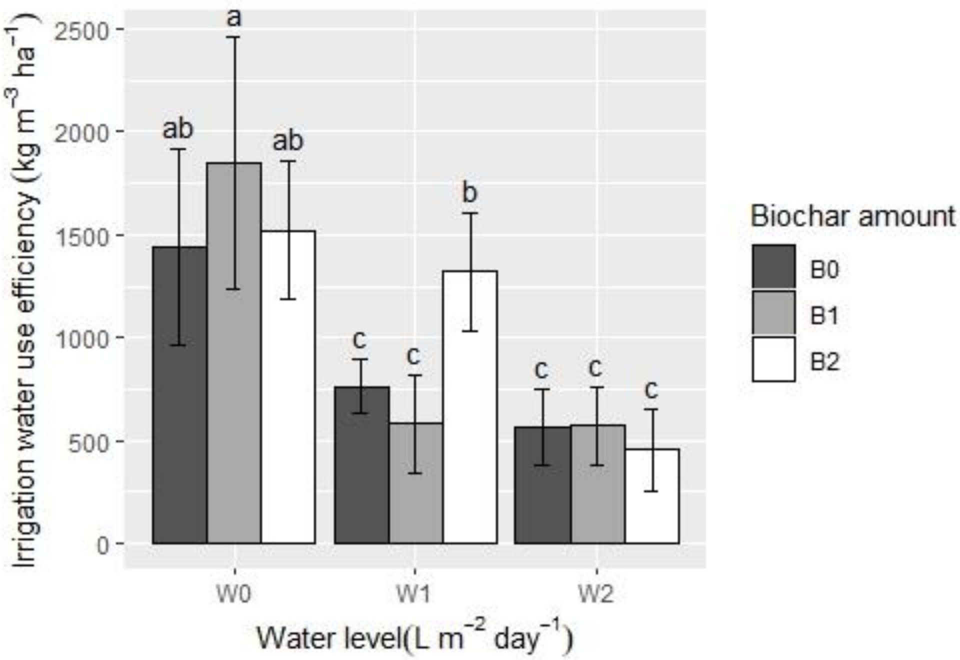

Figure 35: Biochar effect on irrigation water use efficiency calculated through the tomato fruit yield in the first growing season (2021-2022)

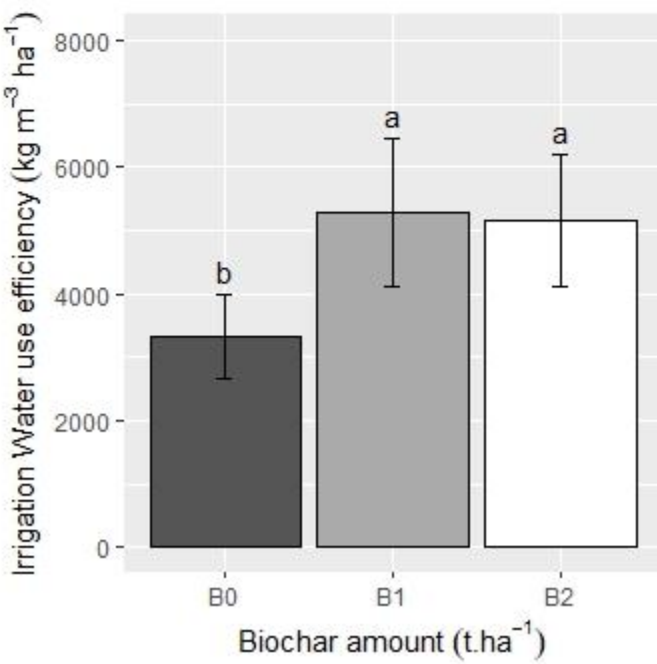

Figure 36: Effect of biochar on water use calculated through the tomato fruit yield in the second growing season (2022-2023)

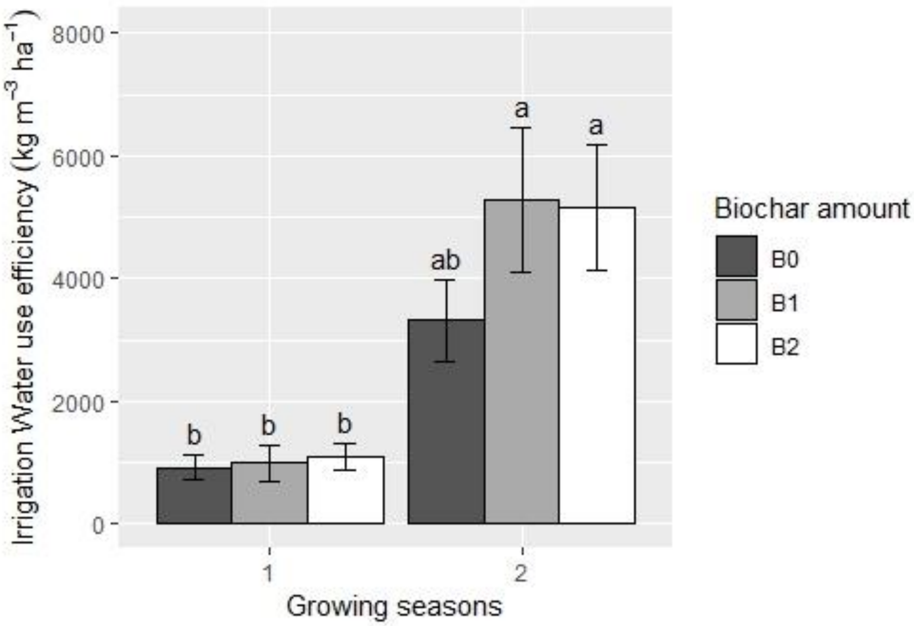

Figure 37: Effect of biochar on water use calculated through the tomato fruit yield over the two growing seasons.

II. Discussion

II.1 Effect of biochar on soil hydrodynamic properties

Biochar is becoming more and more attractive to researchers due to its effects on soil remediation and fertility (Yu et al., 2019). This assertion has been confirmed by our findings that suggest an improvement in soil porosity and bulk density of the site experiment due to biochar application into the soil. Furthermore, our results reveal that the effect of biochar in sandy loam soil on such properties is immediate and can be noticed in the first year of application which correspond to the first growing season. Ghorbani et al. (2019) have found a similar immediate effect of biochar on loamy sand and clay soils. Thus the effect of biochar on soil bulk density could be an inherent characteristic attributed to the biochar composition itself. Blanco-Canqui, (2017) suggested that the bulk density of biochar is usually less than that of the soil in which it has been incorporated could be one of the explanations for its reducing impact on soil bulk density. Furthermore, our study has shown that reducing soil bulk density could be a function of the applied quantity of biochar. This result perfectly aligns with the findings of Yu et al. (2019), who indicated that the soil bulk density followed by biochar application diminishes as the amount of the latter increase in the limit of a certain threshold (60t ha^{-1}) beyond which there is no effect. The second growing season of our experiment has shown a global decrease in soil bulk density, suggesting that the biochar could have greater performance over the years. Some researchers have found eight years of biochar's practical effect on Senegal's sandy soil properties (Faye et al., 2021). The decrease in soil bulk density has a direct effect on porosity. In fact, the porosity increases as the soil bulk density decreases. Liu et al. (2017) state that biochar particle size plays a major role in modifying soil porosity. Additionally, Aslam et al. (2014) indicate that Biochar in the soil can create intra-pores relative to its particle size.

Our biochar, made locally, is a mixture of different particle sizes (table 1). It influences the porosity at all levels, namely micropores, mesopores, and macropores. Our biochar is a mixture of different particle sizes and is an advantage for soil porosity improvement. The same results were found by Alghamdi et al. (2021), who indicated that the influence of biochar on soil pores could be linked to biochar particle size. Indeed each pore size has a particular influence on soil water retention Liu et al., (2017). Thus the mixture of biochar particle size will contribute simultaneously to the water retention and its movement into the soil like the infiltration. This influence of biochar particle size on the porosity, which is tightly related to the bulk density, might be the reason for the increment in soil moisture content at field capacity during our experiment. In fact, the increase in soil field capacity is a good indicator of improving microporosity. However, contrary to the bulk density and the porosity which followed the increase in biochar amount, our results have indicated that more water has been retained in the treatment with the application rate of 15t ha^{-1} of Biochar compared to B2 and the control. This result differs from the one found by De Melo Carvalho et al. (2014), which suggests a proportional increase of soil water holding capacity according to the increase in biochar amount.

Nevertheless, Dugan et al. (2010) confirm that the increment in soil water holding capacity is not dependent on the biochar amount. For Liu et al. (2017), the ability of biochar to improve the soil moisture content at field capacity is a consequence of the combined effect of its porosity, particle size, and shape. In addition, Edeh et al. (2020) did not see any increment in soil moisture content at field capacity when they performed a meta-analysis of "biochar's effects on soil water properties". The no effect of biochar on soil moisture might be explained by the type of soil involved in that experiment, knowing that the effect of biochar on different soil parameters depends on the type of soil (Dai et al., 2020).

We can retain in this section that the biochar effect on bulk density and porosity is dependent particularly on biochar properties (particle size, shape), biochar amount, and soil type. However, the effect of biochar on soil moisture content at field capacity is more or less a function of biochar and soil type. In the short-term use of biochar, properties such as bulk density, porosity and soil holding capacity are the first parameters to be affected.

II.2 Effect of biochar on tomato growth and yield under different rates of different irrigation regimes

II.2.1 Tomato growth and development

In the first growing season of experimentation, an interaction was noticed between biochar-and water levels. As discussed in the previous section, the effectiveness of soil in retaining more water following biochar application is immediate. Thus, in the first growing season, the plant height and stem diameter results were highly influenced by the biochar effect on soil moisture content and a sufficient water supply. The particle size of biochar has probably played a great role in the development of the tomato. In fact, the mixture of size has led to two main effects: better water flow and retention. Thus in treatment where we have a greater quantity of biochar together, the infiltration should be better, leading to better development of crops. Naika et al.(2005) suggested that the top layer of soil should be permeable for optimum tomato development. In the second year, the effect of biochar dominated the effect of water. The effect of biochar on soil and its utility to crops is stated to increase over the years, according to Faye et al. (2021). The long-term effect could be the reason for the unique influence of biochar observed in the second season.

As the plant height and stem diameter, the biomasses (above-ground and root) have been influenced in the first growing season by the amount of applied irrigation. Even though the effect of biochar on soil water-holding capacity started in the first growing season, it can be observed that it became effective almost at the end of the growing season. Hence, in the first growing season, relative to the growth parameters and biomasses, only the amount of water applied water influences tomato development. However, the development of tomatoes was better in the second growing season of production, probably because biochar started to impact those parameters though the improvement of nutrient availability. The late effect of biochar on certain soil properties was confirmed by Blanco-Canqui, (2017), who found that biochar might need more time, greater or equal to two years, to affect some selected soil physical properties. Another explanation for the late effect could be that biochar, in the first application, less than 3 months, tends to immobilise some nutrients and release them later. According to Vaccari et al. (2015), biochar, through its cation exchange site, can retain and release nutrients for crops.

Furthermore, our work has shown that biochar, regardless of the amount, can allow better exploitation of soil by the root (fig. 20), which guarantees greater access to water and nutrients. Our findings contrasted with the result of Busscher et al. (2010), who stated that at rates lower than 44t ha^{-1}, the penetration resistance is not impacted by biochar application. The root development in the soil is directly linked to the decrease in soil bulk density and to the improvement of soil porosity, which allows a better development of soil biota which in turn can contribute to making the soil more porous. Lehmann et al. (2011) have confirmed through a review paper that biochar can effectively increase the soil's microorganism abundance. The combination of a good root system and great above-ground could explain the tomato yield over the two seasons.

II.2.2 Tomato fruit yield

The yield is the best unit of measure when it comes to assessing the performance of any soil amendment. In the first season of our experiment, the results indicated that the biochar amount influenced the yield obtained in our tomato production in combination with the quantity of water irrigation. In fact, in the first season, the effect of biochar in terms of nutrient retention and release was ineffective. As concluded earlier, only soil properties related to water retention were noticed, leading to a combined effect between biochar amount and irrigation water level. Differential results on biochar performance have been noticed under the various water irrigation amounts. B1 (7t.ha^{-1}) performs better under W0 (8L m^{-2} day^{-1}) than under reduced irrigation. Under W1 (6L m^{-2} day^{-1}), the biochar amount of 30kg.ha^{-1}, that is, B2, has shown the best yield (3.9 t.ha^{-1}) compared to the control and B1. In addition, B2 is not significantly different from B0 ($0kg.ha^{-1}$) under W0. The biochar particle size can explain these differences in yield according to its amount.

Indeed, the mixture of different particle sizes will play an important role in water retention and movement. The smaller particles (<2mm) affect the micro and mesoporosity, thus increasing the soil's water retention capacity. At the same time, the greater particles create new pores, probably greater than the soil's macropores, which could regulate the water fluxes. This effect of mixed particle size can serve as a solution to regulate soil hydraulic conductivity reduction that could emanate from the effect of fine particles. Jačka et al. (2018) stated that the fine particle of biochar is an important contributor to reducing soil saturated hydraulic conductivity. Thus, if the applied quantity of biochar with fine particles into the soil is huge, it can lead to a drastic reduction in infiltration rate due to pore size reduction, which can favour the water logging that probably could be harmful to crops. In the second season, biochar has given a greater fruit yield and better fruit quality in terms of fruit size and weight regardless of the amount of water applied compared to the control. Akhtar et al. (2014) found similar results; they obtained greater yield and better quality tomatoes upon the reduced irrigation applied on biochar compared to full irrigation without biochar. These findings might be related to the fact that the effect of biochar on soil, water and nutrients status has increased during the seasons. In addition, the time between the seasons seems enough for biochar to start making nutrients available for crops. The tomato development, average size, weight, and the total number of fruits per treatment parameters, which are all significantly different from the control in the second season, seem to be a great indicator of soil nutrient status. The results have revealed that to enhance the effectiveness of biochar, in short-term utilisation, to meet crop's water and nutrient needs, up to at least 50%, it could be either activated or incubated for at least one year before use. These effects could not be measured directly, and then they were assumed according to previous studies. A similar conclusion has been drawn by Esmaeelnejad et al. (2016). The authors found in their experiment on biochar incubation that its total porosity, but in particular, the mesoporosity, has increased over incubation days with sometimes an evolution of 23.8% between 0 and 180 days.

II.3 Effects of biochar on irrigation water use efficiency

One of this study's important goals was to determine the efficiency of the water use in irrigating tomatoes through the tomato above-ground biomass and yield. The above-ground biomass yield and the fruit yield are closely linked; the first can be used to predict the second one. The results show that the water use efficiency calculated from both above-ground biomass and tomato yield is optimum with biochar amendment. The same results were found by Agbna et al. (2017b), who confirmed that the combination of deficit irrigation-biochar could increase irrigation water use efficiency. However, Aller et al.(2017) did not find an effect of biochar on water use efficiency in sandy loam soil after biochar application. According to Amoakwah et al. (2017), a biochar application rate below 10t ha^{-1} did not show any significant difference in the main driver of water use efficiency, which is water retention in soil, compared to the control in sandy loam soil. Our results suggest that when combined with biochar in the Sahelian zone, like in Senegal, the amount of water to produce tomatoes could be reduced by 50% without compromising the yields. These findings correlate perfectly with the results obtained by Akhtar et al. (2014) but at 70% of full irrigation. During the two years of experimentation, using biochar has allowed us to optimise water use in tomato irrigation significantly. Thus, our results show more interesting futures for reaching sustainable goals regarding saving and managing different water sources through agriculture. Thanks to its increasing capacity to ensure greater held water in the soil, biochar can lead to an optimum production with half reduction of the normal water supply in sandy loam soil.

Chapter V: Conclusion and recommendations

I. Conclusion

The results of this study have shown that biochar is a material that could have a different effect according to its inherent properties, soil type, and the applied water amount in irrigation systems. Different parameters of the soil are affected depending on the amount applied and the duration of biochar in the sandy loam soil. When incorporated into sandy loam soil, the hydrodynamic properties, such as bulk density, porosity, and soil moisture content at field capacity, are affected first and almost immediately after application. Our results showed that the biochar particle is an important driver of most of the effects that biochar could have on different soil types. The effect of biochar on soil fertility status is at least a mean-term effect. This progressive effect of biochar over the years affects the growth and yield parameter of tomatoes, with always a significant difference between the first and the second season. The biochar particle size and applied amount into the soil, its effect on soil water holding capacity, and soil nutrient status are the main drivers of the improvement of the yield of tomatoes under reduced irrigation. Over the seasons, the increased positive effect of biochar on soil allows for optimising the water for irrigation. In fact, in sandy loam soil in Senegal, biochar has allowed a water saving of 50% without compromising the yield. The use of biochar by local farmers could positively impact the operating account of global tomato production.

Nevertheless, generally, it could be used to remediate problem soils for a sustainable long-term duration. Hence, in arid and semi-arid zones, biochar could be of great interest in improving water yield in agriculture. The application of biochar into the soil can be used as an adaptation strategy by farmers to cope with climate change effects in terms of drought adaptation and water economy in irrigation. However, a set of conditions should be met before using biochar as an amendment. The knowledge of the type of soil on which the biochar is to be applied is a prerequisite for optimising the positive effects of the Biochar on soil properties.

II. Recommendation

At the end of this study, which does not claim to be complete, we present these recommendations to optimise the positive effects of biochar on soil water holding capacity and irrigation water use efficiency. To our knowledge, no study points out the effect of biochar and reduced irrigation in farmer's fields under different environmental conditions, and further research is needed.

When using biochar in reduced water availability we recommend the use of $15t.ha^{-1}$ in irrigated tomato and in sandy loam soil. But when the water is available it is preferable to use a greater amount such as $30t.ha^{-1}$ as indicated in our study. In different types of soil, the results would be different. Thus, our recommendation is to explore the possibility of performing the same experiment in various soil conditions and farmers' conditions. Different environments will confirm or improve our findings for using biochar to improve water management. We particularly recommended that this experiment be redone in sandy soils where the issue of the expensive cost of water due to more water application and the high infiltration rate is affecting farmers' incomes. We were not able to assess how long biochar can make water available for tomatoes, hence we recommended a specific study aimed to give a better understanding of that parameter. This duration is important to know for it can be used to manage drought spells in different situations.

In addition, the tomato was the sole crop used in this experiment. Our results cannot be extended to other crops. It will be interesting to have another experiment with different crops.

Biochar should not be used only in irrigation production. In the context of climate change, it is valuable to test the effect of biochar on rainfall conditions to determine its effect on drought spells in arid and semi-arid condition

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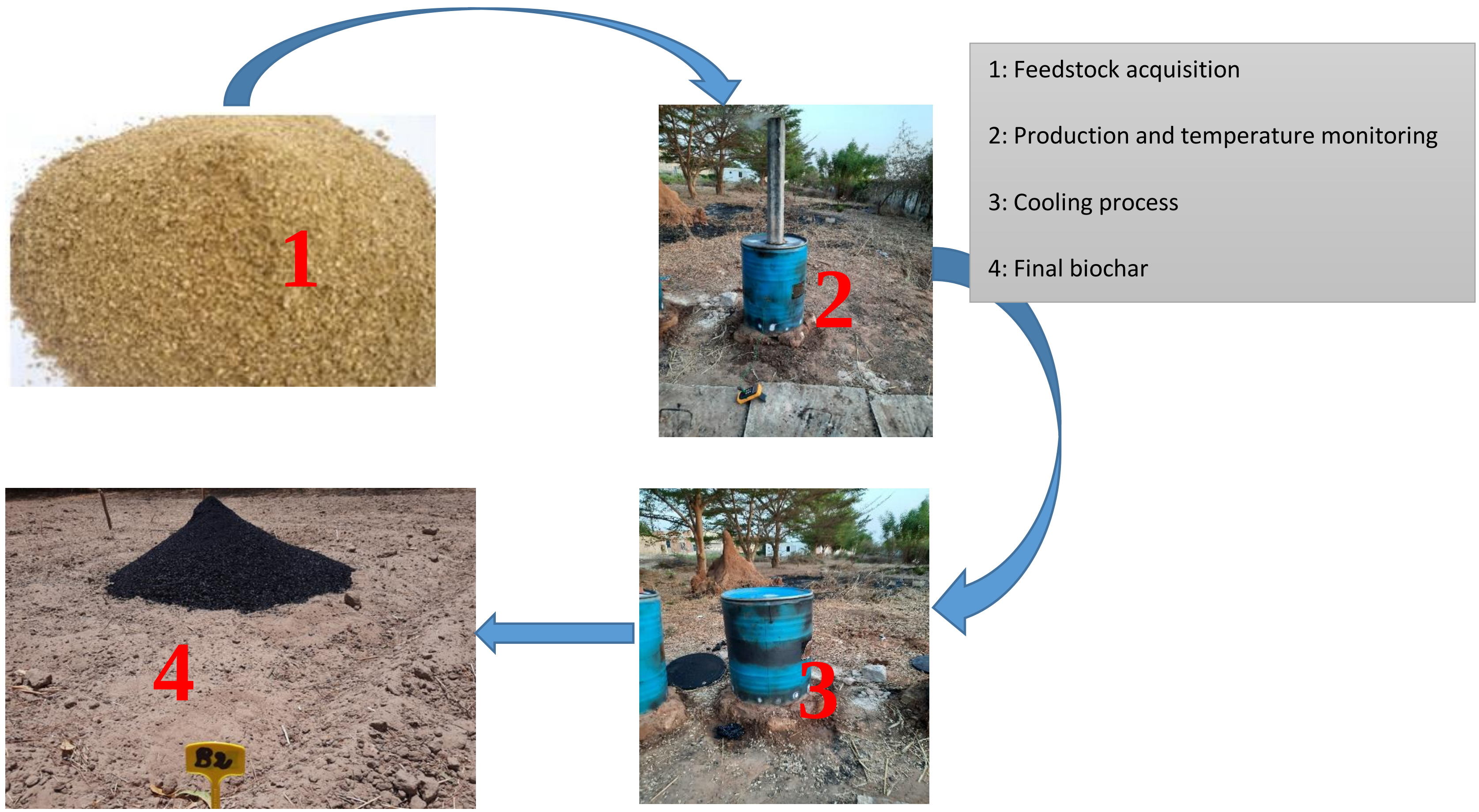
Appendices

Appendices 1: Biochar production process and route



Appendices 2: Technical information of Tomato F1 MONA variety

TECHNISEM

Tomate F1 MONA

Solanum lycopersicum L.

"Nouvelle variété pour les chaleurs humides "

Soucieux de renouveler et diversifier régulièrement notre offre, nous proposons avec F1 MONA une nouvelle solution pour les conditions chaudes et humides. L'excellente capacité de nouaison de cette variété lui permet en effet de nouer là où des variétés classiques subiraient des chutes de fleurs.

PLANTE

- Croissance déterminée
- Très bonne vigueur
- Très bonne nouaison

FRUIT

- Forme ronde épaisse
- Bonne fermeté
- Rouge vif à maturité
- 80 - 90 g
- Jointed
- Collet vert

TOLERANCES

- Résistances FOL 0 et 1 (HR)
- Tolérance au nématodes (IR)

PRECOCITE

- 65 - 70 jours après repiquage

TECHNISEM

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