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The effects of biochar, compost and their mixture and nitrogen fertilizer on yield and nitrogen use efficiency of barley grown on a Nitisol in the highlands of Ethiopia

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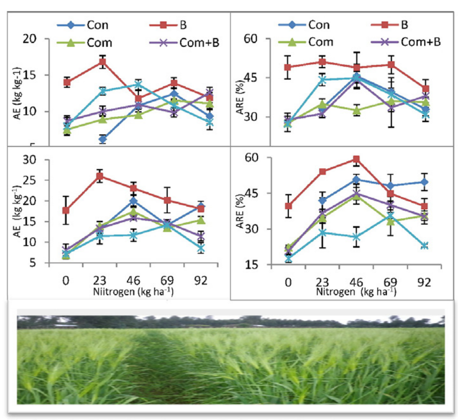
HIGHLIGHTS

- The effects of Com, B and Com + B and N fertilizer on yield and N use efficiency of barley were investigated.
- Com or Com + B with N fertilizer increased grain yield up to 60% compared to the yield with the highest N fertilizer alone.
- Grain and straw N contents were significantly increased by organic amendments and N fertilizer at both sites.
- B or Com + B with moderate rates of N (23–69 kg N ha^{-1}) significantly improved the AE, ARE and PE at both sites.

GRAPHICAL ABSTRACT



Agronomic efficiency (AE) and apparent nitrogen recovery efficiency (ARE) of barley under organic amendments (Con: control, B: biochar, Com: compost, Com + B and COMBI: co-composted biochar) and N fertilization at Holetta (upper half) and Robgebeya (lower half) sites of contrasting soil fertility levels.

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ABSTRACT

The effects of organic amendments and nitrogen (N) fertilizer on yield and N use efficiency of barley were investigated on a Nitisol of the central Ethiopian highlands in 2014. The treatments were factorial combinations of no organic amendment, biochar (B), compost (Com), Com + B and co-composted biochar (COMBI) as main plots and five N fertilizer levels as sub-plots, with three replicates. Application of organic amendment and N fertilizer significantly improved yield, with grain yield increases of 60% from Com + B + 69 kg N ha^{-1} at Holetta and 54% from Com + 92 kg N ha^{-1} at Robgebeya, compared to the yield from the maximum N rate. The highest total N uptake was obtained from Com + B + 92 kg N ha^{-1} at Holetta (138 kg ha^{-1}) and Com + 92 kg N ha^{-1} at Robgebeya (101 kg ha^{-1}). The agronomic efficiency (yield increase per unit of N applied, AE), apparent recovery efficiency (increase in N uptake per unit of N applied, ARE) and physiological efficiency (yield increase per unit of N uptake, PE) responded significantly to organic amendments and N fertilizer. Mean AE and ARE were highest at B + 23 kg N ha^{-1} at Holetta and at B + 23 and B + 46 kg N ha^{-1} at Robgebeya. The PE ranged from 19 to 33 kg grain kg^{-1} N uptake at Holetta and 29–48 kg grain kg^{-1} N uptake at Robgebeya. The effects of organic amendments and N fertilizer on AE, ARE and PE were greater at Robgebeya than at Holetta. The enhancement of N use efficiency through application of organic amendments emphasizes the importance of balanced crop

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nutrition, ensuring that barley crops are adequately supplied with N and other nutrients. Overall, the integration of both organic and inorganic amendments may optimize N uptake efficiency and reduce the amount of N fertilizer required for the sustainable barley production in the long-term.

1. Introduction

Soil nutrient depletion and low nutrient use efficiency are major constraints for the productivity of crops in Sub-Saharan Africa. Barley (*Hordeum vulgare* L.) is one of the world's main cereals, ranking fourth in production after wheat, maize and rice (FAO, 2013). It is the fifth most important cereal crop in Ethiopia after tef (*Eragrostis tef*), maize, sorghum and wheat in production area and tonnage (CSA, 2013). Barley is grown predominantly under rain-fed conditions by subsistence farmers in the highlands of the country (2000 to 3500 m asl), in areas receiving mean annual rainfall > 1000 mm (Agegnehu et al., 2014). The crop covers ~1.018 million ha but the national average yield is very low at 1.75 t ha^{-1} (CSA, 2013) compared to the global average yield of 2.6 t ha^{-1} (Ullrich, 2011) due to poor soil fertility, particularly N and P, and low N use efficiency (Agegnehu et al., 2011). Depletion of soil nutrients by cropping is a major problem in the country; Haileslassie et al. (2005) reported a depletion rate of 122 kg N ha^{-1} yr^{-1}, 13 kg P ha^{-1} yr^{-1} and 82 kg K ha^{-1} yr^{-1} at the national level. Although barley grows across a wide range of soil conditions (Agegnehu et al., 2011), highly weathered reddish brown clay soils (Nitisols) are the most important soils for production in Ethiopia (Bekele and Höfner, 1993).

Although there is a considerable potential for increased barley production, productivity is constrained by low soil pH, nutrient deficiencies and low levels of fertilizer application (Agegnehu et al., 2011). Soil acidity adversely affects morphological, physiological and biochemical processes in plants and thus N uptake and use efficiency (Fageria and Baligar, 2005; Marschner, 2011). Inefficient use of fertilizer contributes to the depletion of scarce financial resources, increased unit production costs and potential environmental risks. Hence, optimizing the efficiency of N fertilizer use must be a major consideration for subsistence producers. Cereal-dominated cropping systems, aimed at meeting farmers' subsistence requirements, coupled with low usage of fertilizer, have led to wide spread depletion of soil nutrients in the major barley growing regions of the country (Agegnehu et al., 2014). Only 48.3% of the total area of land covered by barley receives fertilizer, which is the lowest among all the cereals grown in Ethiopia (Mulatu and Lakew, 2011). Heavy rains during the main cropping season (June to August) also cause substantial soil nutrient losses due to intense leaching and erosion on Nitisols (Tarekegne et al., 1997). Several studies have demonstrated considerable potential for increasing barley yields by applying organic and inorganic fertilizers and improved crop management practices (Agegnehu et al., 2014; Hejcman et al., 2013; Tarekegne et al., 1997) and these practices may also be beneficial for nutrient use efficiency.

Use of nitrogen fertilizer in low-input subsistence farming may improve yields and quality, and lower risk of crop failure, but response to fertilizer may be limited by low inherent physical, biological and chemical fertility of soil. Nitrogen use efficiency in crop plants is defined in several ways (Baligar et al., 2001; Dawson et al., 2008; Fageria and Baligar, 2005). In simple terms, N use efficiency is the ratio of output (economic yield) to input (fertilizers) for a process or system (Dawson et al., 2008; Fageria, 2008). Fertilizer N use efficiency is governed by three major factors, which include N uptake by the crop, N supply from soil and fertilizer, and N losses from soil–plant systems. The crop N requirement is the most important factor influencing N use efficiency (Ladha et al., 2005). Nitrogen use efficiency in cereal grain production is low for a variety of reasons (Raun and Johnson, 1999; Raun et al., 2002). Nitrogen use efficiency of cereals is estimated to be 42% and 29% in developed and under-developed nations, respectively (Raun and Johnson, 1999). Worldwide, N use efficiency of cereals is about 33%, and the 67% not accounted for represents a $15.9 billion annual loss in N fertilizer costs (Raun and Johnson, 1999). Fan et al. (2004) also reported that the average N fertilizer recovery in cereals in China was 30–35%. Thus, improving N use efficiency through a combination of agronomic and soil management methods is of paramount importance in terms of profitability and environmental management. In cereals, nutrient use efficiency has been expressed relative to either to the total nutrient supply in the soil and fertilizer (Giambalvo et al., 2004) or to the applied fertilizer nutrient alone (Baligar et al., 2001; Fageria, 2008). Given the difficulty of precise measurements of available soil nutrients and the economic importance of fertilizer nutrients, the latter approach is preferred (Sinebo et al., 2004; Xu et al., 2012). The components of fertilizer N use efficiency are agronomic efficiency, apparent recovery efficiency and physiological efficiency (Baligar et al., 2001; Fageria, 2008; Xu et al., 2012). Various authors have reported that apparent N recovery efficiency is a suitable indicator to evaluate the efficiency of fertilizer management practices (Baligar et al., 2001; Shejbalová et al., 2014; Tarekegne and Tanner, 2001).

The rate of N fertilizer application depends on the purpose for which barley is grown. It is desirable to apply N fertilizer at a higher rate for feed or food barley than for malting barley, as protein is more important in food barley than in malting barley and barley with high protein content is difficult to malt (Agegnehu et al., 2014; Jankovic and Ikanovic, 2011). In Ethiopia, where pH, organic carbon and N content of most soils are low, the N fertilizer rates for barley production typically range between 23 and 46 kg N ha^{-1} (Agegnehu et al., 2014). Soils with low organic carbon contents have low crop yield and low use efficiency of added nutrients. Fertilizer N efficiency is influenced by the long-term dynamics of organic matter of a soil (Bruulsema et al., 2004). Soil organic matter is vital for sustainable yields as it is able to retain water and nutrients as well as providing habitat and energy for soil biota and improving soil aggregation (Alburquerque et al., 2013; Courtney and Mullen, 2008; Lal, 2009). Fertilizer application in Ethiopia has been limited to date, and improvement of agricultural productivity necessitates more than the application of inorganic fertilizers alone.

Previous studies indicated that the application of biochar and N fertilizer on a light soil within temperate climate increased yield of spring barley by 30% compared to N fertilizer only (Gathorne-Hardy et al., 2009) and maize biomass by 2.7–3.5 times relative to NPK fertilizer alone on different soil types and agro-climatic conditions in China (Zhu et al., 2015). This indicates that an integrated soil fertility management approach may have more sustainable agronomic and economic impact than a focus on inorganic fertilizer alone. No previous studies have been conducted to assess the effects of biochar, compost, biochar-compost and their interactions with N fertilizer on yield, N uptake and nitrogen use efficiency of barley in the Ethiopian highlands. The objectives of this study were to determine the effects of organic amendments, N fertilizer and their interaction on: 1) plant N concentration and uptake; and 2) nitrogen use efficiency of barley under rain-fed conditions on weathered Nitisols.

2. Materials and methods

2.1. Characteristics of experimental sites

The experiment was conducted in the main cropping season of 2014 at Holetta Agricultural Research Center (9°3′ 19.43″ N, 38° 30′ 25.43″ E, at 2400 m asl) and on a farmer's field at Robgebeya in the central