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**Combined effects of biochar and plant growth-promoting bacteria
(PGPR) on the mitigation of drought stress in barley (*Hordeum
vulgare* L.)**

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ABSTRACT

Barley (*Hordeum vulgare* L.) is a strategic cereal crop in Algeria, but its productivity is increasingly threatened by drought in semi-arid environments. This thesis evaluated whether native Saharan plant growth-promoting rhizobacteria (PGPR) consortia and biochar could improve barley tolerance to severe water deficit. A greenhouse pot experiment was conducted on the barley variety Fouara using a randomized complete block design with four blocks and a factorial combination of PGPR treatments (T0, T2, T7, T11), biochar application (B0/B1), and two water regimes (non-stressed and 80% soil drying). Physiological, biochemical, morphological, edaphic, agronomic, and multivariate parameters were assessed. The results showed that drought strongly reduced relative water content (−7.12%), chlorophyll content (−16.56%), plant growth, biomass accumulation, grain number (−68.10%), grain yield (−65.96%), and harvest index (−19.16%), while increasing electrolyte leakage (+58.33%) and stress-related metabolites such as proline (+56.18%) and soluble sugars (+28.79%). PGPR inoculation, especially T7 and T11, mitigated these adverse effects by improving plant hydration (+37.88%), preserving chlorophyll (up to 10.33 mg/g FW), enhancing nutrient status (soil N: +300.0%; assimilable P: +2533.9%), and maintaining reproductive performance (+65.00%). Biochar improved soil water retention and nutrient buffering and strengthened the beneficial effect of the bacterial consortia. The combined biochar–PGPR treatments, particularly T11 and T7, produced the best overall performance and were clearly separated from the stressed controls in the PCA and hierarchical clustering analyses. These findings demonstrate that native Saharan PGPR and biochar can act as effective biostimulants for improving barley resilience and productivity under drought-prone conditions.

Keywords: barley, drought stress, PGPR, biochar, biostimulants, sustainable agriculture.

RÉSUMÉ

L'orge (*Hordeum vulgare* L.) constitue une culture stratégique en Algérie, mais sa productivité est de plus en plus menacée par les épisodes de sécheresse dans les zones semi-arides. Cette thèse a évalué la capacité de consortiums de rhizobactéries promotrices de croissance (PGPR) d'origine saharienne associés à du biochar à améliorer la tolérance de l'orge à un déficit hydrique sévère. L'expérimentation a été réalisée en pots sous serre sur la variété Fouara selon un dispositif en blocs aléatoires complets randomisés comportant quatre blocs et un plan factoriel intégrant les traitements bactériens (T0, T2, T7, T11), l'amendement en biochar (B0/B1) et deux régimes hydriques (non stressé et 80 % de tarissement du sol). Les paramètres physiologiques, biochimiques, morphologiques, édaphiques, agronomiques et multivariés ont été analysés. Les résultats ont montré que la sécheresse a fortement réduit la teneur relative en eau (-7,12 %), les pigments chlorophylliens (-16,56 %), la croissance végétative, l'accumulation de biomasse, le nombre de grains (-68,10 %), le rendement en grains (-65,96 %) et l'indice de récolte (-19,16 %), tout en augmentant la fuite d'électrolytes (+58,33 %) ainsi que les métabolites de stress tels que la proline (+56,18 %) et les sucres solubles (+28,79 %). L'inoculation par PGPR, en particulier T7 et T11, a atténué ces effets négatifs en améliorant l'hydratation des plants (+37,88 %), en préservant la chlorophylle (jusqu'à 10,33 mg/g FW), en renforçant l'état nutritionnel (N du sol : +300,0 % ; P assimilable : +2533,9 %) et en maintenant les performances reproductives (+65,00 %). Le biochar a amélioré la rétention d'eau et le tamponnement nutritif du substrat, tout en renforçant l'effet bénéfique des souches bactériennes. Les traitements combinant biochar et PGPR, notamment T11 et T7, ont donné les meilleurs résultats globaux et se sont nettement distingués des témoins stressés dans l'analyse en composantes principales et la classification hiérarchique ascendante. Ces résultats démontrent que les PGPR sahariennes et le biochar peuvent constituer des biostimulants efficaces pour améliorer la résilience et la productivité de l'orge en conditions de sécheresse.

Mots clés : Orge, stress hydrique, PGPR, biochar, biostimulants, agriculture durable.

ملخص

يُعدّ الشعير (*Hordeum vulgare L.*) من المحاصيل الاستراتيجية في الجزائر، غير أنّ إنتاجيته أصبحت مهددة بشكل متزايد بفعل موجات الجفاف في المناطق شبه الجافة. هدفت هذه الأطروحة إلى تقييم قدرة تجمعات (Consortia) من البكتيريا الجذرية المحفزة للنمو النباتي (PGPR) ذات الأصل الصحراوي، مع إضافة البيوشار، على تحسين تحمل الشعير للإجهاد المائي الشديد. وقد أجريت التجربة في أوعية داخل الدفيئة على صنف Fouara وفق تصميم عشوائي كامل في أربعة مكررات، وبنظام عاملي يجمع بين المعاملات البكتيرية ((T0, T2, T7, T11)، وإضافة البيوشار (B0/B1)، ونظامين مائيين (غير مجهد و80% جفاف التربة). وتمت دراسة مجموعة من الصفات الفسيولوجية والكيميائية الحيوية والمورفولوجية والتربوية والزراعية، إضافة إلى التحليل متعدد المتغيرات. أظهرت النتائج أنّ الجفاف خفّض بشكل واضح المحتوى النسبي للماء (7,12%-)، ومحتوى الكلوروفيل (16,56%-)، والنمو الخضري، وتراكم الكتلة الحيوية، وعدد الحبوب في السنبل (68,10%-)، والمحصول الحبيبي (65,96%-)، ودليل الحصاد (19,16%-)، مع ارتفاع تسرب الإلكتروليتات (58,33%+) وتراكم المركبات المرتبطة بالإجهاد مثل البرولين (56,18%+) والسكريات الذائبة (28,79%+). وقد ساهم تلقيح النباتات بـ PGPR، خاصة المعالجات T7 و T11، في التخفيف من هذه التأثيرات السلبية من خلال تحسين حالة الماء في النبات (37,88%+)، والحفاظ على الكلوروفيل (حتى 10.33 mg/g FW)، وتعزيز الحالة الغذائية (N التربة: 300,0%+؛ P القابل للاستخلاص: 2533,9%+)، والحفاظ على الأداء التكاثري (65,00%+). كما ساعد البيوشار على تحسين احتباس الماء والتخزين الغذائي في التربة، وعزّز التأثير الإيجابي للسلاسل البكتيرية. وأعطت المعاملات المزدوجة التي جمعت بين البيوشار و PGPR، خصوصاً T7 و T11، أفضل النتائج الكلية، وظهرت بوضوح منفصلة عن الشواهد المجردة في تحليل المكونات الرئيسية والتحليل العنقودي الهرمي. وتؤكد هذه النتائج أن PGPR الصحراوية والبيوشار يمكن أن يشكلوا منشطات حيوية فعالة لتحسين صمود وإنتاجية الشعير تحت ظروف الجفاف.

الكلمات المفتاحية: الشعير، الإجهاد المائي، PGPR، البيوشار، المنشطات الحيوية، الزراعة المستدامة.

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