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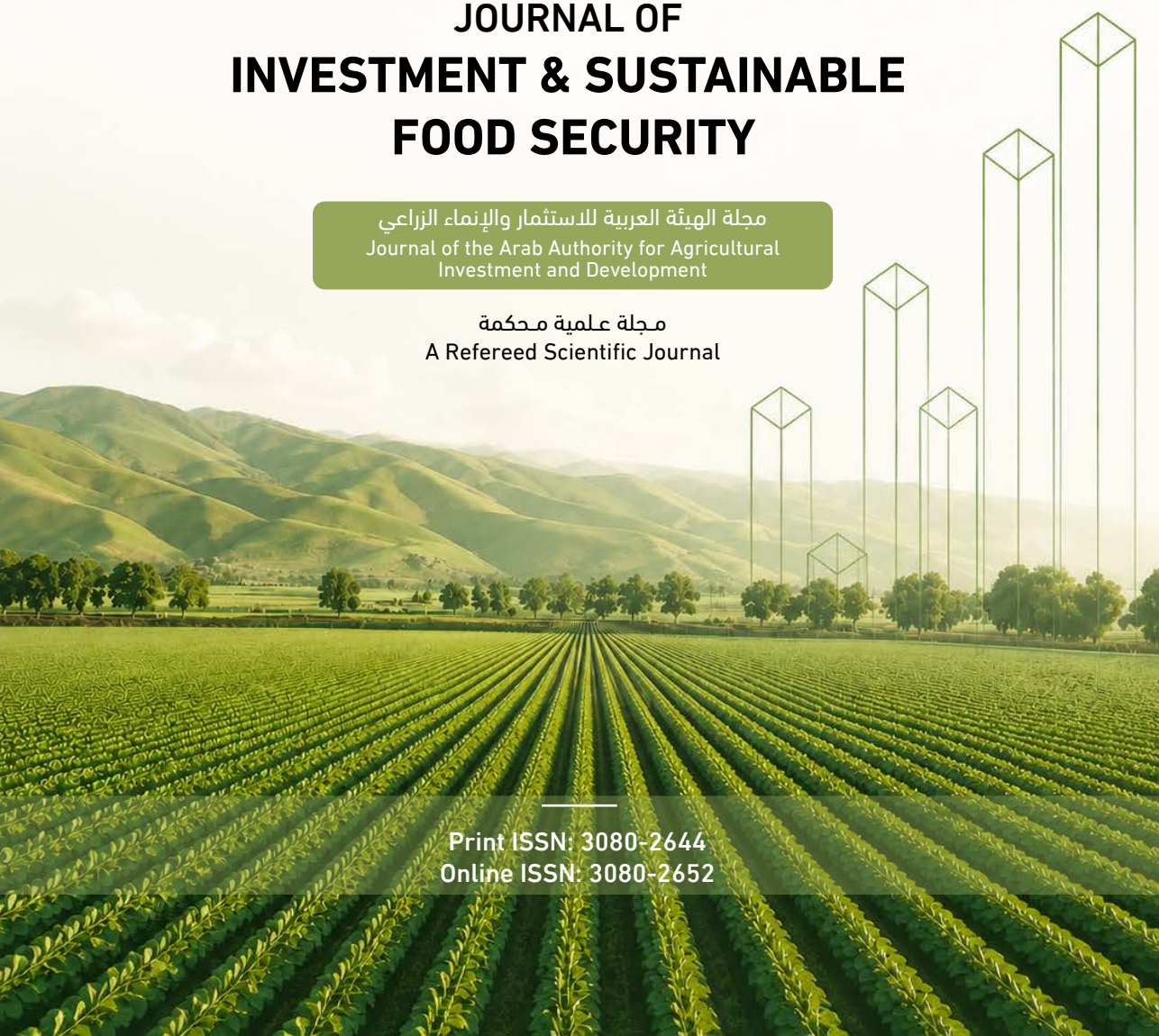
مجلة

الاستثمار والأمن الغذائي المستدام

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الهيئة العربية للاستثمار والإنماء الزراعي في سطور

الهيئة العربية للاستثمار والإنماء الزراعي هيئة مالية عربية مستقلة تأسست بموجب اتفاقية بين الدول العربية في العام 1976، تهدف إلى المساهمة في تحقيق الأمن الغذائي وتعظيم العائد على الاستثمار وتوفير خدمات مساندة مبتكرة وفق أفضل المعايير الدولية وتعزيز التعاون الإقليمي والدولي. تسهم الهيئة في رأس مال 41 شركة ومشروعاً، وتنتشر شركاتها في 12 دولة عربية، وتمتلك الهيئة العربية للاستثمار والإنماء الزراعي خبرات واسعة في مجال الاستثمار والتصنيع الزراعي. وتقوم الهيئة بتمويل الشركات على أسس ومعايير استثمارية احترافية، بهدف تحقيق الربحية العالية للمساهمين، وتحقيق التنمية الاقتصادية والاجتماعية للمجتمعات العربية. تتوزع استثمارات الهيئة على أربعة قطاعات رئيسية هي التصنيع الزراعي والإنتاج الحيواني والإنتاج النباتي والخدمات الزراعية. كما تدعم خطط التنمية الزراعية المستدامة والأمن الغذائي في الدول العربية بهدف تقليل الفجوة الغذائية وتحسين حياة السكان في المجتمعات التي تحتضن شركاتها ومشاريعها، وتقوم الهيئة أيضاً بدعم شرائح صغار المزارعين، ونقل التقانات الزراعية لهم وإتاحة برامج تمويلية مبتكرة بالشراكة مع المنظمات والصناديق الائتمانية والاستثمارية العالمية والإقليمية والكثير من الأنشطة التنموية ونشر نتائج الأبحاث العلمية لتعميم المعرفة لصالح تنمية المجتمعات.

حقوق النشر

جميع حقوق النشر محفوظة © **للهيئة العربية للاستثمار والإنماء الزراعي.**

لا يجوز إعادة نشر أو نسخ أو ترجمة أو تخزين أو توزيع أي جزء من هذه المجلة بأي وسيلة كانت، إلكترونية أو مطبوعة أو رقمية، دون الحصول على موافقة كتابية مسبقة من الهيئة العربية للاستثمار والإنماء الزراعي، باستثناء ما تسمح به سياسات النشر والاستخدام الخاصة بالمجلة.

الآراء والأفكار الواردة في البحوث المنشورة تعبّر عن وجهة نظر مؤلفيها، ولا تعكس بالضرورة رأي الهيئة العربية للاستثمار والإنماء الزراعي أو هيئة التحرير.

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عن المجلة

تصدر هذه المجلة مرة واحدة سنوياً عن الهيئة العربية للاستثمار والإنماء الزراعي، بالتعاون العلمي مع عدد من الجامعات المرموقة في الوطن العربي. وتلتزم المجلة بشكل كامل بمبادرة الوصول المفتوح، حيث يتم توفير وصول فوريٍّ وسهلٍ لجميع البحوث بمجرد نشرها. المجلة ملتزمةً بتطوير المعرفة والممارسة في مجالات الاستثمار الزراعي والأمن الغذائي بتوفير منصة للباحثين والمهنيين وصانعي السياسات والمستثمرين لمشاركة البحوث والحلول المبتكرة التي تدعم الزراعة المستدامة ونظم الأغذية المرنة، لا سيما في العالم العربي. ومن خلال تعزيز الحوار متعدد التخصصات ونشر رؤى قائمة على الأدلة، تهدف المجلة إلى المساهمة في تطوير نظم غذائية زراعية شاملة وفعالة ومستدامة، وتنشر مخطوطات ومراجعات كتب وملخصات رسائل جامعية باللغتين العربية والإنجليزية.

هيئة التحرير:

الدكتور عبيد سيف حمد الزعابي - رئيس الهيئة العربية للاستثمار والإنماء الزراعي/ رئيس مجلس الإدارة - المشرف العام على المجلة

أعضاء هيئة تحرير المجلة

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.3	الأستاذ الدكتور محمد اليافعي	رئيس هيئة التحرير المشارك - جامعة الإمارات العربية المتحدة
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.6	الأستاذ الدكتور نايف الشمري	عضو - جامعة الكويت
.7	الأستاذ الدكتور محمد يونس العلاف	عضو - جامعة الموصل
.8	الأستاذ الدكتور عصام محمد السباعي	عضو - جامعة كفر الشيخ
.9	الأستاذ الدكتور فرج علي صالح	عضر - مركز البحوث الزراعية - مصر
.10	الأستاذ الدكتور سيف القايدي	عضو - جامعة الإمارات العربية المتحدة
.11	الأستاذة الدكتورة بيان عبدالجبار السعدي	عضو - جامعة بغداد
.12	الأستاذ الدكتور خالد بن نهار الرويس	عضو - جامعة الملك سعود - المملكة العربية السعودية
.13	الأستاذ الدكتور خالد المصمودي	عضو - جامعة الإمارات العربية المتحدة
.14	الأستاذ الدكتور مالك نصر مالك	عضو - جامعة الخرطوم - جمهورية السودان
.15	الأستاذ الدكتور المهدي بن ميمون	عضو - أستاذ بالمعهد الوطني للعلوم الزراعية بتونس
.16	الدكتور عمر عبد القادر	عضو - الهيئة العربية للاستثمار والانماء الزراعي

الأهداف والنطاق:

1. تشجيع الباحثين على التركيز في أبحاثهم على الأساليب الحديثة في الاستثمار والتمويل الزراعي والغذائي.
2. تشجيع الباحثين في التركيز في أبحاثهم على معالجة المشاكل البيئية، وتلك التي تركز على الزراعة المستدامة والبيئة.
3. تحسين جودة المنتجات الزراعية من خلال نتائج الأبحاث المقبولة للنشر في المجلة.
4. تشجيع استخدام التقنيات والأساليب الحديثة المتطورة في الزراعة والصناعة الغذائية من خلال نتائج الأبحاث المقبولة للنشر في المجلة.
5. تشجيع الباحثين على التركيز في أبحاثهم على التقنيات الحديثة في تصنيع المنتجات الزراعية بما يساهم في تحقيق التكامل الاقتصادي المستدام.

مجالات المجلة

تركز المجلة بشكل أساسي على نشر الأبحاث في المجالات الآتية:

- الإنتاجية الزراعية ودورها في دعم التنمية المستدامة
- الاقتصاد الزراعي والاستخدام الأمثل للموارد الاقتصادية
- الابتكار والتقانات الحديثة في القطاع الزراعي
- الأمن الغذائي المستدام
- الاستثمار والتمويل الزراعي والتنمية الاقتصادية
- الاستثمار في المحافظ الاستثمارية
- الاستثمار في التصنيع الغذائي والتبادل التجاري
- الاستثمار والتمويل في انتاج السلع الغذائية الأساسية

شروط النشر:

1. تنشر المجلة البحوث العلمية الأصيلة والتي تشكل إضافة جديدة في التخصص في مجال الزراعة والاقتصاد والاستثمار الزراعي. ويمكن أن يكون البحث مكتوبا باللغة العربية أو الإنجليزية.
2. لا يكون البحث قد سبق نشره أو مقدماً للنشر في مجلة أخرى ويتعهد الباحث بذلك وبعدم تقديمه للنشر إلى جهة أخرى حتى يتم اتخاذ القرار المناسب في هذا الشأن.
3. يمكن أن يكون البحث مستلّاً من رسالة ماجستير أو رسالة دكتوراه، شريطة أن تكون الرسالة من إعداد الباحث نفسه.
4. ألا يكون البحث جزءاً من كتاب منشور.
5. لا يجوز نشر البحث أو أجزاء منه في مكان آخر بعد إقرار نشره في مجلة الاستثمار والأمن الغذائي المستدام إلا بعد الحصول على إذن كتابي بذلك من رئيس التحرير.

6. موافقة المؤلف على نقل حقوق النشر كافة إلى المجلة، وإذا رغبت المجلة في إعادة نشر البحث فإن عليها أن تحصل على موافقة مكتوبة من صاحبه.
7. في حال تضمن البحث أي إشارة لها علاقة بشكل أو بآخر بخلافات سياسية أو نزاعات عرقية أو دينية أو تعصب بجميع أشكاله، فإنه سيتم رفض البحث من قبل هيئة التحرير .
8. القيام بتعبئة نموذج الإقرار والتعهد وإرفاقه مع ملفات الطلب
9. يجب على المؤلفين الإفصاح عن مصادر التمويل والإفصاح عن أي تضارب في المصالح المالية أو غيرها.

إرشادات إلى الباحثين:

1. يجب على المؤلفين الامتثال لتعليمات التقديم التي تحددها المجلة التي تلتزم بتنسيق أسلوب APA وحسب الترتيب الأبجدي أن يكونوا ملتزمين بالسلوك البحثي المسؤول ومعايير النشر الأخلاقية.
2. يجب أن يكون البحث أصيلاً وغير منشور سابقًا، ولا يجري النظر في نشرها في أي مكان آخر.
3. يرجى التأكد من أن بحثك يتضمن ملخصاً بعدد كلمات بين 250-300 كلمة، وكلمات مفتاحية ذات صلة، مع الالتزام بالعدد المحدد وهو من 4-6 كلمات.
4. يجب ألا يزيد عدد كلمات البحث عن 9000 كلمة، ولا يقل عن 4000 كلمة.
5. التنويع في المراجع على أن لاتقل عن (30) مرجع. يجب أن تتم الإشارة الى المراجع في داخل البحث كما يلي:

   <u>حالة المؤلف الواحد</u>

   مثال (1): "هذه وجهة نظر الشمري(2024)"

   مثال (2): "هناك تفسير آخر وهو أن حجم التداول يتأثر بمستويات أداء الشركات أكثر من أي عامل آخر)الشمري ،2024)"

   <u>حالة مؤلفين إثنين:</u>

   مثال(1): "هذه وجهة نظر الشمري والتميمي(2024)"

   مثال(2): "هناك تفسير آخر وهو أن حجم التداول يتأثر بمستويات أداء الشركات أكثر من أي عامل آخر (الشمري والتميمي،2024)".

   <u>حالة ثلاثة مؤلفين أو أكثر:</u>

   مثال(1): "هذه وجهة نظر الشمري واخرين(2024)"

   مثال(2):"هناك تفسير آخر وهو أن حجم التداول يتأثر بمستويات أداء الشركات أكثر من أي عامل آخر .(الشمري وآخرين،2024)."
6. أن يحتوي البحث على: عنوان البحث باللغة العربية والإنجليزية وملخص باللغتين العربية والإنجليزية في صفحة واحدة بحدود (250-300) كلمة لكل ملخص، وأن يتضمن البحث كلمات دالة على التخصص الدقيق للبحث باللغة العربية والإنجليزية وسيرة ذاتية مختصرة للباحث أو الباحثين.
7. يذكر اسم المؤلف وعنوانه الحالي ووظيفته بعد عنوان البحث مباشرة باللغتين العربية والإنجليزية

8. إن سياسة المجلة تستوجب (بقدر الإمكان) أن يكون البحث تطبيقيا متضمنا مقدمة عامة يوضح فيها مبررات الدراسة، مشكلة الدراسة وأهميها والفجوة البحثية ثم الإطار النظري بما في ذلك الدراسات السابقة وأسئلة الدراسة وفرضياتها، ثم منهجية البحث وتحليل نتائج البحث ومناقشة النتائج والاستنتاجات والتوصيات.
9. يجب على المؤلفين تجنب جميع أنواع السلوك غير الأخلاقي مثل الانتحال والتلفيق والتزوير، علما بأن نسبة الاقتباس (التشابه) المسوح بها يجب ألا تزيد عن 15% بما في ذلك استخدام الذكاء الاصطناعي كمصدر للمعلومات. وفي حال ارتفاع النسبة لغاية 40% يطلب من الباحث المراجعة وتخفيض النسبة إلى المستوى المقبول مع إرفاق تقرير Turnitin الذي يوضّح عدم وجود انتحال، ويشير إلى نسبة تشابه لا تتجاوز 15%، وفي حال زيادة النسبة على 40% يتم يرفض البحث.
10. يجب على المؤلفين تقديم أعمال أصلية، ويجب أن يستشهدوا بعمل الآخرين بشكل صحيح،
11. يطلب من المؤلفين تأكيد حصولهم على إذن كتابي من جميع مؤلفيهم المشاركين الذين ساهموا بشكل كبير في العمل.
12. يعتبر تقديم نفس البحث إلى أكثر من مجلة سلوك نشر غير أخلاقي.
13. يستند بيان أخلاقيات النشر وسوء الممارسة الخاص بمجلة الاستثمار والأمن الغذائي المستدام على مدونة قواعد السلوك والمبادئ التوجيهية لأفضل الممارسات التي تهمّ محرري المجلاّت العلمية، والتي أصدرتها لجنة أخلاقيات النشر (COPE) سنة 2011. (يمكن الاطلاع على مزيد من التفاصيل على الرابط: https://publicationethics.org.
14. وبمجرد قبول العمل للنشر يتعين عليهم نقل حقوق النشر إلى الناشر (الهيئة). إذا كانت المجلة ترغب في إعادة طبع البحث، فيجب الحصول على إذن مسبق من المؤلفين.
15. تقدم البحوث مطبوعة بخط (Times New Roman) حجم (14) للنصوص في المتن، ويكتب البحث على وجه واحد، مع ترك مسافة 1.5 بين السطور.
16. إذا اكتشف المؤلف خطأً خطيراً في عمله المنشور، فمن مسؤوليته إخطار رئيس هيئة التحرير بسحب الخطأ أو تصحيحه.
17. إذا طلب المؤلف سحب البحث وهو لا يزال قيد التحكيم، يتعين عليه دفع غرامة تساوي قيمة المكافأة المدفوعة للمحكمين، وإذا رفض الباحث دفع الغرامة يحرم من النشر في المجلة لمدة ثلاث سنوات. في حال قبول البحث للنشر، وطلب الباحث سحبه من المجلة فإنه يطلب من الباحث دفع غرامة تساوي قيمة المكافأة المدفوعة للمحكمين.
18. تدرج الرسوم البيانية والأشكال التوضيحية في النص، وتكون الرسوم والأشكال باللونين الأبيض والأسود، وترقم ترقيماً متسلسلاً، وتكتب أسماؤها والملاحظات التوضيحية أسفلها.
19. تدرج الجداول في النص، وترقم ترقيماً متسلسلاً، وتكتب أسماؤها أعلاها. أما الملاحظات التوضيحية، فتكتب أسفل الجدول.
20. جميع حقوق الطبع محفوظة، ولا يسمح بإعادة طبع أي جزء من المجلة أو نسخة بأي شكل وبأي وسيلة كانت إلكترونية أو آلية بما في ذلك التصوير والتسجيل والإدخال في أي نظام لحفظ المعلومات أو استعادتها دون الحصول على موافقة كتابية من رئيس. هيئة التحرير.

آلية تحكيم البحوث:

1. تخضع كل مخطوطة لعملية تحكيم سرية وصارمة من قبل خبراء في مجال التخصص؛ مما يضمن جودة ورصانة البحث.
2. يتم تقييم البحوث المقدمة في بداية الأمر من قبل هيئة التحرير لتقرير ما إذا كان البحث مستوفيا الشروط الأساسية للنشر وهل أنه مؤهل للإرسال للتحكيم. وقد يرفض البحث في هذه المرحلة لأسباب من بينها عدم إرتباط الموضوع بنطاق المجلة أو بسبب الجودة المنخفضة. ويحق لهيئة التحرير رفض أي بحث دون الكشف عن الأسباب.
3. يتم إرسال البحوث التي تعتبر مؤهلة للتحكيم إلى اثنين من المحكمين على الأقل ويمكن أن يوصي المحكم بإمكانية ألنشر مع تغييرات طفيفة أو إمكانية النشر مع تغييرات جذرية أو رفض البحث (غير قابل للنشر).
4. يتم إرسال تقارير المحكمين إلى المؤلف (المؤلفين) للتعليق عليها.
5. يتحمل المؤلفون وحدهم المسؤولية عن المحتويات وليست هيئة التحرير أو المجلة.
6. ترسل خطابات اعتذار للمؤلفين الذين لم تقبل بحوثهم للنشر.
7. تتم عملية التحكيم البحوث في غضون ثلاث أشهر.

محتويات العدد

الأبحاث باللغة العربية

تحليل التباين الوراثي لصفة الغلة البذرية ومكوناتها لطرز وراثية من الفول (Vicia faba L) في ظروف الزراعة المطرية بمحطة بحوث إزرع – أكساد 15-1
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تحليل التباين الوراثي لصفة الغلة البذرية ومكوناتها لطرز وراثية من الفول في ظروف الزراعة المطرية بمحطة بحوث إزرع – أكساد(*Vicia faba* L.)

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الملخص:

نُفِّذت تجربة البحث في محطة بحوث إزرع التابعة للمركز العربي لدراسات المناطق الجافة والأراضي القاحلة (أكساد) في الموسم الزراعي 2024، بهدف تقدير المعايير الوراثية لصفة الغلة البذرية ومكوناتها في 28 طرازاً وراثياً من الفول، إضافة إلى الشاهد المحلي (الصنف البلدي)، استُعمل تصميم القطاعات كاملة العشوائية بثلاثة مكررات. تبيّن من النتائج وجود فروق معنوية بين الطرز المدروسة والشواهد في جميع الصفات المدروسة: عدد العناقيد الثمرية/نبات، عدد القرون/نبات، عدد البذور/قرن، عدد البذور/نبات، وزن 100 بذرة، والغلة البذرية، وقد تفوق على الشاهد 3 طرز في صفة عدد العناقيد الثمرية/نبات، و 12طرازاً في صفة عدد القرون/نبات، و18 طرازاً في صفة عدد البذور/نبات، في حين أظهر 5 طرز فروقاً معنويةً مقارنة بغلة الشاهد البذرية على مستوى دلالة إحصائية 5%، وهي: WI11-18-3xEthiopia bulk-54 وEddamerxsel2009lat.620-1-2 وBaracaxGiza 843-34 وBaracaxGiza 843-36وGoraxSel.Br/20640-1/2010-1 بالقيم (1090،1050 ،1054 ، 1038، 1015 كغ. هكتار-1، على التوالي). تفاوتت الصفات المدروسة في قيم معاملي التباين الوراثي GCV والمظهريPCV ، إذ سُجلت أعلى قيم للتباين الوراثي في صفات عدد القرون/نبات، عدد البذور/نبات، والغلة البذرية بمقدار (25، 26.6، 29%، على التوالي). وكانت قيمة درجة التوريث والتقدم الوراثي النسبي مرتفعة لصفات عدد القرون/نبات، عدد البذور/نبات، وزن 100 بذرة، والغلة البذرية (92-53، 88-50، 97-27.6، 53-43.5%، على التوالي)، في حين أظهرت صفة عدد البذور/قرن قيمة معتدلة لدرجة التوريث وأخرى مرتفعة للتقدم الوراثي النسبي (27،43 %، على التوالي). ارتبطت الغلة البذرية إيجابياً مع صفات عدد العناقيد الثمرية/نبات، وعدد القرون/نبات، وعدد البذور/نبات، ويمكن أن تُعدّ من مؤشرات الانتخاب التي تُستعمل في تحسين الغلة البذرية ومكوناتها للطرز الوراثية المدروسة باتباع عدد قليل من دورات التربية والتحسين بالانتخاب المباشر.

الكلمات المفتاحية: الفول، تحليل التباين، معامل التباين الوراثي والمظهري، معامل التوريث الواسع، التقدم الوراثي.

المقدمة:

يُعدّ الفول Faba bean (Vicia faba L.) من أقدم محاصيل البقوليات الغذائية في العالم، إضافة إلى فول الصويا (Glycine max L.) والبازلاء (Pisum sativum L.)، ويُعرف شعبياً بعدة تسميات ومنها الفاصوليا العريضة، فول الحصان، الفاصوليا العجيبة، الفاصوليا الحقلية، فاصوليا القراد، الفاصوليا الشتوية، حبوب الحمام (Mihailovic et al., 2005; Torres et al., 2010). وهو محصول ثنائي الصبغيات (n = 2x = 12) ذاتي التلقيح ويحدث التلقيح الخلطي بواسطة الحشرات. يمتلك محصول الفول القدرة على التأقلم والنمو في ظروف مناخية مختلفة (Kaur et al., 2014). يتميز الفول باحتواء بذوره على نسبة مرتفعة من البروتين 22-24%، وتتكون من 79% جلوبيولين و7% ألبومين و6% جلوتيلين، وبذلك يتفوق بمحتواه العالي من البروتين على العديد من محاصيل البقوليات الأخرى (Burstin et al., 2011).

يُستعمل الفول غذاءً للإنسان في معظم الدول النامية، وأيضاً يُستعمل في تغذية الثروة الحيوانية في الدول المتقدمة (Singh et al., 2010). كما أن له أهمية كبيرة في زيادة خصوبة التربة والحفاظ عليها خاصة في المناطق الجافة وشبه الجافة (Kopke & Nemecek, 2010). وإن زيادة إنتاجية الفول تتطلب استنباط أصناف عالية الغلة، إضافة إلى التوسع الأفقي في زراعته، الأمر الذي يتطلب وجود اختلافات وراثية عند اختيار الآباء في برنامج التربية والتهجين. فإن التباين الوراثي والتقدم الوراثي لهما أهمية قصوى لتحليل السلوكية الوراثية والمساهمات النسبية للعوامل الوراثية وغير الوراثية في إجمالي التباينات المظهرية في عشائر الفول، ويعكس التباين الوراثي مستوى التقدم الوراثي في تربية المحاصيل وعدد دورات التربية والتحسين (Ouji et al., 2017). وجد Dewangan et al. (2022) قيماً مرتفعة للتباين الوراثي ولدرجة التوريث والتقدم الوراثي في صفات مكونات الغلة، وعزى ذلك إلى سيطرة الفعل الوراثي التراكمي في الطرز المدروسة، كما أوصى Abo-Hegazy (2022) باستعمال الانتخاب المباشر للغلة البذرية ومكوناتها في محصول الفول، نتيجة لارتفاع قيمتي درجة التوريث والتقدم الوراثي، وأشار Kumar et al. (2022a) لدى اختباره عدداً من أصناف الفول إلى أن تحسين صفتي وزن 100 بذرة وعدد القرون والبذور/نبات، ساهم في تحسين الغلة البذرية. وبيّن Ahmad (2016) وجود علاقة ارتباط إيجابية بين صفة الغلة البذرية وصفتي عدد القرون وعدد الحبوب/نبات، كما سجل Peyman (2014) وجود علاقة ارتباط موجبة ومعنوية بين الغلة البذرية وبعض مكوناتها عدد القرون/نبات، عدد الحبوب/قرن، عدد الفروع/نبات، عدد البذور/نبات، والغلة البذرية/القطعة التجريبية. يهدف البحث إلى دراسة التباين وتقدير المعايير الوراثية وعلاقات الارتباط لصفة الغلة البذرية ومكوناتها في بعض الطرز الوراثية من محصول الفول.

مواد البحث وطرائقه:

نُفِّذت تجربة البحث فى محطة بحوث إزرع (محافظة درعا) التابعة للمركز العربى لدراسات المناطق الجافة والأراضى القاحلة/أكساد، خلال الموسم الزراعى 2024. تقع المحطة فى منطقة الاستقرار الثانية على ارتفاع 575 م وخط عرض 032.53 شمالاً وطول 036.15 شرقاً، وتتميز بمناخ بارد وماطر شتاءً وحار وجاف صيفاً، ومعدل هطولها المطري 290 ملم/سنة، وقد بلغت كمية الأمطار الهاطلة بالموسم 310 ملم. تتصف تربة المحطة بالطينية الثقيلة والفقيرة بمحتواها العضوي (جدول 1).

الجدول 1. التحليل الكيميائي والفيزيائي لتربة موقع زراعة التجربة، محطة بحوث إزرع.

التحليل الكيميائي							التحليل الميكانيكى		
EC Ds/m	PH	المادة العضوية %	كربونات الكالسيوم %	N الكلي %	P المتاح mg/kg	K المتاح mg/kg	رمل %	سلت %	طين %
0.712	7.7	1.015	7.56	0.08	5.34	602.8	14.3	19.9	65.6

تم تحليل البيانات الناتجة عن الصفات المدروسة باستخدام برنامج GenStat Release 12.1 (VSN International Ltd., UK).وقد تم إجراء تحليل التباين (ANOVA) وفق تصميم القطاعات الكاملة العشوائية (RCBD) لدراسة الفروق بين الطرز الوراثية. كما تم التحقق من افتراضات التحليل الإحصائى، بما فى ذلك التوزيع الطبيعى وتجانس التباين، قبل إجراء التحليل. وتم حساب المعاملات الوراثية، بما فى ذلك معامل التباين الوراثى (GCV) والمظهري(PCV) ، ودرجة التوريث بالمفهوم الواسع، والتقدم الوراثى المتوقع، وفق المعادلات القياسية المعتمدة.

الصفات المدروسة:

- عدد العناقيد الثمرية/نبات: سُجِّل متوسط عدد العناقيد الثمرية لخمسة نباتات بالقطعة التجريبية فى طور تشكل القرون.
- عدد القرون/نبات: سُجِّل متوسط عدد القرون لخمسة نباتات بالقطعة التجريبية فى طور النضج الفيزيولوجى.
- عدد البذور/قرن: سُجِّل متوسط عدد البذور لخمسة نباتات بالقطعة التجريبية فى طور النضج التام.
- عدد البذور/نبات: سُجِّل متوسط عدد البذور لخمسة نباتات بالقطعة التجريبية فى طور النضج التام.
- وزن 100 بذرة (غ): تم تسجيل وزن عينة عشوائية مكونة من 100 بذرة لكل قطعة تجريبية على حدة.
- الغلة الحبية (طن. هكتار-1): سُجِّل وزن البذور الناتجة عن فرط قرون النباتات الجافة لكل قطعة تجريبية على حدة، وقُدِّرت الإنتاجية بتحويل أوزان البذور إلى كغ. هكتار-1.

المعايير الوراثية: قُدِّرت المعايير التالية:

لحساب التباين الوراثي للصفات المدروسة، تم استخدام معامل التباين الوراثي كما يلي:

$$GCV\ (\%) = (\sqrt{\sigma^2 g} / \bar{X}) \times 100$$

حيث:

σ^2 = التباين الوراثي للصفة

$\bar{X}$ = المتوسط العام للصفة

يعكس هذا المعامل نسبة التباين الوراثي بالنسبة لمتوسط الصفة، ويعطي فكرة عن مدى اختلاف الطرز الوراثية في الصفة المدروسة. تم حساب معامل التباين المظهري (PCV %) باستخدام المعادلة التالية:

$PCV\ (\%) = (\sqrt{\sigma^2 p} / \bar{X}) \times 100$ حيث:

$\sigma^2 p$ = التباين المظهري (Phenotypic variance) = التباين الوراثي + التباين البيئي

$\bar{X}$ = المتوسط العام للصفة

يعكس هذا المعامل مقدار التباين الكلي للصفة، بما يشمل التأثيرات الوراثية والبيئية.

((Sivasubramanian and Madhavamenon, 1973; Burton, 1952

تم حساب التقدم الوراثي المتوقع (GA) باستخدام المعادلة التالية:

$$GA = K \times \sigma p \times H^2$$

حيث:

GA = التقدم الوراثي المتوقع (Genetic Advance)

K = الفارق الانتخابي (Selection differential) عند شدة اختيار معينة (هنا 5%)

σp = الانحراف المعياري للصفة (Phenotypic standard deviation)

H^2 = درجة التوريث بالمفهوم الواسع (%)

يُستخدم GA لتقدير مقدار التحسن المتوقع في الصفة بعد جيل واحد من الانتخاب المباشر.

(Johnson et al., 1955a)

تم حساب التقدم الوراثي النسبي (GAM %) باستخدام المعادلة التالية:

$GAM\ (\%) = (GA / \bar{X}) \times 100$

حيث:

GA = التقدم الوراثي المتوقع

$\bar{X}$ = المتوسط العام للصفة

يعطي GAM النسبة المئوية للتحسن المتوقع مقارنة بالمتوسط العام للصفة، مما يسهل مقارنة الصفات المختلفة.

النتائج والمناقشة:

عدد العناقيد الثمرية/نبات:

يُستنتج من نتائج التحليل الإحصائي لصفة عدد العناقيد الثمرية/نبات لطرز الفول المدروسة (الجدول 2)، وجود تباين في قيم صفة العناقيد الثمرية/نبات، إذ تراوحت بين 1 و4 عناقيد/نبات، وكان أقلها للطراز الوراثي Hashbenge وأعلاها للطراز BaracaxGiza 843-36، وقد تفوق على الشاهد ثلاثة طرز هي BaracaxGiza 843-36، GoraxSel.Br/20640-1/2010-1، WI11-18-3xEthiopia bulk-54

بقيم (4، 3، 3 عناقيد/نبات، على التوالي)، تماثل هذه النتيجة ما وجده (Kolig et al., 2022; Rehaan et al., 2020) والعائد إلى الاختلاف الوراثي بين الطرز المدروسة. كما يُلاحظ ارتفاع قيمة معامل التباين الوراثي 21% ومعامل التباين المظهري 26%، ويمكن أن يُعزى ذلك إلى انخفاض التأثير البيئي على هذه الصفة، التي عبّرت عن مكوناتها الوراثية إلى حد بعيد، وقد ترافق ذلك مع ارتفاع قيمتي درجة التوريث والتقدم الوراثي النسبي (62، 33)%، على التوالي)، مما يؤكد أن سلوك صفة عدد العناقيد/نبات يُعزى بمعظمه إلى التأثير الوراثي الناتج عن فعل المورثات التراكمية مما يجعل للانتخاب المباشر أهمية كبيرة في تحسينها، تتوافق هذه النتيجة مع ما توصل إليه:

(Ouje et al., 2017; Kolig et al., 2022; Verma et al., 2015).

عدد القرون/نبات:

يتبيّن من نتائج التحليل الإحصائي لصفة عدد القرون/نبات (الجدول 2) وجود تباين وراثي واسع بين متوسطات الطرز المدروسة، إذ تراوح من 3 قرون/نبات في الطرز الوراثية Sakha 2 x IG159162، GoraxSel.Br/20640-1/2010xS2011-111، Sel.Br/20640-1/2010xS2011-111، Ed-damer x ILB4358، GoraxSel.Br/20640-1/2010-3

إلى 7 قرون/نبات في الطراز BaracaxGiza 843-36، وقد تفوق 12 طرازاً وراثياً على الشاهد (3 قرون/نبات)، وبفروق معنوية في صفة عدد القرون في النبات، وهذا التباين الواسع يعود إلى اختلاف التراكيب الوراثية للطرز الوراثية في صفة عدد القرون/نبات، وهذا يتوافق مع ما سجله (Kolig et al., 2022). أظهرت صفة عدد القرون في النبات امتلاكها قيمة مرتفعة لكل من معامل التباين الوراثي والمظهري ودرجة التوريث والتقدم الوراثي النسبي وكانت القيم (25، 27، 92، 53%، على التوالي)، فالقيمة المرتفعة لدرجة التوريث والتقدم الوراثي النسبي تدل على سيطرة الفعل الوراثي التراكمي، وأن الانتخاب المباشر يكون فعّالاً لتحسين هذه الصفة (Ouje et al., 2017).

الجدول 2. متوسط أفضل عشرة طرز وراثية ومعامل التباين الوراثي والمظهري ودرجة التوريث والتقدم الوراثي النسبي لصفتي عدد العناقيد والبذور/نبات لطرز من الفول.

الرقم المتسلسل	الطرز الوراثية	عدد العناقيد/نبات*	الطراز الوراثي	عدد القرون/نبات*
1	baracaxGiza 843-36	3.7 a	baracaxGiza 843-36	7 a
2	GoraxSel.Br/20640-1/2010-1	3.3 ab	GoraxSel.Br/20640-1/2010-1	6 ab
3	WI11-18-3xEthiopia bulk-54	3.3 ab	WI11-18-3xEthiopia bulk-54	6 ab
4	Sakha 2 x IG159162	3 abc	Eddamerxsel2009lat.620-1-2	6 ab
5	Eddamerxsel2009lat.620-1-2	3 abc	baracaxGiza 843-34	5 bcd

الرقم المتسلسل	الطرز الوراثية	عـــــــدد العناقيد/نبات*	الطراز الوراثي	عـــــــدد القرون/نبات*
6	WS11-124-1xsel . 2006 latt.(ILB 2583)	2.7 abcd	WS11-124-1xsel . 2006 latt.(ILB 2583)	5 bcd
7	Camolina	2.7 abcd	Camolina	5 bcd
8	WS11-51-2xWS11-124-1	2.7 abcd	WS11-51-2xWS11-124-1	5 bcd
9	WI11-309-2xWS11-106-40	2.7 abcd	WI11-309-2xWS11-106-40	5 bcd
10	Camolina	2.7 abcd	Hudeiba 93xIndia 1-133	5 bcd
11	الشاهد - بلدي	2 cde	الشاهد - بلدي	3 i
أقل فرق معنوي LSD 5%		0.59		0.56
معامل الاختلاف % CV		15		8.5
معامل التباين الوراثي % GCV		21		25
معامل التباين المظهري % PCV		26		27
درجة التوريث بالمفهوم الواسع % H		62		92
التقدم الوراثي النسبي GAP		33		53

* وجود فروق معنوية بين متوسطات الطرز الوراثية للصفة المدروسة على مستوى دلالة إحصائية 0.05. المتوسطات ذات الأحرف الأبجدية المشتركة لا يوجد بينها فروق معنوية على مستوى دلالة إحصائية 0.05.

عدد البذور/قرن:

يتضح من الجدول 2، وجود فروق معنوية بين متوسطات الطرز المدروسة في صفة عدد البذور/قرن، وتراوحت ما بين بذرتين في الطرز الوراثية 1-1-14-88134 S، Eddamer، BaracaxGiza 843-36، Hudieba93 X Sel.2010TER192 -1//Sel.F7/8975/05 و5 بذور في الطرز الوراثية WI11-309-2xWS11-106-65، 1-28 Hudeiba 93xIndia، Hashbenge، ومع ذلك كانت أفضل الطرز التي حققت زيادة في عدد البذور من فئة الشاهد البلدي (3 بذور/القرن)، تماثل هذه النتيجة مع ما وجداه Tadesse and Bekele (2003)، في دراستهما لمكونات الغلة للأصناف من الجلبان. كما يُلاحظ ارتفاع قيم معامل التباين الوراثي (25%) والمظهري (27%) والتقدم الوراثي النسبي (24%) لصفة عدد البذور في القرن، بينما كانت درجة التوريث ذات قيمة متوسطة بلغت 43%، ويبيّن الفارق البسيط بين قيمتي معامل التباين الوراثي والمظهري أن سلوك هذه الصفة عائد للتأثير الوراثي أكثر منه للتأثير البيئي، ويتحكم بها المورثات التراكمية، مما يجعل من الانتخاب المباشر مناسباً لتحسين عدد البذور بالقرن (Ouje et al., 2017; Kolig et al., 2022).

عدد البذور/نبات:

يتبيّن من نتائج تحليل صـفة عدد البذور/نبات (الجدول 3)، تباين في متوسـطات الطرز المدروسـة التي تراوحت من 8 بذور/نبات للطراز Sakha 2 x IG159162 إلى 12 بذرة للطراز WI11-18-3xEthiopia bulk-54، وقد سجل 18 طرازاً وراثياً فروقاً معنوية على الشاهد الصنف البلدي (7 بذور/نبات)، ويمكن أن يُعزى هذا المدى الواسـع من التباين إلى القاعدة الوراثية الواسـعة لمجموعة الطرز المدروسـة وإلى اختلاف تركيبها الوراثي في ظروف الزراعة المطرية شـبه الجافة، يماثل ذلك ما سـجلاه Deepak and Kumar (2023) من تباين كبير بين متوسطات أصناف الفول التي قاما بتقييمها.

امتلكت صـفة عدد البذور في النبات قيماً مرتفعة لمعامل التباين الوراثي والمظهري ودرجة التوريث والتقدم الوراثي النسـبي وكانت (26.6، 33.1، 88، 50%، على التوالي)، وقد كانت صـفة عدد البذور التي ينتجها النبات خاضـعة للفعل المورثي التراكمي في ظل تأثير بيئي محدود، وتتوافق تلك النتائج مع ما توصل إليه Dewangan ومساعديه (2022) و(Koli et al., 2016) في دراسته لغلة الفول ومكوناتها.

الجدول 3. متوسـط أفضـل عشـرة طرز وراثية ومعامل التباين الوراثي والمظهري ودرجة التوريث والتقدم الوراثي النسبي لصفتي عدد البذور/قرن وعدد البذور/نبات لطرز وراثية من الفول.

الرقم المتسلسل	الطراز الوراثي	عـــــــدد البذور/قرن*	الطراز الوراثي	عـــــــدد البذور/نبات*
1	WI11-309-2xWS11-106-65	5 a	WI11-18-3xEthiopia bulk-54	21 a
2	Hudeiba 93xIndia 1-28	5 a	Eddamerxsel2009lat.620-1-2	19 ab
3	Hashbenge	5 a	baracaxGiza 843-34	18 ab
4	baracaxGiza 843-34	4 ab	Rebeya 40	17 bc
5	S2011-112xSuperaquadulce	4 ab	GoraxSel.Br/20640-1/2010-1	16 bcd
6	Hudeiba 93xsel2009lat.620-1-1	4 ab	baracaxGiza 843-36	16 bcd
7	WI11-18-3xEthiopia bulk-54	4 ab	S2011-112xSuperaquadulce	15 bcd
8	GoraxSel.Br/20640-1/2010-0	4 ab	WI11-309-2xWS11-106-40	13 cde
9	Rebeya 40	4 ab	WS11-124-1xsel . 2006 latt.(ILB 2583)	13 cde
10	WI11-18-3xEthiopia bulk-	4 ab	Nubaria2xSuperaquadolce	13 cde

الرقم المتسلسل	الطراز الوراثي	عـــــــدد البذور/قرن*	الطراز الوراثي	عـــــــــدد البذور/نبات*
11	الشاهد - بلدي	3 abc	الشاهد - بلدي	7 i
أقل فرق معنوي LSD 5%		0.99		1.9
معامل الاختلاف % CV		18.1		9.7
معامل التباين الوراثي % GCV		25		26.6
معامل التباين المظهري % PCV		27		33.1
درجة التوريث بالمفهوم الواسع % H		43		88
التقدم الوراثي النسبي GAP		24		50

* وجود فروق معنوية بين متوسطات الطرز الوراثية للصفة المدروسة على مستوى دلالة إحصائية 0.05. المتوسطات ذات الأحرف الأبجدية المشتركة لا يوجد بينها فروق معنوية على مستوى دلالة إحصائية 0.05.

ربط المعاملات الوراثية بالأدبيات الحديثة:

تم دعم نتائج المعايير الوراثية في هذا البحث بالاستشهاد بالأدبيات الحديثة. على سبيل المثال، أظهرت دراسة حديثة أجريت على Garden Pea (Pisum sativum L. var. hortense) أن معاملات التباين الوراثي والمظهري (GCV وPCV) كانت مرتفعة في صفات عدد القرون والبذور، كما لوحظ أن القيم العالية لدرجة التوريث (H^2) ترافقها تقديرات عالية للتقدم الوراثي المتوقع (GA) والنسبة المئوية للتقدم الوراثي (GAM)، مما يشير إلى وجود قابلية كبيرة للتحسين باستخدام الانتخاب المباشر في برامج التحسين الوراثي. هذه النتائج تدعم الحسابات الحالية في بحثنا وتؤكد صحة المنهج المتبع لحساب المعايير الوراثية (Meena et al., 2025; Journal of Advances in Biology & Biotechnology).

بالإضافة إلى ذلك، أظهرت دراسة حديثة أجريت على فول (Vicia faba L.) أن معاملات التباين الوراثي والمظهري (GCV وPCV) ودرجة التوريث (H^2) والتقدم الوراثي المتوقع والنسبي (GA وGAM) كانت مرتفعة أيضاً، مما يؤكد أن الصفات الوراثية المدروسة قابلة للتحسين باستخدام الانتخاب المباشر، وتتوافق مع النتائج المحسوبة في هذا البحث (Dewangan et al., 2025). كما تدعم النتائج الحديثة في فول (Vicia faba L.) من خلال تحليل QTL عالي الكثافة وجود ارتباط قوي بين الصفات الوراثية المعقدة ومكونات الغلة، حيث تم تحديد مؤشرات وراثية ثابتة عبر الخرائط الجينية للعديد من الصفات المتعلقة بالإنتاج. وتؤكد هذه النتائج الحديثة على أهمية دراسة التباين الوراثي ودرجة التوريث (H^2) والتقدم الوراثي (GA) كأدوات فعّالة في برامج التحسين الوراثي للفول، كما هو موضح في تحليلنا الحالي للمعايير الوراثية (Aguilar-Benitez et al., 2025). وزن 100 بذرة (غ):

يُستنتج من نتائج التحليل الإحصائي في الجدول 4، وجود فروق معنوية بين متوسطات الطرز المدروسة في صفة وزن 100 بذرة، وتراوحت الأوزان من 47.3 غ للطراز الوراثي S2011-112xSuperaquadulce إلى 78 غ للطراز الوراثي (ILB 2583 latt. 2006 .)WS11-124-1xsel، في حين كان الطرازان الوراثيان (ILB 2583 latt. 2006 .)WS11-124-1xsel وRebeya 40 أفضل الطرز التي حققت

زيادة في وزن 100 بذرة بلغت (3.7، 0.53%، على التوالي)، مقارنة بوزن 100 بذرة للشاهد المحلي والبالغ 75.2 غ، تماثل هذه النتيجة مع ما وجده (Tadesse and Bekele, 2003; Deepak and Kumar, 2023; Sharifi, 2014)، من تباين في مكونات الغلة ومنها وزن 100 بذرة.

يُستنتج من نتائج تقدير التباين للطرز المدروسة لصفة وزن 100 بذرة اعتدال قيمتي معامل التباين الوراثي والمظهري (13.6، 13.8%، على التوالي)، ولوحظ ارتفاع في قيمتي درجة التوريث والتقدم الوراثي النسبي (97، 27.6%، على التوالي)، مما يدل على أن معظم قيمة معامل التوريث ناتجة عن التأثير التراكمي للمورثات، ويكون الانتخاب المباشر فعالاً في مثل هذه الحالة (Abo-Hegazy, 2022; Gull et al., 2022).

الغلة البذرية (كغ):

يُلاحظ من نتائج التحليل الإحصائي لصفة الغلة البذرية وجود تباين وراثي واسع، إذ تراوحت الغلة البذرية من 313 كغ.هـ-1 للطراز الوراثي Hudieba93 X Sel.2010TER192-1//Sel.F7/8975/05 إلى 1090 كغ.هـ-1 للطراز الوراثي WI11-18-3xEthiopia bulk-54، وتفوق معنوياً في الغلة البذرية الطرز WI11-18-3xEthiopia bulk-54، Eddamerxsel2009lat.620-1-2، BaracaxGiza 843-34، BaracaxGiza 843-36، GoraxSel.Br/20640-1/2010-1 بقيم مقدارها (1090، 1054، 1050، 1038، 1015 كغ.هـ-1، على التوالي)، مقارنة بالشاهد البلدي (337 كغ.هـ-1)، على مستوى دلالة إحصائية 5% (الجدول 4)، ويمكن أن يُعزى ذلك إلى تباينات مكونات الغلة البذرية (Kosev et al., 2019; Deepak and Kumar, 2023; Fikere et al., 2020).

تبيّن من تقدير المؤشرات الوراثية للطرز المدروسة ارتفاع قيم معامل التباين الوراثي والمظهري والتقدم الوراثي النسبي في صفة الغلة البذرية بقيم (29، 39، 43.3%، على التوالي)، بينما كانت قيمة معامل التوريث معتدلة 53%، تتوافق هذه النتيجة مع ما سجله كل من (Waly, 2021; Hamza, 2017; Tafere et al., 2013) في بحوثهم على الفول، إذ وجدوا ارتفاعاً في قيمة التقدم الوراثي النسبي، وتُعدّ مؤشراً على إسهام الفعل الوراثي التراكمي في توريث الغلة البذرية من جيل إلى جيل.

الجدول 4. متوسط أفضل عشرة طرز وراثية ومعامل التباين الوراثي والمظهري والتوريث والتقدم الوراثي النسبي لصفتي وزن 100 بذرة والغلة البذرية لطرز وراثية من الفول.

الرقم المتسلسل	الطراز الوراثي	وزن 100بذرة* (غ)	الطراز الوراثي	الغلة البذرية* (كغ/هـ)
1	WS11-124-1xsel . 2006 latt.(ILB 2583)	78.0 a	WI11-18-3xEthiopia bulk-54	1090 a
2	BPL 5071	75.6 ab	Eddamerxsel2009lat.620-1-2	1054 a
3	الشاهد - بلدي	75.2 ab	BaracaxGiza 843-34	1050 a
4	baracaxGiza 843-36	74.6 ab	baracaxGiza 843-36	1038 a
5	S 88134-14-1-1	74.0 ab	GoraxSel.Br/20640-1/2010-1	1015 a

الرقم المتسلسل	الطراز الوراثي	وزن 100بذرة* (غ)	الطراز الوراثي	الغلة البذرية* (كغ/هـ)
6	Eddamer	71.3 ab	WS11-124-1xsel 2006 latt.(ILB 2583)	929 ab
7	Hudieba93 X Sel.2010TER192-1//Sel.F7/8975/05	70.9 bc	Rebeya 40	789 ab
8	Hudeiba 93xIndia 1-133	70.5 bcd	WS11-51-2xWS11-124-1	750 ab
9	Sel.Br/20640-1/2010xS2011-111	68.1 cd	Hudeiba 93xIndia 1-133	733 ab
10	GoraxSel.Br/20640-1/2010-1	66.9 cde	WI11-309-2xWS11-106-40	673 ab
11	Camolina	66.7 e-f	الشاهد - بلدي	313 b
أقل فرق معنوي LSD 5%		2.5		300
معامل الاختلاف CV %		2.8		27.3
معامل التباين الوراثي GCV %		13.6		29
معامل التباين المظهري PCV %		13.8		39.8
معامل التوريث H %		97		53
التقدم الوراثي GAP		27.6		43.5

* وجود فروق معنوية بين متوسطات الطرز الوراثية للصفة المدروسة على مستوى دلالة إحصائية 0.05. المتوسطات ذات الأحرف الأبجدية المشتركة لا يوجد بينها فروق معنوية على مستوى دلالة إحصائية 0.05.

علاقات الارتباط لصفة الغلة البذرية ومكوناتها:

يتبيّن من الجدول 5، ارتباط الغلة البذرية إيجابياً ومعنوياً مع صفات عدد العناقيد الثمرية/نبات، وعدد القرون/نبات، وعدد البذور/نبات (0.790، 0.887، 0.906 =r، على التوالي)، بينما كانت علاقات الارتباط ضعيفة وسالبة للغلة البذرية مع صفة وزن 100 بذرة، وكذلك بين صفة عدد القرون/نبات وعدد البذور/القرن (0.091 -، 0.091 -=r، على التوالي)، في حين ارتبطت صفة وزن 100 بذرة سلبياً ومعنوياً مع صفات عدد البذور/القرن وعدد البذور/نبات (0.801 -، 0.431 -=r، على التوالي)، وهذه النتائج تتوافق مع ما سجلاه Ahmad (2016) وPeyman (2014).

الجدول 5. علاقات الارتباط لصفة الغلة البذرية ومكوناتها لطرز وراثية من الفول.

الصفات	عدد العناقيد الثمرية/نبات	عدد القرون/نبات	عدد البذور/قرن	عدد البذور/نبات	وزن 100بذرة (سم)	الغلة البذرية (يوم)
عدد العناقيد الثمرية/نبات	-					
عدد القرون/نبات	0.922*	-				

عدد البذور/قرن	0.190	-0.134	-			
عدد البذور/نبات	*0.685	*0.789	*0.406	-		
وزن 100بذرة (غ)	0.072	0.047	*-0.801	*-0.431	-	
الغلة البذرية (كغ/هـ)	*0.790	*0.887	0.155	*0.906	-0.091	-

* وجود فروق معنوية بين متوسطات الطرز الوراثية للصفة المدروسة على مستوى دلالة إحصائية 0.05.

الاستنتاجات:

تباينت طرز الفول المدروسة في قيم معاملي التباين الوراثي GCV والمظهري PCV للصفات المدروسة السابقة، إذ سُجلت أعلى قيم للتباين الوراثي في صفات عدد القرون/نبات، عدد البذور/نبات، والغلة البذرية بمقدار (25، 26.6، 29%، على التوالي). وكانت قيمة درجة التوريث والتقدم الوراثي النسبي مرتفعة لصفات عدد القرون/نبات، عدد البذور/نبات، وزن 100 بذرة، والغلة البذرية (92-53، 88-50، 97-27.6، 53-43.5%، على التوالي)، في حين أبدت صفة عدد البذور/قرن قيمة معتدلة لدرجة التوريث وأخرى مرتفعة للتقدم الوراثي النسبي (27،43 %، على التوالي). وبناءً على النتائج الإيجابية السابقة يتطلب تحسين الغلة البذرية ومكوناتها في برنامج التربية عدداً قليلاً من دورات التربية والتحسين باستعمال الانتخاب المباشر.

ارتبطت صفات عدد العناقيد الثمرية/نبات، وعدد القرون/نبات، وعدد البذور/نبات إيجابياً مع الغلة البذرية، ما يؤهلها أن تُستعمل مؤشرات انتخاب يستعملها المربي في تحسين الغلة البذرية لمحصول الفول.

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Genetic Variance Analysis of Seed Yield Trait and Its Components in Faba Bean (*Vicia faba* L.) Genotypes under Rain-Fed Conditions in ACSAD – Izraa Research Station

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Abstract:

The research experiment was carried out at the Izraa Research Station of the Arab Center for the Studies of Arid Zones and Drylands (ACSAD) in the agricultural season 2024, with the aim of estimating the genetic parameters of the yield trait and some other plant traits in 28 genotypes of Faba bean, in addition to the local control variety. The randomized complete block design with three replicates was used in the research. The results showed that there were significant differences between the studied models in all the studied traits: number of pods/plant, number of seeds/pod, number of seeds/plant, weight of 100 seeds, and seed yield. 12 models outperformed the control in the number of pods/plant and 18 models in the number of seeds/plant, while 5 genotypes showed significant differences in seed yield over the control at the 5% level of statistical significance, which are WI11-18-3xEthiopia bulk-54, Eddamerxsel2009lat.620-1-2, Baraca x Giza 843-34, Baraca x Giza 843-36, and GoraxSel.Br/20640-1/2010-1 with values (1090, 1054, 1050, 1038, 1015 kg. ha-1, respectively). The studied traits varied in the values of the genetic variation coefficients (GCV) and phenotypic variation (PCV), as the highest values of genetic variation were recorded in the traits number of pods/plant, number of seeds/plant, and seed yield by (25, 26.6, 29%, respectively). The degree of heritability and relative genetic progression were high for the traits number of pods/plant, number of seeds/plant, weight of 100 seeds, and seed yield (53-92, 50-88, 27.6-97, 43.5-53%, respectively). The trait number of seeds/pod showed a moderate value for the degree of heritability and a high value for relative genetic progress (43.27%, respectively). Seed yield was positively associated with the characteristics of the number of fruit clusters/plant, the number of pods/plant, and the number of

seeds/plant, and is considered one of the selection indicators that can be used to improve seed yield and its components in the studied models through a few breeding cycles and improvement by direct selection.

Key words: Faba bean, analysis of variance, genotypic and phenotypic coefficient of variation, broad-sense heritability, genetic advance.

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تطبيقات الاستشعار عن بعد والطائرات غير المأهولة (الدرون) في مراقبة الحالة العامة لأشجار النخيل خصوصًا آفة سوسة النخيل

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الملخص:

تواجه القطاعات الزراعية في الوطن العربي بوصفها من أعمدة الأمن الغذائي والتنمية تحديات متشابكة ناجمة عن الآفات والأمراض النباتية والتغيرات المناخية. تشير التقديرات الدولية إلى أن الآفات والأمراض النباتية تتسبب عالميًا بخسائر تصل إلى نحو 40% من إجمالي الإنتاج الزراعي بكلفة تُقدَّر بأكثر من 220 مليار دولار سنويًا للأمراض النباتية وحدها **(FAO, 2021)**. وتُعد آفة سوسة النخيل الحمراء *(Rhynchophorus ferrugineus)* من أخطر الآفات التي تهدد أشجار النخيل في الشرق الأوسط وشمال أفريقيا حيث تتجاوز خسائرها الاقتصادية 500 مليون دولار جراء موت آلاف الأشجار المنتجة للتمور. كما تعاني المنطقة العربية من تدهور أكثر من 26 مليون هكتار من الأراضي الزراعية بخسائر اقتصادية تتجاوز 9 مليارات دولار سنويًا **(UNCCD, 2022)** في ظل استهلاك القطاع الزراعي العربي لنحو 85% من الموارد المائية العذبة وبلوغ معدل التوتر المائي في الإقليم 440% مقارنة بمتوسط عالمي قدره 68% **(World Bank, 2020)**.

في هذا السياق تبرز أهمية تطبيقات الاستشعار عن بعد والطائرات بدون طيار (الدرون) كأدوات ابتكارية لتعزيز استدامة القطاع الزراعي من خلال رصد الحالة العامة للنبات بواسطة المؤشرات الطيفية مثل المؤشر النباتي للفرق الطبيعي (NDVI) ومؤشر الحافة الحمراء للفرق الطبيعي (NDRE)

- Normalized Difference Vegetation Index (NDVI)
- Normalized Difference Red Edge Index (NDRE)

إضافة إلى تقنية الليدار (LiDAR) والتصوير الحراري بما يمكّن من الكشف المبكر عن الإصابات والاضطرابات الفسيولوجية قبل ظهور الأعراض المرئية.

اعتمدت هذه الدراسة المنهج الوصفي التحليلي الكمي القائم على معالجة معطياتSentinel-2 وبيانات الدرون لمنطقة الدراسة وحساب المؤشرات الطيفية والحرارية (NDVI, NDRE, PRI, LST) ومقارنتها بالأساليب التقليدية.

أظهرت النتائج تفوقًا واضحًا لتقنيات الاستشعار عن بعد والدرون في السرعة والشمولية والدقة والكشف المبكر بنسبة إصابة كلية بلغت 5.9% ونسبة إجهاد عام بلغت 8.3% في منطقة الدراسة مما يؤكد أن الاستثمار في هذه الحلول الذكية يمثل خطوة محورية نحو زراعة أكثر كفاءة واستدامة في البيئات القاحلة وشبه القاحلة التي تميّز معظم الدول العربية.

الكلمات المفتاحية:

(الاستشعار عن بعد، الطائرات بدون طيار (الدرون)، سوسة النخيل الحمراء، المؤشرات الطيفية، صحة النخيل)

المقدمة:

يُعد قطاع النخيل من أهم الموارد الزراعية والاقتصادية في الوطن العربي حيث تحتل الدول العربية الصدارة عالميًا في إنتاج التمور وتصديرها وتمتلك أكثر من 70% من إجمالي أشجار النخيل على مستوى العالم. وتكمن أهمية النخيل في دوره الحيوي في الأمن الغذائي وتوفير فرص العمل وتعزيز الاستقرار الاجتماعي في المناطق الريفية فضلًا عن رمزيته الثقافية والدينية. ورغم هذه الأهمية الاستراتيجية يواجه قطاع النخيل تحديات بيئية خطيرة أبرزها انتشار آفة سوسة النخيل الحمراء (*Rhynchophorus ferrugineus*) المعروفة بقدرتها التدميرية الصامتة إذ تصيب جذع النخلة داخليًا دون ظهور أعراض واضحة في المراحل الأولى مما يتسبب في خسائر اقتصادية فادحة تبلغ ملايين الدولارات سنويًا في دول مثل السعودية والإمارات ومصر إذا لم يتم الكشف عنها والتعامل معها مبكرًا.

تعتمد طرق الكشف التقليدية على الفحص البصري والفخاخ الفرمونية والتقنيات اليدوية وهي غالبًا غير فعالة في المراحل المبكرة من الإصابة. من هنا تبرز أهمية الابتكار التكنولوجي في حماية هذه الثروة الزراعية حيث يتجه البحث والتطوير نحو أنظمة إنذار مبكر تجمع بين دقة المستشعرات الأرضية وشمولية بيانات الاستشعار عن بعد والدرون **(Ellsäßer et al., 2020–2022)**. فقد أحدثت هذه التقنيات ثورة في مجال الزراعة وخاصة في مراقبة صحة المحاصيل على نطاق واسع لما توفره من بيانات طيفية وحرارية وهيكلية للأشجار باستخدام منصات متعددة كالأقمار الصناعية والطائرات بدون طيار (UAVs) والمستشعرات الأرضية المحمولة تُستخدم لرصد التغيرات الفيزيولوجية والبيوكيميائية في الأشجار المصابة مثل انخفاض محتوى الكلوروفيل وتغيرات درجة الحرارة السطحية واضطرابات البنية النسيجية مما يمنح المزارعين وقتًا ثمينًا لاتخاذ الإجراءات الوقائية والعلاجية.
(Ellsäßer et al., 2020–2022). وانطلاقًا من هذه المعطيات تسعى الدراسة الحالية إلى بناء إطار عمل متعدد المصادر لمراقبة أشجار النخيل والكشف المبكر عن آفة سوسة النخيل الحمراء على النحو المفصّل في أهداف البحث التالية.

أهداف البحث:

- تطوير إطار عمل للمراقبة المتعددة المصادر لأشجار النخيل باستخدام الصور الفضائية ومعطيات الدرون.
- استخراج مؤشرات ومعادلات طيفية لتحديد حالة الإجهاد للأشجار والمتغيرات الحرارية بهدف الكشف عن الإجهاد والآفات.
- تقييم قابلية استخدام الطائرات بدون طيار (الدرون) في إدارة سوسة النخيل الحمراء وتحديد المناطق عالية الخطورة.
- إنشاء خرائط لتوزيع أشجار النخيل المصابة بسوسة النخيل الحمراء وخرائط الإجهاد العام.

مراجعة الأدبيات:

تناولت دراسات عديدة أهمية استخدام الاستشعار عن بعد في مراقبة الغطاء النباتي من خلال المؤشرات الطيفية التي تساعد في الكشف عن التغيرات الفسيولوجية للنبات قبل ظهور الأعراض البصرية **(Paul et al., 2024)**.

أشارت أبحاث حديثة إلى إمكانية استخدام الطائرات بدون طيار المجهزة بكاميرات متعددة الأطياف (Multispectral) وحرارية (Thermal) في الكشف المبكر عن إصابة سوسة النخيل عبر ملاحظة تغيرات درجة حرارة جذع النخلة أو مؤشرات الإجهاد المائي والكلوروفيل ومعرفة الفروق في القيم الطيفية والحرارية بين النخيل المصاب والسليم قبل ظهور الأعراض البصرية **(Delalieux et al., 2023)**.

استُخدمت معطيات الليدار (LiDAR) لمعرفة البنية الثلاثية الأبعاد لتاج الشجرة (crown) وارتفاع النخلة وحجم كتلتها الخضرية بما يساعد في استخراج مؤشرات فيزيولوجية لا تظهر في الصور الطيفية وحدها **(Alsanea et al., 2022)**.

تجمع مراجعات وبحوث حديثة على أهمية الجمع بين تقنيات الاستشعار عن بعد وتطبيقات الدرون والمستشعرات الأرضية ونماذج الذكاء الاصطناعي وتعلم الآلة مستفيدة من التطور السريع في الشبكات العصبونية ونماذج حديثة مثل (ResNet, MobileNet, DenseNet) لتصنيف الصور الجوية والميدانية للكشف عن النخيل المصاب والتفريق بين مراحل الإصابة **Torky, M. &(others). (2023).**

وبناءً على ما تقدم من الدراسات السابقة تتضح الحاجة إلى إطار منهجي يدمج المعطيات الفضائية ومعطيات الدرون معًا للاستفادة من مزايا كل منهما وهو الإطار الذي صُممت وفقه منهجية الدراسة الحالية المفصّلة في القسم التالي:

المنهجية:

اعتمدت هذه الدراسة المنهج الوصفي التحليلي الكمّي (Quantitative Descriptive-Analytical Approach) القائم على معالجة وتحليل معطيات الاستشعار عن بعد والطائرات بدون طيار باستخدام المؤشرات الطيفية والحرارية ومقارنة نتائجها بالمسوحات الميدانية والأساليب التقليدية بهدف الكشف المبكر عن الإجهاد النباتي العام والإصابة بآفة سوسة النخيل الحمراء ورسم خرائط توزعها في منطقة الدراسة. وتتألف المنهجية من المراحل الأساسية التالية: (تحديد منطقة الدراسة، جمع المعطيات الفضائية ،جمع معطيات الدرون ميدانيًا
وأخيرًا حساب المؤشرات الطيفية والحرارية وتحليلها) كما يوضحها التفصيل التالي:

تحديد منطقة الدراسة

الجدول (1): الإحداثيات الجغرافية لمنطقة الدراسة

الزاوية	Latitude N	Longitude E
الزاوية العليا (شمال شرق)	N °34.539019	E °38.266904
الزاوية السفلى (جنوب غرب)	N °34.531526	E °38.247536

المساحة الكلية 150 هكتارًا، وعدد الأشجار التقريبي 58500 شجرة، ضمن منطقة زراعية تحتوي على بساتين نخيل ذات تربة رملية طينية، ومناخ صحراوي جاف، مع تعرّض محتمل للإجهاد الحراري والمائي وسوسة النخيل.



الشكل (1): صورة فضائية من القمر الصناعي **Sentinel-2A** توضح منطقة الدراسة وتظهر بساتين النخيل

المعطيات الاستشعارية الفضائية المستخدمة:

الاستشعار عن بعد:

هو عملية جمع المعلومات عن جسم أو ظاهرة دون الاتصال المادي المباشر بهدف الحصول على بيانات عن المحاصيل والأراضي الزراعية ومعرفة حالتها العامة .تُقدّم هذه التقنية مزايا هامة مقارنة بالأساليب التقليدية وتُمكّن من تحديد المتغيرات والتباين في الحالة العامة والإجهاد للغطاء النباتي **(Kazanskiy, 2025; Al-Mahmoud & van der Meer, 2023).**

البيانات الفضائية:

استخدام صور الأقمار الصناعية (Sentinel-2 للبيانات الطيفية وLandsat 8/9 للبيانات الطيفية والحرارية) لتغطية مساحات أوسع وتحليل الاتجاهات العامة والمتغيرات والإجهاد خصوصًا في حال عدم توفر الدرون **(Kazanskiy, 2025).**

البيانات الميدانية:

إجراء مسوحات ميدانية للتحقق من دقة البيانات المُجمّعة عن بعد تشمل الفحص البصري للأشجار وأخذ عينات من الأوراق أو الجذوع وتحديد الأشجار المصابة فعليًا بواسطة متخصصين.

معطيات الطائرات بدون طيار (الدرون) والقدرات التي تتميز بها: يسمح استخدام الطائرات بدون طيار المجهزة بكاميرات متعددة الأطياف وحرارية وصور (RGB) عالية الدقة بالمراقبة الدورية المنتظمة ورصد المتغيرات بمرور الوقت **(Paul et al., 2024)**. ومن أهم هذه التجهيزات:

الكاميرات متعددة الأطياف وفوق الطيفية (Multispectral & Hyperspectral Cameras): قادرة على التقاط بيانات من مجالات طيفية متعددة، تسمح بتحليل التغيرات في الانعكاس الطيفي للأوراق وهي مؤشر مبكر على الإجهاد المائي أو نقص المغذيات أو الإصابة بالآفات مثل سوسة النخيل الحمراء قبل ظهور علامات الاصفرار أو الذبول مرئيًا **(Al-Mahmoud & van der Meer, 2023).**

الكاميرات الحرارية (Thermal Cameras): تلتقط الإشعاع الحراري المنعكس من الأشجار وتحدد الاختلافات في درجة حرارة الأنسجة الناتجة عن الإجهاد أو الإصابة بالآفات حيث يؤدي نشاط اليرقات داخل جذع الشجرة إلى ارتفاع درجة الحرارة في المناطق المصابة **(Farhan et al., 2024).**

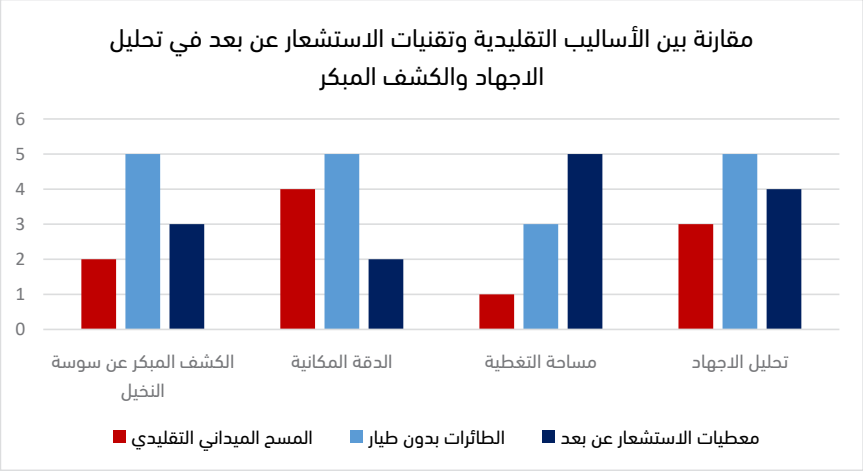
الصور الجوية عالية الدقة (High-Resolution RGB Cameras): تُستخدم لرسم خرائط دقيقة لأعداد الأشجار وكثافتها وتحديد مواقع الأشجار الفردية ورصد التغيرات الهيكلية في تيجان الأشجار وبناء نماذج ثلاثية الأبعاد لتقييم الأضرار **(Delalieux et al., 2023).**

معطيات الليدار (LiDAR): تستخدم أشعة الليزر لإنشاء نماذج ثلاثية الأبعاد دقيقة لهيكل الشجرة بما في ذلك ارتفاعها وحجم تاجها وكثافة أوراقها وهي بيانات حاسمة في تقدير الكتلة الحيوية وتقييم الصحة الهيكلية للنخيل كما يمكنها الكشف عن تشوهات بنية الشجرة الناجمة عن سوسة النخيل الحمراء حتى لو كانت الآفة غير مرئية على السطح **(Alsadik et al., 2024)**.

تتفوق تقنيات الاستشعار عن بعد والطائرات بدون طيار في الكشف المبكر عن إصابة سوسة النخيل الحمراء على الوسائل التقليدية من خلال عدة جوانب حيوية، كما يوضحها الجدول التالي والرسم البياني المصاحب له.

الجدول (2): تفوق تقنيات الاستشعار عن بعد والطائرات بدون طيار في الكشف المبكر عن الإصابة بآفة سوسة النخيل الحمراء

الجانب	الميزة	الأساليب التقليدية	تقنيات الاستشعار عن بعد والطائرات بدون طيار
الشمولية والسرعة	تغطية واسعة وفي وقت قصير	فحص يدوي بطيء، محدود بالعدد والمساحة، ويتطلب جهدًا بشريًا كبيرًا	مسح شامل وسريع خلال وقت قصير باستخدام صور عالية الدقة من طائرات مسيّرة أو أقمار صناعية
الكشف المبكر	الكشف في مراحل أولية جدًا	يعتمد على ظهور أعراض مرئية متأخرة أو أدوات صوتية للكشف عن اليرقات داخل الجذع	يكشف "إجهادًا نباتيًا" مبكرًا قبل ظهور الأعراض المرئية عبر تحليلات متعددة وفائقة الطيف
الدقة والموضوعية	نتائج موضوعية وقابلة للتكرار	عرضة للخطأ البشري، ويعتمد على خبرة الفاحص أو المزارع	يعتمد على بيانات رقمية وتحليلات كمية، يمكن دمجها مع الذكاء الاصطناعي لتحسين الدقة
التكلفة على المدى الطويل	كفاءة اقتصادية أفضل على المدى المتوسط والطويل	تكاليف تشغيلية مرتفعة بسبب الحاجة لفريق ميداني دائم	تكلفة أولية أعلى، تنخفض مع التكرار وتقلل الخسائر الاقتصادية عبر الكشف المبكر
إمكانية المراقبة المستمرة	مراقبة مستمرة وتحليل توجهات صحة النخيل	صعوبة تنفيذ مراقبة دورية منتظمة لمزارع كبيرة	إمكانية إجراء مراقبة دورية ومقارنة البيانات عبر الزمن لاكتشاف التغيرات الدقيقة



الرسم البياني (1): مقارنة بين الأساليب التقليدية وتقنيات الاستشعار عن بعد والدرون في تحليل الإجهاد والكشف المبكر ومساحة المراقبة

المصدر: بيانات الدراسة، بالاستناد إلى (Galieni & Ziv, 2021)

المؤشرات والمعادلات الطيفية المعتمدة في هذه الدراسة:

تعكس الأشجار السليمة كميات مميزة من الضوء في نطاقات طيفية معينة (خاصة في المجال الطيفي الأحمر القريب) وعند تعرضها للإجهاد يتغير نمط الانعكاس الطيفي حيث تلتقط المستشعرات هذه التغيرات قبل ظهور الأعراض المرئية مما يسمح بالتدخل المبكر وتحديد عدد من مسببات الإجهاد منها: **الإجهاد المائي (نقص الري)- نقص العناصر الغذائية- تلف ميكانيكي أو كيميائي- أو هجمات حشرية أو فطرية**. وتُعد المؤشرات الطيفية النباتية والحرارية معادلات رياضية تستخدم قيم الانعكاس الطيفي في عدة مجالات مختلفة لتقييم الحالة العامة للغطاء النباتي وحالة الإجهاد باستخدام معطيات (**Landsat-9, Sentinel-2**).

من أهم هذه المؤشرات:

المؤشر النباتي للفرق الطبيعي (NDVI): أشهر المؤشرات وأكثرها استخدامًا لتقييم كثافة الغطاء النباتي وصحة الأوراق. يعتمد على الفرق بين انعكاس الأشعة تحت الحمراء القريبة (NIR) والنطاق الأحمر (RED). يشير انخفاض قيمة NDVI غالبًا إلى إجهاد نباتي أو تدهور الصحة **(Qi et al., 1994).**

المؤشر النباتي المعزز (EVI): أقل حساسية لتأثيرات الغلاف الجوي والتربة ويعطي نتائج أفضل في المناطق ذات الغطاء النباتي الكثيف والسليم **(Qi et al., 1994).**

مؤشر الحافة الحمراء للفرق الطبيعي (NDRE): يستخدم نطاقات حافة المجال الطيفي الأحمر (Red Edge) والقريبة من الأشعة تحت الحمراء ويمتاز بحساسيته العالية للتغيرات الطفيفة في محتوى الكلوروفيل مما يجعله مثاليًا للكشف المبكر عن الإجهاد العام والإصابة بسوسة النخيل في مراحلها الأولى حتى قبل ظهور الأعراض المرئية بوضوح **(Paul et al., 2024)**.

المؤشرات الحرارية (Thermal Indices): تلعب دورًا حيويًا في تقييم صحة النبات حيث تعكس التغيرات في درجة حرارة سطح النبات الإجهاد المائي أو المرضي باستخدام المجال الطيفي الحراري في المعطيات الفضائية والكاميرات الحرارية المثبتة على الدرون **(El-Refaey & Omar, 2025)**.

الجدول (3): المعادلات الطيفية وأهميتها عند استخدام معطيات Sentinel-2

المؤشر	الأهمية	معادلة Sentinel-2	نقاط القوة	نقاط الضعف
NDVI	يقيس كثافة الغطاء النباتي وصحته بناءً على امتصاص الضوء الأحمر وانعكاس الأشعة تحت الحمراء القريبة	(NIR - Red) / (NIR + Red) NDVI= (B8 - B4)/(B8 + B4) • B8 = NIR (842 nm) • B4 = Red (665 nm)	سريع، شائع، مناسب للمراحل المبكرة	يتشبع في الكثافة العالية، لا يكشف الإجهاد الداخلي
NDRE	يقيس محتوى الكلوروفيل في الأوراق، خاصة في النباتات الناضجة أو ذات الأوراق السميكة	(NIR - RedEdge) / (NIR + RedEdge) NDRE = (B8 - B5)/(B8 + B5) • B5 = Red Edge (705 nm)	يكشف الإجهاد في التاج الداخلي، مناسب للمراحل المتقدمة	أقل دقة في المراحل المبكرة
PRI	يعكس كفاءة التمثيل الضوئي والإجهاد الضوئي أو المائي قبل ظهور أعراض مرئية	PRI approx. (B3 - B4)/(B3 + B4) • B3 = Green (560 nm)	حساس جدًا للإجهاد المبكر	يتأثر بالضوء والزاوية
EVI	يحسّن دقة NDVI في المناطق ذات الكتلة الحيوية العالية أو الضباب الجوي	EVI = 2.5 *(B8 - B4)/(B8 + 6 *B4 - 7.5 * B2 + 1) • B2 = Blue (490 nm)	أكثر حساسية من NDVI	يتطلب وجود مجال طيفي Red Edge

المصدر: (Montero et al., 2023)

تحليل المؤشرات الطيفية والحرارية :

تم حساب مؤشرات (NDVI, NDRE, PRI, LST) لكل شجرة أو مجموعة أشجار ورسم خرائط وتحليل الفروقات والتباين الحراري لتحديد المناطق المجهدة ومواقع البؤر المصابة باستخدام برامج نظم المعلومات الجغرافية (GIS) وبرامج تحليل المعطيات الفضائية **(Paul et al., 2024)**.

آلية ومراحل العمل للكشف المبكر والمراقبة:

المسح الأولي من خلال جمع الصور الفضائية المتعددة الطيفية والحرارية (**Landsat**-9, **Sentinel-**) وتطبيق المعالجة المسبقة (تصحيح هندسي وإشعاعي) وتحليل المعطيات ومراقبة المنطقة المدروسة.

حساب المؤشرات الطيفية (NDVI, NDRE, EVI) والمؤشر الحراري (LST) بهدف تحديد المناطق التي تظهر عليها علامات الإجهاد العام وتحليل المؤشرات وتحديد الإجهاد والبؤر الساخنة وترتيب أولويات المراقبة ورسم خرائط صحية للنخيل.

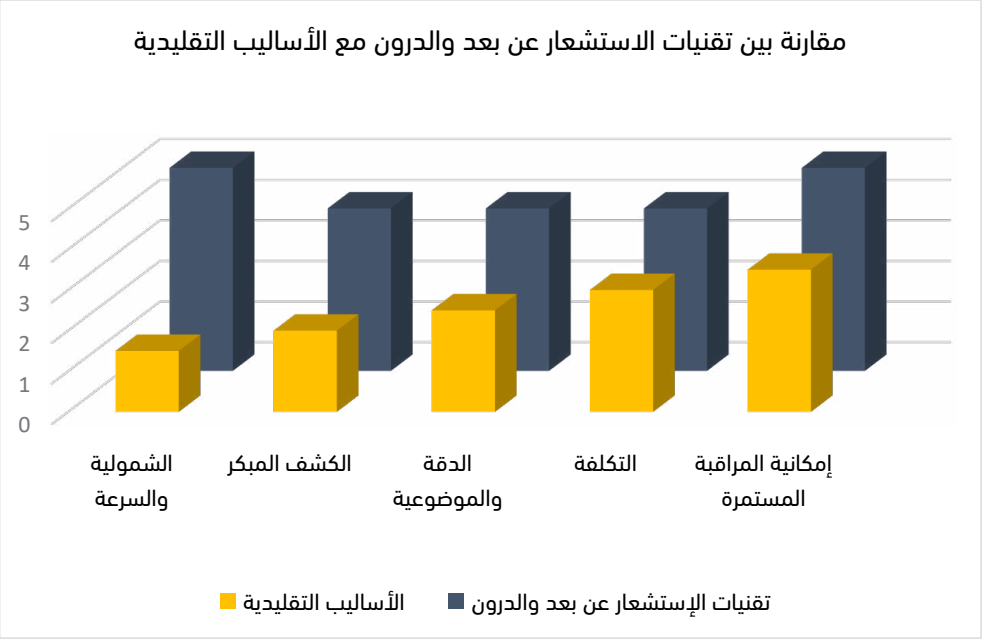
إجراء مسوحات دورية جوية للمناطق ذات الأولوية باستخدام طائرات بدون طيار مجهزة بكاميرات عالية الطيفية وحرارية وصور جوية عالية الدقة المكانية وتكرار هذه الرحلات خلال فترة النشاط العالي للآفة وحساب المؤشرات وتحديد الفروقات الحرارية والتمايز الطيفي لكل شجرة.

التحقق الميداني وتتبع الأشجار المصابة وهي مرحلة حاسمة للتحقق من صحة النتائج المستخلصة من معطيات الاستشعار عن بعد والدرون باستخدام أجهزة استشعار صوتية للكشف عن نشاط اليرقات الأولي وبداية الإصابة.
التدخل والمعالجة بعد التأكد من النتائج وتحديد الأشجار المصابة حيث تختلف إجراءات المعالجة حسب درجة الإصابة (الحقن بالمبيدات المناسبة، العزل، قطع الأشجار المصابة ،وتطبيق إجراءات وقائية للأشجار السليمة).

التقييم والمتابعة بعد المعالجة حيث تستمر المراقبة الدورية بواسطة الدرون بهدف تقييم فعالية التدخل ومتابعة أي عدوى جديدة.

النتائج:

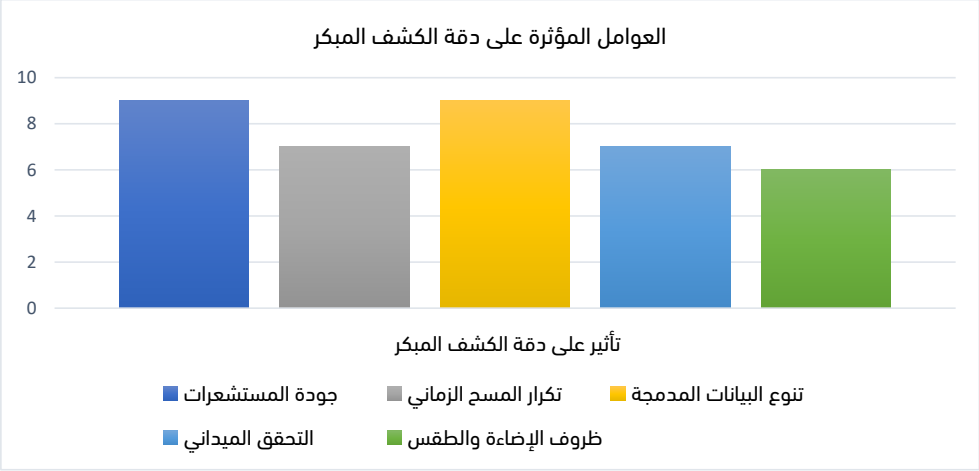
الرسوم البيانية وجداول المقارنات حول المنهجية المتبعة



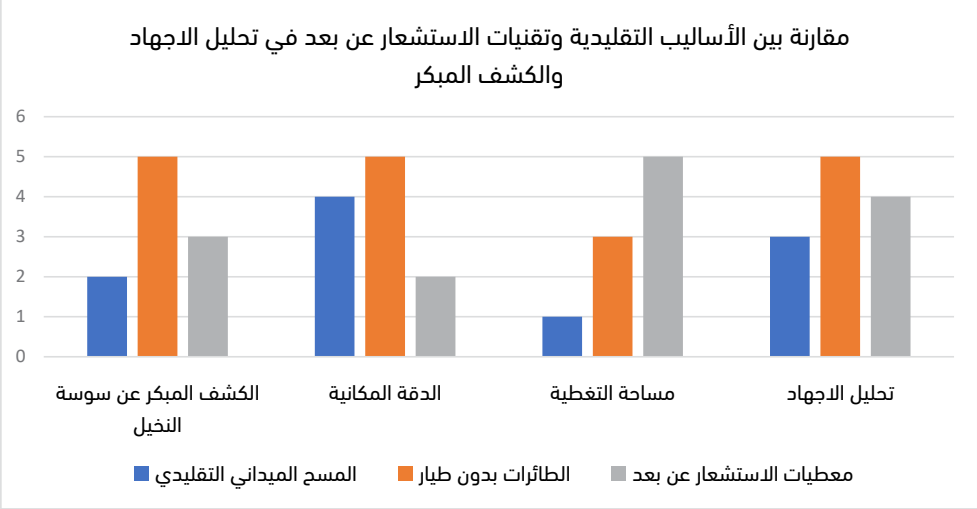
الرسم البياني (2): الدمج بين صور الأقمار الصناعية والدرون يساهم في تحسين دقة الكشف بشكل ملحوظ

المصدر: (Yildiz et al., 2025)

تتعزز كفاءة الكشف عن سوسة النخيل من خلال فهم العلاقة بين التقنيات المستخدمة وعدد من العوامل المؤثرة، منها جودة المستشعرات، وتنوع البيانات المستخدمة، وتكرار المسح الميداني، والظروف المناخية (Mendel et al., 2023).



الرسم البياني (3): العوامل المؤثرة في تحديد دقة الكشف المبكر عن الإصابة

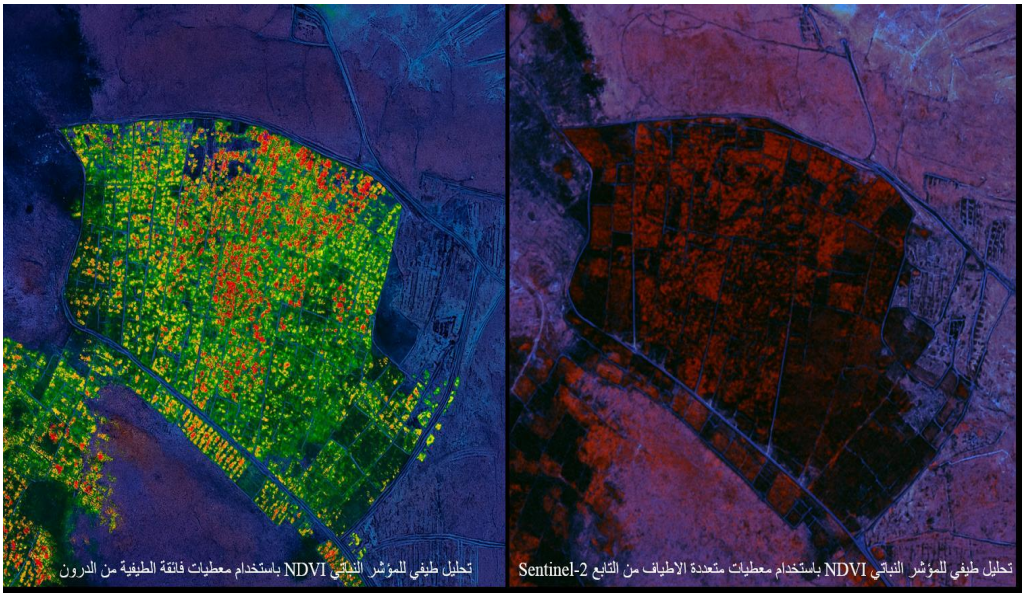


الرسم البياني (4): مقارنة بين الأساليب التقليدية وتقنيات الاستشعار عن بعد في تحليل الإجهاد والكشف المبكر

المصدر: (El-Refaey & Omar, 2025)

لوحظ تحسّن ملحوظ في تحديد حالة الإجهاد العام وتحديد مناطق الإصابة عند تحليل مؤشر NDVI من المعطيات الناتجة عن الدرون مقارنة مع تحليل المؤشر نفسه باستخدام معطيات Sentinel-2.

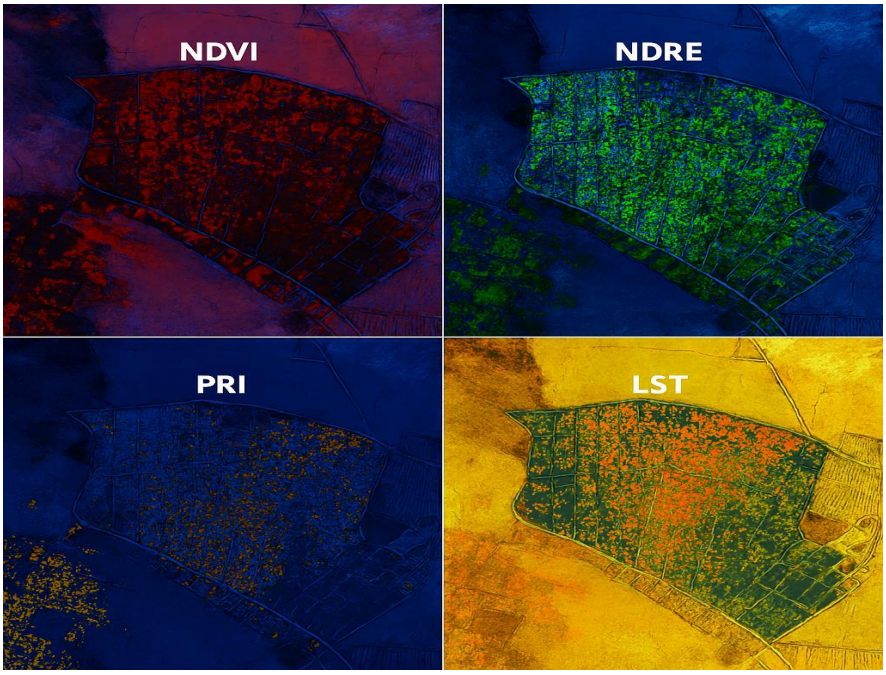
الشكل (2): تحليل طيفي للمؤشر (NDVI) باستخدام معطيات متعددة الأطياف (يمين) ومعطيات فائقة الطيفية من الدرون (يسار)



أظهرت النتائج أن المؤشرات الطيفية (NDVI, NDRE, PRI) وتكاملها مع المؤشر الحراري (LST) قادرة على التمييز بين النخيل السليم والمصاب قبل ظهور الأعراض البصرية حيث تم الحصول على هذه النتائج بناءً على تحليل المؤشرات وفق العتبات الطيفية والحرارية الموضحة في الجدول التالي.

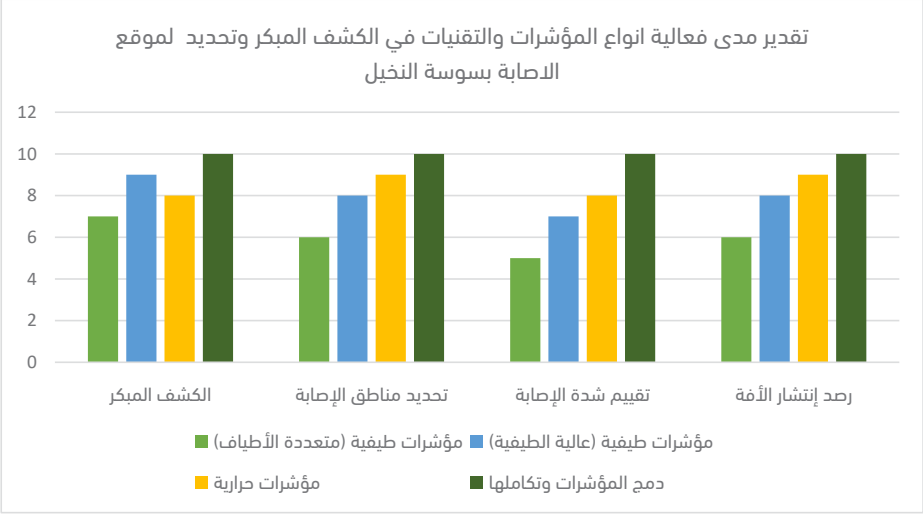
الجدول (4): عتبات المؤشرات الطيفية والحرارية المستخدمة في رسم خرائط الإجهاد والإصابة

المؤشر	سليم	مجهد	مشتبه	مصاب
NDVI	> 0.65	0.45–0.65	0.30–0.45	< 0.30
NDRE	> 0.40	0.25–0.40	0.15–0.25	< 0.15
PRI	> 0.05	-0.05–0.05	-0.10–-0.05	< -0.10
LST (°C)	< 32	32–35	35–37	> 37



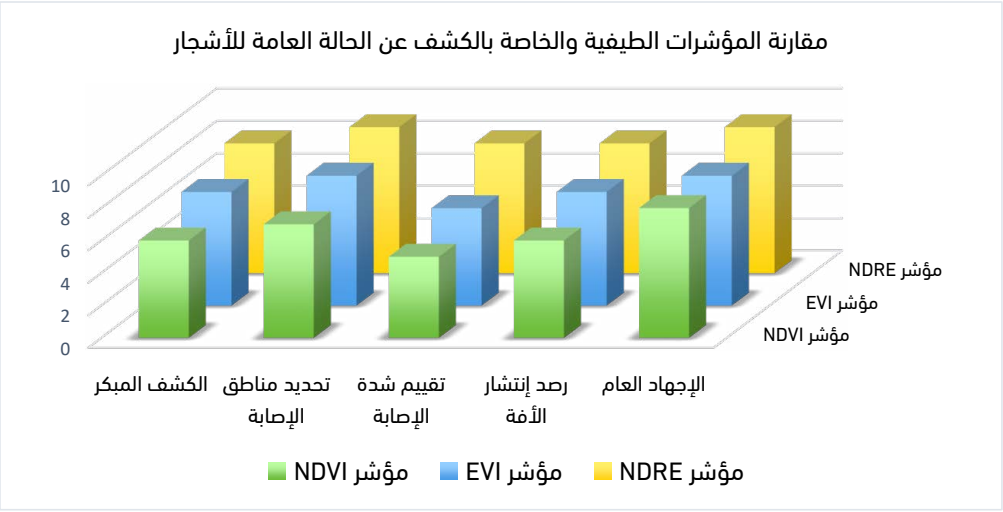
الشكل (3): المؤشرات الطيفية والحرارية (NDVI, NDRE, PRI, LST) المستخدمة في منطقة الدراسة

توضح هذه المؤشرات مدى فعالية أنواع المؤشرات والتقنيات في الكشف المبكر وتحديد موقع الإصابة بسوسة النخيل وأهمية دمج هذه المؤشرات وتكاملها **(Delalieux et al., 2023).**



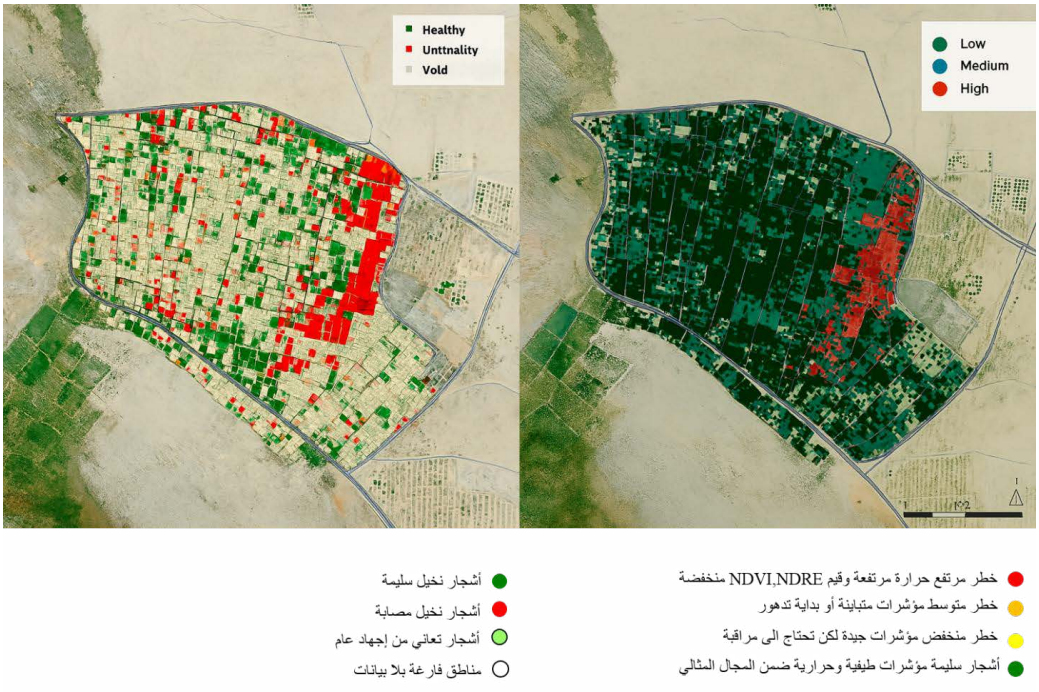
الرسم البياني (5): تقدير مدى فعالية أنواع المؤشرات والتقنيات في الكشف المبكر وتحديد موقع الإصابة بسوسة النخيل

من خلال تطبيق المؤشرات الطيفية النباتية، تبين أن مؤشر NDRE يتمايز عن بقية المؤشرات في دقة الكشف عن الإجهاد والإصابة ورصد انتشار الإصابة **(Rehman et al., 2022).**



الرسم البياني (6): مقارنة المؤشرات الطيفية الخاصة بالكشف عن الحالة العامة للأشجار (NDVI, EVI, NDRE)

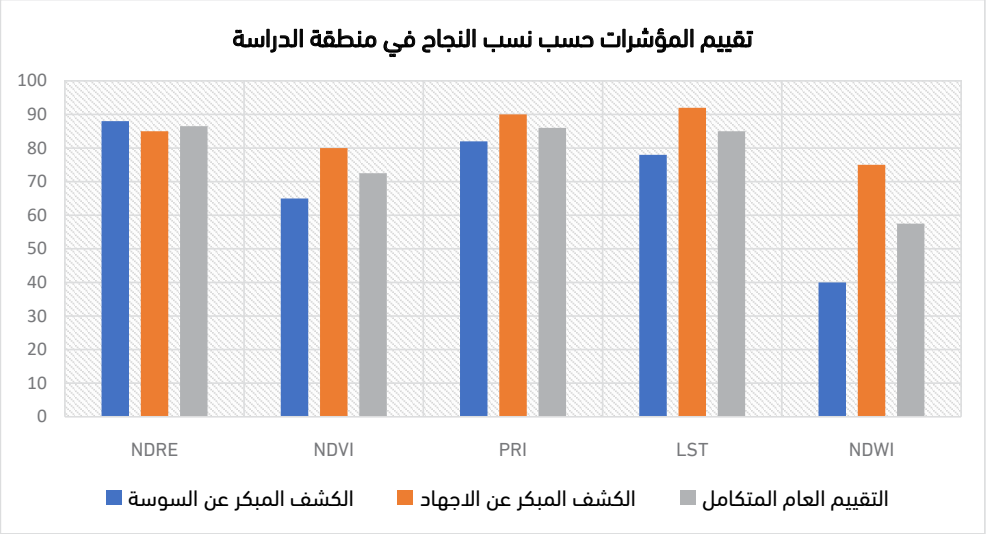
أظهرت نتائج تحليل المؤشرات الطيفية والحرارية القدرة على تحديد بؤر الإصابة والحصول على خرائط توضح درجات الخطورة كما يبينها الشكل التالي.



الشكل (4): خرائط توضح درجات المخاطر والإصابة في منطقة الدراسة

الجدول (5): تقييم المؤشرات حسب نسبة النجاح

المؤشر	نسبة النجاح فى الكشف عن السوسة	نسبة النجاح فى كشف الإجهاد العام	التقييم العام	ملاحظات
NDRE	88%	85%	86.5%	يكشف تغيرات الكلوروفيل في التاج الداخلي، حساس جدًا
PRI	82%	90%	86%	يكشف الإجهاد الفسيولوجي قبل ظهور الأعراض البصرية
LST	78%	92%	85%	يكشف الإجهاد الحراري ومناطق الإصابة المحتملة
NDVI	65%	80%	72.5%	جيد للمراقبة العامة، لكنه يتشبع في الكثافة العالية
NDWI	40%	75%	57.5%	مفيد للجفاف، لكنه غير حساس للإصابة المبكرة



الرسم البياني (7): تقييم المؤشرات حسب نسب النجاح في منطقة الدراسة

تقرير النتائج والإصابة في منطقة الدراسة

للكشف المبكر عن سوسة النخيل من المفيد استخدام المؤشرات**(NDRE + PRI + LST)** كمجموعة أساسية مع معطيات الدرون (فائقة الطيفية، حرارية، RGB عالي الدقة) وفق المتغيرات التالية:

- انخفاض مؤشر NDRE يشير إلى انخفاض محتوى اليخضور وضعف النشاط التمثيلي.
- ارتفاع مؤشر PRI يرتبط بتحديد مستوى وكفاءة عملية التمثيل الضوئي ويرتبط باستجابة النبات للإجهاد العام.
- ارتفاع مؤشر حرارة سطح النبات (LST) يعكس المتغيرات الحرارية الناتجة عن انخفاض التبخر والنتح وهو مؤشر إضافي يساعد في تحديد الإجهاد.

وبالنتيجة فإن تزامن هذه المتغيرات يُعد مؤشرًا هامًا لتحديد بدء الإصابة أو الإجهاد النباتي مما يتطلب اتخاذ إجراءات وقائية ضرورية لحماية الأشجار والتحقق الحقلي من الحالة في المنطقة المحددة.

لمراقبة الإجهاد النباتي العام من المهم الاستفادة من المؤشرات الطيفية والحرارية التالية:

(PRI + LST + NDVI) حيث توفر تغطية فسيولوجية وقراءة للمتغيرات الحرارية والتبدلات على الحالة العامة للأشجار من خلال تكامل ودمج تلك المؤشرات.

نسبة الإصابة الكلية في منطقة الدراسة: 5.9% | نسبة الإجهاد العام: 8.3%

المناقشة:

تشير هذه النتائج إلى فعالية تقنيات الاستشعار عن بعد والدرون في مراقبة الحالة العامة للأشجار والكشف عن الإجهاد والإصابة بآفة سوسة النخيل، مما يساهم في تقليل الخسائر الاقتصادية وتوفير الوقت والجهد. وتُعد هذه التقنيات ثورة حقيقية في مجال مراقبة صحة أشجار النخيل ومكافحة آفة سوسة النخيل الحمراء، حيث أصبح من الممكن الآن مراقبة بساتين وأشجار النخيل بدقة والكشف عن الإصابات في مراحلها المبكرة. وهذه القدرة على الكشف المبكر ليست مجرد تحسين تقني بل استراتيجية حاسمة لتقليل الخسائر الاقتصادية الفادحة وحماية الأمن الغذائي والحفاظ على الموروث الثقافي والبيئي لأشجار النخيل.

تحليل الحالة والمناقشة العامة

- أظهرت الخريطة الأولية أن المناطق الشرقية والجنوبية الشرقية من الواحة تحتوي على أعلى تركيز من الأشجار المصابة وهو ما يتوافق مع مؤشرات NDVI وNDRE ومؤشر درجة الحرارة LST. **El-Refaey, M., & Omar, S. (2025).**
- أظهرت المناطق الغربية والشمالية الغربية مؤشرات طيفية جيدة مما يدل على حالة نباتية مستقرة نسبيًا.
- صُنّفت المناطق إلى ثلاث درجات خطورة (مرتفعة- متوسطة- منخفضة) بناءً على المؤشرات الطيفية والحرارية.
- تمثل المؤشرات الطيفية أدوات دقيقة لرصد الحالة الفسيولوجية للنبات دون تدخل مباشر.
- تفيد المؤشرات الطيفية في تصنيف الأشجار حسب درجة الإصابة وتحديد المناطق التي تحتاج إلى تدخل عاجل.
- يُعد ارتفاع حرارة السطح مؤشرًا مباشرًا للإجهاد الحراري خاصة في البيئات الجافة مثل تدمر.
- تم دمج LST مع المؤشرات الطيفية لتحديد المناطق التي تعاني من إجهاد مزدوج فسيولوجي وحراري.
- يمثل دمج تقنيات الاستشعار عن بعد والطائرات بدون طيار نهجًا تحويليًا في مكافحة آفة سوسة النخيل الحمراء والحفاظ على ثروة النخيل من خلال توفير قدرات غير مسبوقة للكشف المبكر والمراقبة الدقيقة **(Wang & Zhang, 2025).**

الصور الفضائية (Sentinel-2)

- توفر تغطية دورية واسعة النطاق بدقة تصل إلى 10 أمتار مما يسمح برصد التغيرات الزمنية في صحة الأشجار.
- ساعدت الصور الخام في بناء قاعدة بيانات مكانية دقيقة وربطها بالمؤشرات الطيفية والحرارية.

- استُخدمت لتصميم خرائط التوزع وخرائط الخطورة والنماذج التنبؤية.

تقنيات ومعطيات الدرون

- مكّنت الدرون من جمع بيانات عالية الدقة على مستوى كل نخلة خاصة في المناطق التي يصعب الوصول إليها.
- استُخدمت كاميرات طيفية وحرارية محمولة على الدرون لرصد مؤشرات NDVI وLST ميدانيًا.
- ساهمت في التحقق من صحة النتائج المستخرجة من الصور الفضائية وتحديث قاعدة البيانات الميدانية.
- تقدم تقنيات الاستشعار عن بعد والطائرات بدون طيار مع جميع الملحقات والتجهيزات المتطورة حلولًا مبتكرة وفعالة لمراقبة صحة أشجار النخيل والكشف المبكر عن سوسة النخيل الحمراء **(Boulila et al., 2023).**

التحديات والقيود العملية

- **حجم البيانات الكبير:** الصور الفضائية والدرون تنتج كميات ضخمة من البيانات تتطلب تخزينًا ومعالجة عالية الأداء.
- **تكلفة التشغيل والصيانة:** ارتفاع التكلفة الأولية لشراء الدرون والملحقات والبرمجيات الخاصة بتحليل هذه المعطيات يتطلب استثمارات كبيرة ومع ذلك تُعد مجدية اقتصاديًا على المدى الطويل مقارنة بالخسائر الناجمة عن الآفة.
- **تفاوت جودة الصور:** الغيوم والزاوية الشمسية والتداخل الطيفي قد تؤثر على دقة المؤشرات المستخرجة.
- **تأخر التحديث الزمني:** بعض الأقمار الصناعية توفر صورًا كل 5–10 أيام مما يحد من الرصد الفوري.
- **تعدد المنصات:** اختلاف تنسيقات البيانات بين Sentinel وLandsat وغيرها يتطلب خبرة في التوحيد والمعالجة.
- **صعوبة الدمج الزمني والمكاني:** توحيد بيانات من مصادر مختلفة (فضائية -جوية) يتطلب نماذج متقدمة لضمان الاتساق.
- **القيود التنظيمية:** تشغيل الدرون يتطلب تصاريح خاصة في العديد من الدول وقد يُمنع في المناطق الحساسة.
- **الاعتماد على الظروف الجوية:** الرياح والأمطار والحرارة تؤثر على أداء الدرون وجودة الصور.
- **محدودية التغطية:** تغطي الدرون مساحات محدودة مقارنة بالأقمار الصناعية مما يتطلب تخطيطًا دقيقًا للرحلات.
- **الحاجة إلى معايرة دقيقة:** تتأثر مؤشرات مثل NDVI وLST بنوع المستشعر وزاوية الالتقاط وظروف السطح.

- **تداخل العوامل المؤثرة:** قد ينتج الإجهاد النباتي عن عوامل متعددة (ماء- حرارة- آفات) مما يصعّب تفسير المؤشرات منفردة.
- **نقص الكفاءات المتخصصة:** يتطلب تحليل البيانات الطيفية والحرارية خبرة في الاستشعار عن بعد والذكاء الاصطناعي ونظم المعلومات الجغرافية.
- **ضعف البنية التحتية الرقمية:** في بعض المناطق يعيق غياب الحوسبة السحابية أو الإنترنت عالي السرعة تحليل البيانات الضخمة.
- **الاعتماد على التمويل الخارجي:** تعتمد كثير من المشاريع على منح مؤقتة مما يهدد استمرارية الرصد طويل الأمد.

رغم أن هذه التقنيات تمثل ثورة في مراقبة صحة النباتات وإدارة الموارد الزراعية إلا أن الاستفادة الكاملة منها تتطلب بنية تحتية رقمية قوية وكفاءات بشرية مدربة ونماذج تحليلية متقدمة وتنسيقًا مؤسسيًا وتنظيميًا فعالًا.

الاستنتاجات:

- **الاستشعار عن بعد يوفر أدوات غير تدميرية دقيقة:** تتيح المؤشرات الطيفية (NDVI-NDRE) تقييم الحالة الفسيولوجية للنباتات دون الحاجة إلى تدخل مباشر مما يقلل من التكاليف ويزيد من سرعة الرصد.
- **الصور الفضائية تعزز الرؤية الشاملة عبر الزمن والمكان:** توفر الأقمار الصناعية (Landsat, Sentinel-2) تغطية دورية واسعة النطاق مما يسمح بتحليل التغيرات الموسمية ومراقبة مناطق يصعب الوصول إليها ميدانيًا.
- **توفر الدرون معطيات وصورًا بدقة مكانية عالية:** تتيح الطائرات المسيّرة جمع بيانات طيفية وحرارية على مستوى الشجرة الواحدة مما يعزز دقة التصنيف والتحقق الميداني.
- **دمج المؤشرات الطيفية والحرارية يزيد من دقة التشخيص:** الجمع بين مؤشرات الغطاء النباتي ودرجة حرارة السطح يسمح بتحديد نوع الإجهاد (مائي- حراري- بيولوجي) بشكل أكثر موثوقية.
- **إمكانية تصميم نماذج تنبؤية تدعم التخطيط الاستباقي:** يمكّن تحليل التغيرات الزمنية في المؤشرات من توقع تطور الإصابة أو الإجهاد، مما يساعد في توجيه التدخلات قبل تفاقم المشكلة.

التوصيات بهدف تعزيز الاستفادة من هذه التقنيات

- تطوير منصات مفتوحة المصدر لتحليل البيانات الطيفية والحرارية لتسهيل الوصول إلى الأدوات التحليلية خاصة في الدول النامية أو المناطق ذات البنية التحتية المحدودة.
- دمج البيانات متعددة المصادر في نظم دعم القرار الزراعي عبر واجهات تفاعلية تربط بين الصور الفضائية وبيانات الدرون والملاحظات الأرضية لتوجيه التدخلات بدقة.
- تعزيز التدريب وبناء القدرات لدى الفرق الزراعية والبيئية من خلال برامج تدريبية متخصصة في نظم المعلومات الجغرافية وتحليل المؤشرات وتشغيل الدرون.
- تشجيع البحث التطبيقي متعدد التخصصات، يجمع بين علوم الزراعة والبيئة والذكاء الاصطناعي والاستشعار عن بعد لتطوير حلول متكاملة ومستدامة.
- دعم السياسات الوطنية لتبني الزراعة الذكية عبر إدماج هذه التقنيات في خطط مكافحة التصحر وإدارة المياه ومراقبة الآفات وربطها بمؤشرات الأداء البيئي.
- الاستثمار في تطوير الكفاءات البشرية القادرة على استخدام هذه التقنيات وتحليل البيانات بوصفه حجر الزاوية في بناء مستقبل مستدام لزراعة النخيل.
- بناء منظومة تقييم متكاملة تجمع بين الرصد الفضائي والتحليل الميداني توفر أساسًا علميًا لاتخاذ قرارات دقيقة في إدارة صحة النخيل ومكافحة الإجهاد البيئي.
- تأسيس وحدة تنسيق محلية تشرف على جمع البيانات وتحليلها وتوجيه التدخلات بناءً على النماذج التنبؤية لضمان الاستفادة الكاملة من هذه التقنيات.

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Remote sensing and drone applications for monitoring the general condition of palm trees, especially the red palm weevil

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Abstract:

Agriculture in the Arab world ,a pillar of food security and rural livelihoods, faces interlinked challenges from plant pests, diseases, and climate change. Plant pests and diseases cause losses of approximately 40% of global agricultural production, costing more than $220 billion annually for plant diseases alone **(FAO, 2021)**.

The red palm weevil (Rhynchophorus ferrugineus) alone has caused losses exceeding $500 million in the Middle East and North Africa. The region also suffers degradation of more than 26 million hectares of agricultural land, with losses exceeding $9 billion annually **(UNCCD, 2022)**, while the Arab agricultural sector consumes about 85% of freshwater resources amid a regional water-stress level of 440% versus a global average of 68% **(World Bank, 2020).**

In this context, the importance of remote sensing applications and drones as innovative tools to enhance the sustainability of the agricultural sector is highlighted, through monitoring the general condition of plants using spectral indicators such as the Natural Difference Vegetation Index (NDVI) and the Natural Difference Red Edge Index (NDRE).

- Normalized Difference Vegetation Index (NDVI)
- Normalized Difference Red Edge Index (NDRE)

In addition to LiDAR technology and thermal imaging which enables the early detection of injuries and physiological disorders before visible symptoms appear.

This study adopted a quantitative descriptive-analytical approach based on **Sentinel-2** imagery and **UAV** data for a study area, computing spectral and thermal indices (NDVI, NDRE, PRI, LST) and benchmarking them against conventional field methods.

Results showed a clear advantage of remote sensing and drones in speed, coverage, accuracy, and early detection, with a total infestation rate of 5.9% and a general stress

rate of 8.3% in the study area. Investing in these smart solutions is therefore a pivotal step toward more efficient and sustainable agriculture in the arid and semi-arid environments that characterize most Arab countries.

Keywords:

Remote Sensing, UAV/Drone, Red Palm Weevil, Spectral Indices, Palm Health.

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الابتكار في معالجة الترب الجبسية لتعزيز متانة البنى التحتية للري باستخدام التقنيات الحديثة

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الملخص:

تُمثل الترب الجبسية تحديًا هندسيًا كبيرًا، خاصة في المناطق الجافة وشبه الجافة التي تعتمد على مشاريع الري. فعلى الرغم من تمتعها بخصائص ميكانيكية جيدة في حالتها الجافة، إلا أنها تفقد متانتها وتصبح عُرضة للانهيار عند الترطيب، مما يهدد استدامة المنشآت الهيدروليكية كقنوات الري والسدود. يقدم هذا البحث حلًّا ابتكاريًا لمعالجة هذه المشكلة باستخدام تقنية حديثة قائمة على الإسفلت السائل، بهدف تعزيز قدرة التربة على التحمل ومنع الانهيار.

تم دراسة عينات من ترب جبسية من منطقتين مختلفتين في سوريا، حيث تم تحليل الخصائص الفيزيائية والميكانيكية للتربة بتغيير نسبة الجبس بشكل منهجي. كجزء مبتكر من الدراسة، تم تطبيق تقنية المعالجة بالإسفلت السائل على التربة بمحتواها الأصلي من الجبس، وتم تقييم تأثيره على خصائص مثل مقاومة الضغط غير المحصور، وقيمة دليل تحمل كاليفورنيا (CBR)، وقابلية الانهيار والانتفاخ.

أظهرت النتائج أن إضافة الإسفلت السائل أدت إلى تحسن ملحوظ في خصائص التربة، حيث بلغت مقاومة الضغط غير المحصور ذروتها عند نسبة (6%) للتربة الرملية (SM) و(8%) للتربة الغضارية (CH)، كما تحسنت قيمة (CBR) بشكل كبير حتى نسبة (8%) للتربة الرملية و(10%) للتربة الغضارية. بالإضافة إلى ذلك، انخفضت قابلية الانهيار والانتفاخ انخفاضًا كبيرًا مع زيادة نسبة المعالجة بالإسفلت السائل، مما يؤكد فعالية هذه التقنية في تحسين متانة التربة.

يبرز هذا البحث إمكانية استخدام الإسفلت السائل كحل مبتكر وفعّال لمعالجة الترب الجبسية، مما يساهم في تعزيز متانة وقدرة تحمل منشآت الري ويطيل عمرها الافتراضي. نوصي بتطبيق هذه التقنية في المشاريع الزراعية والهيدروليكية في المناطق الجافة. كما نأمل أن يشكل هذا البحث أساسًا لأبحاث مستقبلية تستكشف تقنيات معالجة أخرى ومقارنتها بالنتائج التي توصلنا إليها.

الكلمات المفتاحية: الترب الجبسية، معالجة التربة، الإسفلت السائل، قابلية الانهيار، الابتكار الزراعي، تقنيات الري المستدام.

المقدمة:

تتميز الترب الجبسية بخصائص ميكانيكية عالية وذات بنية مستقرة في حالتها الجافة إلا أنها تصبح عرضةً للانهيار عند ترطيبها، لذلك فهي تتطلب اهتماماً خاصاً عند تنفيذ المشاريع والمنشآت الهندسية وخاصةً المنشآت الهيدروليكية كأقنية الري والسدود.

تعتبر أقنية الرّي من أهم المنشآت التي تُستخدم لاستجرار المياه من المصادر المائية "كالأنهار أو البحيرات" إلى المناطق التي تفتقر إلى المصادر المائية وخاصةً في المناطق الجافة وشبه الجافة التي لا يتجاوز معدل الهطول السنوي للأمطار 250 mm سنوياً كما هو الحال في المنطقة الشرقية والشمالية الشرقية من الجمهورية العربية السورية حيث قامت الحكومة السورية بتنفيذ مشروع ري لمدينة الرقة، المشروع عبارة عن أقنية ري إسمنتية مكشوفة بطول 600 كم ولم يؤخذ بالحسبان وجود الجبس في أرضية الأساسات وعند دخول أقنية الري حيز التشغيل عام 1973 حدث تسريب للمياه بين الأقنية مما أدى إلى إذابة الجبس أسفل الأساسات مسبباً الانهيار والهبوط في منشآت الري بعد 20 -10 يوماً من الاستثمار (MLA, Ministry of Local Administriation, 2008) (Aldagher, 2000).

في العراق: أدى الذوبان المستمر للجبس في تربة الأساس لسد الموصل إلى نشوء فراغات داخل بنية التربة مما دفع بالمهندسين إلى حقن أرضية السد بالإسمنت لملء هذه الفراغات المتكونة (Shakir, 2017). تنتشر الترب الجبسية بشكل شاسع في العالم وتشغل أكثر من 90 مليون هيكتار وتبلغ مساحة هذه الترب في سوريا حوالي (20-22%) من مساحتها وتنتشر بكثرة في المناطق الشرقية والشمالية الشرقية (Ilaiwi, 1983).

تعتمد انحلالية الجبس في الماء على عدة عوامل (Food and Agricultural Organaziation of the United Nation, 1990):

- منها التركيب الكيمائي للمحلول المائي
- درجة الحرارة
- الضغط
- نوع الشوارد المنحلة وتركيزها في المحلول، وسرعة جريان الماء

إن سلوكية الترب التي تحتوي على الجبس تختلف عن بقية أنواع الترب إذ إنَّ خواصه الفيزيائية والكيمائية تميزه عن كافة أنواع المينرالات وتجعل من قياس الرطوبة وتحديد التركيب الحبي والوزن النوعي للتربة ولاحقاً الخصائص المرتبطة بها أمراً معقداً ولهذا فإن وجود الجبس في التربة لا سيما إذا كان مركباً رئيسياً يقتضي استخدام منهجيات نوعية وتقنيات خاصة بالترب الجبسية (Cooper, 1998) .

نظراً للتأثيرات السلبية والمشاكل العديدة التي تسببها الترب الجبسية فقد قام العديد من الباحثين بتحسين خصائص هذه الترب باستخدام عدة إضافات منها (الإسمنت والجير والإسفلت والبوليمرات... وغيرها)، إن اختيار نوع الإضافة (المثبت) يعتمد على ما هو الهدف أو الغاية من التثبيت فإذا كان الغاية من التثبيت زيادة المقاومة يجب اعتماد مثبت يؤمن زيادة في المقاومة، أما إذا كان الغاية هي العزل فيجب البحث عن مثبت يؤمن العزل الكافي لحماية التربة من التغيرات الحجمية التي تطرأ على التربة نتيجة وصول الماء (Al-Harbawy, A.F.Q., Al-Khashab, M.N.,، 2004).

يعتبر التثبيت بالإسفلت شكلاً سلبياً من أشكال التثبيت أي أنه لا يوجد تفاعل كيمائي بين الترب ومادة الإسفلت المضافة، كما أن آلية التثبيت بالإسفلت تختلف اختلافاً كبيراً عن تلك المستخدمة في تثبيت الترب بالإسمنت والكلس. الآلية الأساسية في التثبيت بالإسفلت للترب الناعمة هي العزل مما

يحسن من المقاومة والمتانة حيث تُغلف حبيبات التربة بالإسفلت مما ينتج غشاء أو غلافاً من الإسفلت يمنع تغلغل ووصول المياه إلى حبيبات التربة، أما في الظروف العادية فتؤدي إلى انخفاض مقاومة القص، مقاومة الضغط، ومعامل المرونة وغيرها من الخصائص الميكانيكية، إلا أن جزيئات التربة المغلفة بالإسفلت هي أكثر مقاومة للآثار الضارة للمياه مثل التغير الحجمي المرتبط بتغير الرطوبة (American Road & Transportation Builders Association، 1989)

هدف وأهمية البحث:

إن الاهتمام بدراسة سلوكية الترب الجبسية من وجهة نظر هندسية له أهمية كبيرة في تقدير المخاطر المحتملة واقتراح الحلول المناسبة عند استخدامها كقواعد تأسيس للمنشآت الحديثة المراد إقامتها على هذه الترب، تتركز أهمية البحث في تقديم رؤية واضحة حول تأثير الجبس على الخصائص الهندسية للترب بتغير محتواها من الجبس، كما يركز على مدى ملاءمة الإسفلت في تحسين خصائص الترب الجبسية للترب بتغير محتواها من الجبس.

مراجعة الأدبيات:

تناولت الدراسة تأثير الجبس على حدود القوام (حدود اتربيرغ) ووجدت أن إضافة الجبس إلى التربة تؤدي إلى تقليل حدود السيولة واللدونة وقرينة اللدونة كما أن قابلية الانهيار للترب الطينية الجبسية والتربة الرملية تزداد مع محتوى الجبس (Ismael, N. F, 1993).

كما أشارت الدراسة إلى أن انحلال الجبس يؤدي إلى زيادة نفاذية التربة ونسبة الفراغات وانضغاطيتها كما أشارت النتائج إلى أن الجبس يعمل على خفض قدرة تحمل التربة (American Road & Transportation Builders Association, 1988).

بينت الدراسة أن استخدام الإسفلت السائل يحسن من قدرة تحمل التربة تحت ظروف مشبعة (Shakir, 2017).

منهجية البحث:

يعتمد البحث على المنهج التجريبي حيث تم إحضار عينات من الترب الجبسية من منطقتين مختلفتين، الأولى من محافظة دير الزور وتحديداً من منطقة كباجب على عمق 1.5 متر من سطح الأرض وصُنفت التربة بناءً على نظام التصنيف الموحد USCS على أنها تربة رملية سلتية SM، محتوى الجبس (32%)، أما التربة الثانية فقد أُحضرت من محافظة حمص وتحديداً من منطقة السخنة على عمق أيضاً متر من وصُنفت التربة بناءً على نظام التصنيف الموحد USCS تربة غضارية عالية اللدونة CH ذات محتوى جبسي (30.6%) علماً أن كلتا التربتين هي ترب غير سليمة البنية "عينات مقلقلة".

التجارب المخبرية المنفذة:

تم تحديد الخواص الفيزيائية والميكانيكية للترب بناءً على سلسلة من التجارب:

- الوزن النوعي (ASTM D-2261)
- بروكتور النظامي (ASTM D698-91)
- القص المباشر (ASTM D3080-98)
- التحليل الحبي (ASTM C117-17) (ASTM C136-06)

- حدود آتربيرغ (ASTM D-4318)
- الانتفاخ الحر (ASTM D4546-98)
- احتمالية الانهيار (ASTM D5333-92)
- تجربة الانضغاطية (ASTM D-2435)

حيث تم تقسيم مراحل العمل إلى ثلاث مراحل:

- المرحلة الأولى: وهي تحديد الخواص الفيزيائية والميكانيكية للتربتين خلال إجراء التجارب الواردة في الفقرة السابقة. يبين الجدول (1) الخواص الفيزيائية والميكانيكية الرئيسية للتربتين.
- المرحلة الثانية: يمكن أن نلخصها بنزع الجبس من التربتين ومن ثم إضافته بنسب مختلفة لكلتا التربتين ومن ثم دراسة تغير الخصائص الفيزيائية والميكانيكية لكل نسبة من نسب الجبس المضافة للتربتين.
- بالنسبة للجبس المراد إضافته فقد أُحضر من المنطقة الشرقية على شكل كتل صخرية تم تنظيفها ثم طحنها وتمريرها على المنخل (No 200 ASTM) وذلك لسهولة الخلط مع الترب المدروسة علماً أنه تم تحديد خصائص الجبس من خلال إجراء التحاليل الكيمائية في معمل الإسمنت بطرطوس وتبين أن الصيغة الكيمائية للجبس المستخدم هي ($CaSo_4 2H_2o$) ووزنه النوعي ($G_s = 2.3$) ونسبة الشوائب (8.21%). يبين الجدول (2) خصائص مادة الجبس المستخدمة.
- المرحلة الثالثة: فقد شملت إضافة مادة الإسفلت السائل بنسب متفاوتة إلى الترب بمحتواها الأصلي من الجبس. الجدول (3) يبين خصائص الإسفلت المستخدم.

تم إحضار مادة الإسفلت من مصفاة بانياس عيار (70/50) Bitumen حيث تم تصنيعه وفقاً للمواصفات القياسية السورية. تم خلط مادة الإسفلت بمادة الكيروسين القابلة للتطاير بنسبة (للإسفلت 92% وللكيروسين 8%) بعد تعريض الإسفلت لدرجة حرارة ($80\ C^0$) لمدة ثلاث ساعات وذلك لجعل مادة الإسفلت سائلة لمدة زمنية من أجل خلطها مع التربة المراد دراستها.

الجدول (1) الخواص الفيزيائية والميكانيكية الرئيسية للتربتين

الترب المختبرة		مستودعات كباجب	موقع مبنى بلدية السخنة
رمز التربة		I	II
نسبة الجبس %		32	30.6
محتوى الرطوبة البدائي	$\omega\%$	9.7	18.7
الوزن الحجمي الرطب	γ_b t/m3	1.68	1.80
الوزن الحجمي الجاف	γ_d t/m3	1.53	1.48
الوزن النوعي	G_s	2.51	2.57
نسبة الرمل	S %	61.5	17.1
نسبة السيلت	M %	32.8	42.12
نسبة الغضار	C %	5.7	40.78
حد السيولة	$\%WL$	29	67.2
حد اللدونة	WP %	25.2	36.4
دليل اللدونة	IP %	3.8	30.8

التربة المختبرة		مستودعات كباجب	موقع مبنى بلدية السخنة
زاوية الاحتكاك الداخلي	$\Phi\ degree$	28	10
التماسك	$C\ kPa$	0.21	0.34
الوزن الجاف الأعظمي	$\gamma_{d\ Max}\ \mathrm{t/m3}$	1.64	1.52
الرطوبة الأصولية	$\omega_{opt}\ \%$	11.2	18
احتمالية الانهيار	$\%C_p$	10.31	14.7
التصنيف حسب نظام USCS		SM	CH

الجدول (2) يبين خصائص مادة الجبس المستخدمة

اسم المينرال	النسبة المئوية المتوسطة في الصخر
Al2O3	0.28%
SO3	47.5%
CaO	33.9%
LOI	10.39%
Sio2	1.1%
Fe2o3	0.23%
MgO	0.7%
T.c	5.2%
نسبة CaSo4.2H2O	91.79%
نسبة الشوائب	8.21%

الجدول (3) الخصائص الفيزيائية والكيمائية لمادة الإسفلت المستخدمة

الخصائص		الصنف (70/50)	طريقة الاختبار المعتمدة
الوزن النوعي	G_s	1.05	ASTM
الغرز بدرجة 25o	0.1 mm	(70 – 50)	ASTM D5
درجة التلين	co	(54 – 46)	ASTM D36
المط عند الدرجة 25o كحد أدنى	Cm	100	ASTM D113
درجة الوميض حد أدنى	C^0	230	ASTM D92
نسبة الذوبان في ثلاثي كلور الإيتلين كحد أدنى	% Weight	99.0	ASTM D2042
الفاقد بالتسخين عند درجة حرارة 163o ولمدة خمس ساعات كحد أدنى	% Weight	1.0	ASTM D6
نسبة التغير في الغرز بعد التسخين للدرجة 163o ولمدة خمس ساعات حد أدنى	%	53	ASTM D1754

طريقة إزالة الجبس من التربة:

من أجل دراسة تأثير الجبس على الخصائص الهندسية للتربة تم أولاً إزالة الجبس من التربتين عن طريق أخذ كمية كافية من كل تربة ووضعها في حوض كبير يحتوي على الماء، حُركت التربة داخل الحوض لعدة

دقائق ومن ثم الانتظار إلى أن تترسب، بعد انتهاء عملية الترسيب تم تبديل ماء الحوض للتخلص من الجبس، كُررت العملية عدة مرات وفي كل مرة يتم استبدال الماء داخل الحوض. تم التأكد من غسل الجبس من التربتين بشكل كامل عن طريق تحليل ماء الغسل وقياس كمية الجبس في التربتين.

النتائج:

تم تقسيم النتائج إلى مجموعتين: المجموعة الأولى إظهار تأثير محتوى الجبس على خصائص التربة والمجموعة الثانية إظهار تأثير الإسفلت على الخصائص الهندسية للترب الجبسية:

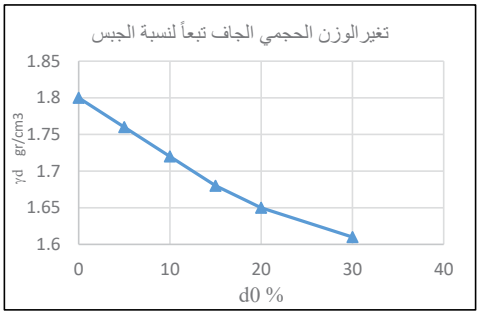
المجموعة الأولى: إظهار تأثير محتوى الجبس على خصائص التربة:

تأثير محتوى التربة من الجبس على الوزن الحجمي الجاف الأعظمي والرطوبة الأصولية:

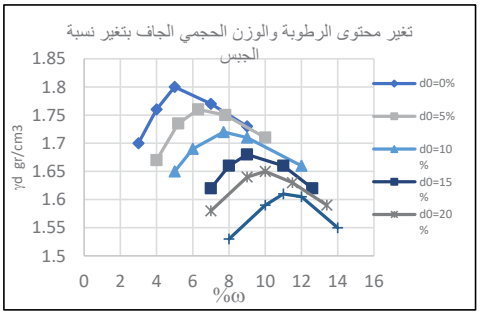
أُجريت تجربة الرّص باستخدام جهاز بروكتور النظامي على خمس عينات من التربة المأخوذة من منطقة كباجب، بعد إزالة الجبس منها وتجفيفها تم إضافة الجبس بالنسب التالية ($d_0 =$ $0, 5, 10, 15, 20, 30$ %) وقد حصلنا على النتائج المبينة في الجدول 4 والأشكال (1، 2، 3).

الجدول 4 تغير الوزن الحجمي الجاف الأعظمي ومحتوى الرطوبة الأصولية بتغير نسبة الجبس

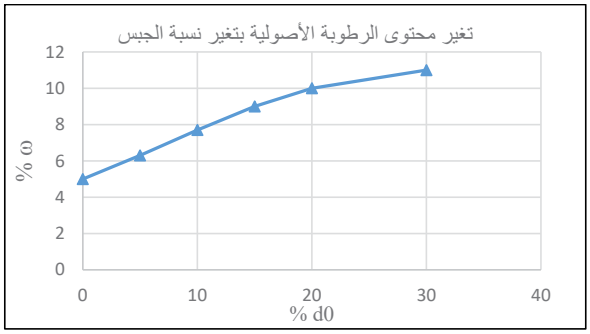
Υ_d	ω	Υ_d	ω	Υ_d	ω	Υ_d	ω	Υ_d	ω	Υ_d	ω
1.53	8	1.58	7	1.62	7	1.65	5	1.67	4	1.7	**3**
1.59	10	1.64	9	1.66	8	1.69	6	1.735	5.2	1.76	**4**
1.61	11	1.65	10	81.6	9	1.72	7.7	1.76	6.3	1.8	**5**
1.605	12	1.63	11.5	1.66	11	1.71	9	1.75	7.8	1.77	**7**
1.55	14	1.59	13.4	1.62	12.6	1.66	12	1.71	10	1.73	**9**



الشكل (2) تغير الوزن الحجمي الجاف بتغير نسبة الجبس



الشكل (1) تغير محتوى الرطوبة والوزن الحجمي الجاف بتغير نسبة الجبس



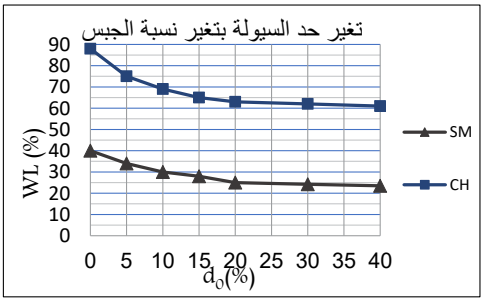
الشكل (3) تغير محتوى الرطوبة بتغير نسبة الجبس

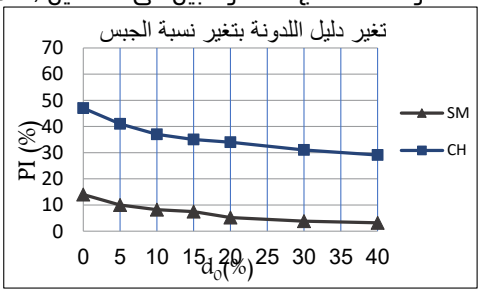
يُلاحظ من الشكل (2) انخفاض قيمة الوزن الحجمي الجاف الأعظمي بزيادة محتوى التربة من الجبس ويُعزى السبب إلى أن الوزن الحجمي للجبس أقل من الوزن الحجمي للتربة وكذلك فإن الشكل (3) يُظهر أن الرطوبة الأصولية تزداد بزيادة محتوى التربة من الجبس لأن الجبس يحتاج إلى رطوبة أكبر أي أنه شره جداً للماء.

تأثير محتوى الترب من الجبس على خصائص اللدونة:

أُجريت تجربة حدود آتربيرغ على التربتين السابقتين بعد نزع الجبس والمارتين من المنخل No 40 ثم تم إضافة الجبس بنسب متفاوتة لكلتا التربتين ((% $\boldsymbol{d_0 = 0, 5, 10, 15, 20, 30, 40}$).

بعد إضافة الجبس للترب تم إضافة الماء إلى العينات من أجل كل نسبة من نسب إضافة الجبس وتُركت لمدة 24 ساعة لإتاحة المجال للتفاعلات الكيمائية الممكن أن تحدث بين التربة والجبس بوجود الماء وكانت النتائج كما هو مبين في الشكلين (4، 5).





الشكل (4) تغير حد السيولة بتغير نسبة الجبس

الشكل (5) تغير دليل اللدونة بتغير نسبة الجبس

نلاحظ من الشكلين (4،5) أن حد السيولة ودليل اللدونة يتناقصان بشكل كبير مع زيادة نسبة الجبس حتى 10% للترب (SM) وحتى نسبة 15% للتربة (CH) حيث يحصل تبادل شاردي كامل لشوارد الكالسيوم $\boldsymbol{Ca^{+2}}$ مع الكاتيونات الموجودة في الغضار، ومن المعروف أن شوارد الكالسيوم تمتاز بقدرتها على تجميع حبيبات الغضار الناعم الموجودة في التربة. هذا الأمر يؤدي إلى حدوث تكتلات وتجمعات

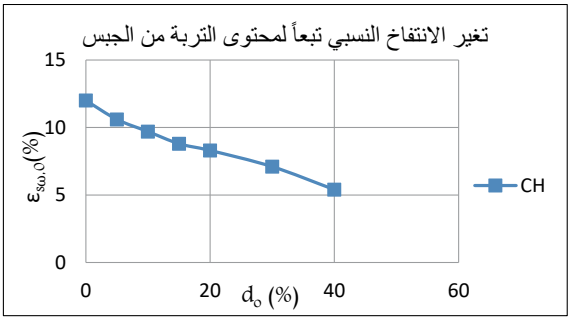
لحبات الغضار ونتيجةً لذلك ينقص السطح النوعي للتربة وبالتالي تقل كمية المياه المغلفة للحبات أي تتناقص الرطوبة.

بينما مع زيادة نسبة الجبس عن النسب السابقة لكلتا التربتين يصبح التغير في قيمة حد السيولة ودليل اللدونة أقل حدة، وقد يُفسر ذلك ببقاء قسم من شوارد الكالسيوم غير متبادلة وذلك على اعتبار أنه تم تثبيت وزن التربة البدائي قبل خلطها بالجبس وبالتالي تساهم بلورات الجبس غير المنحلة في زيادة السطح النوعي ولكن بنسبة أقل من الحالة الأصلية للتربة.

تأثير محتوى التربة من الجبس على الانتفاخ للتربة:

أُجريت تجارب الانتفاخ وفقاً لـ ASTM باستخدام جهاز الانضغاطية (الآدومتر) ذي حلقة مساحتها $\boldsymbol{40cm^2}$. شُكلت العينات من الترب الغضارية عالية اللدونة CH المأخوذة من منطقة السخنة بعد نزع الجبس وبرطوبة أولية قدرها (15%) وبوزن حجمي جاف ($\boldsymbol{1.55\ gr/cm^2}$).

ثم أُضيف الجبس بالنسب التالية ($\boldsymbol{d_0 = 0, 5, 10, 15, 20, 30, 40}$ %)، بعدها أُشبعت العينات بالماء، لكل نسبة من النسب السابقة والسماح لها بالانتفاخ. الشكل (6) يوضح تغير الانتفاخ النسبي الحر للتربة تبعاً لمحتوى التربة من الجبس.



الشكل (6) تغير الانتفاخ النسبي تبعاً لمحتوى التربة من الجبس

يظهر المنحنى السابق في الشكل (6) تغير الانتفاخ النسبي بزيادة محتوى التربة من الجبس. هذا السلوك مرتبط بقابلية الانتفاخ المرتفعة لمينرالات التربة الغضارية الخالية من الجبس مقارنةً مع جزيئات الجبس الخاملة باعتبارها مشبعة بالماء وسطوحها البلورية لا تحتوي على شحنات غير مرتبطة لتسمح بجذب إضافي للماء، وبالتالي فإن كافة مظاهر الانتفاخ في الترب عائدة للمينرالات الغضارية بهذه الحالة، لهذا فهي تتناقص مع ارتفاع المحتوى الجبسي على حساب المحتوى الغضاري في التربة.

تأثير محتوى الجبس على انضغاطية التربة:

لدراسة تأثير محتوى التربة من الجبس على قابليتها للانضغاط، تم إجراء تجربة الانضغاطية ضمن جهاز الآدومتر على العينات من الترب الغضارية عالية اللدونة CH المأخوذة من منطقة السخنة بعد نزع الجبس ومن أجل قيم مختلفة من الرطوبة، تم اعتماد طريقة المنحنيين لتحديد مقدار الانحلال النسبي.

أُجريت التجارب على العينة الأولى برطوبات أولية، أما العينة الثانية فقد عُرضت لتيار مائي مستمر وذلك بوضعها بحلقة انضغاطية تتميز بقدرتها على تصريف بغية غسلها من الجبس، وقد استمرت عملية الغسيل حوالي الشهر تقريباً.

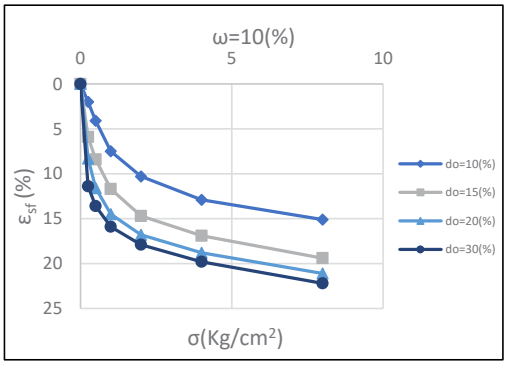
شُكلت العينات بوزن حجمي جاف $\gamma_d = 1.55\ gr/cm^2$ وكانت العينات تتكون من مجموعتين رئيسيتين:

المجموعة الأولى: أُجريت التجارب في ظروف الرطوبة الأولية فقط (دون غمر).

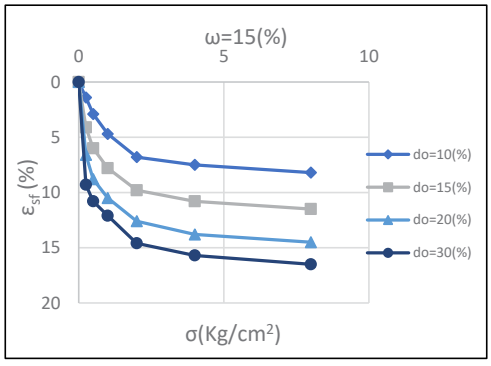
المجموعة الثانية: أُجريت التجارب على العينات بعد تعريضها لتيار مائي مستمر.

علماً أن كلتا المجموعتين تتكون من مجموعات ثانوية، كل مجموعة توافق رطوبة ثابتة واحدة من القيم ($\omega = 10 - 15 - 20 - 25\%$) وكل مجموعة من المجموعات الثانوية تتكون من أربع عينات، كل عينة توافق نسبة محددة من الجبس ($d_0 = 10, 15, 20, 30\ \%$)

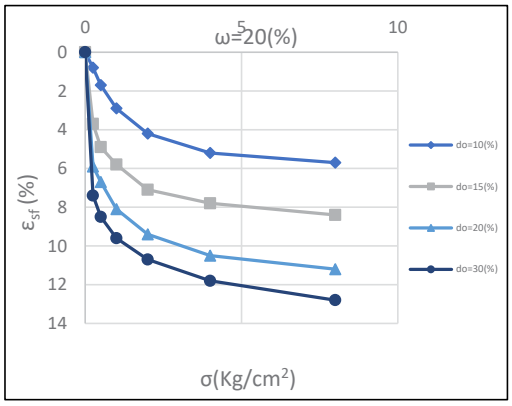
توضح الأشكال التالية (7، 8، 9، 10) العلاقة بين الإجهاد المطبق والهبوط الانحلالي تبعاً لمحتوى التربة من الجبس.



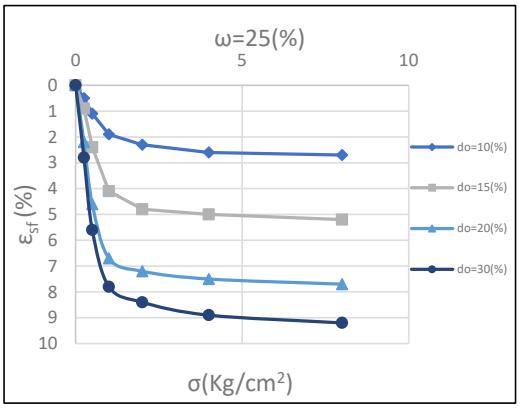
الشكل (7) تغير الهبوط الانحلالي تبعاً للإجهاد المطبق تحت رطوبة أولية (10%)



الشكل (8) تغير الهبوط الانحلالي تبعاً للإجهاد المطبق تحت رطوبة أولية (15%)



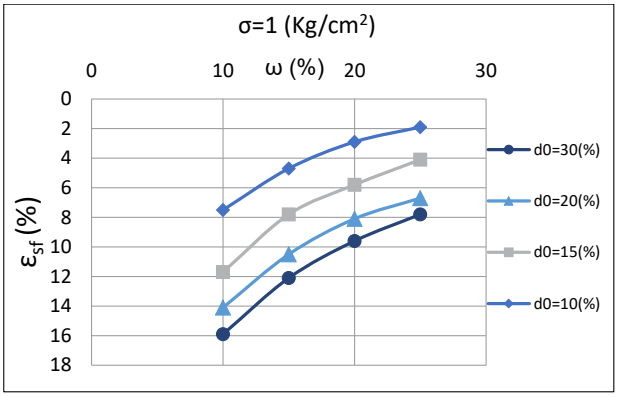
الشكل (9) تغير الهبوط الانحلالي تبعاً للإجهاد المطبق تحت رطوبة أولية (20%)



الشكل (10) تغير الهبوط الانحلالي تبعاً للإجهاد المطبق تحت رطوبة أولية (25%)

نلاحظ من المنحنيات أن الهبوط الانحلالي يزداد بزيادة الإجهادات المطبقة على العينة مهما كان محتوى التربة من الجبس.

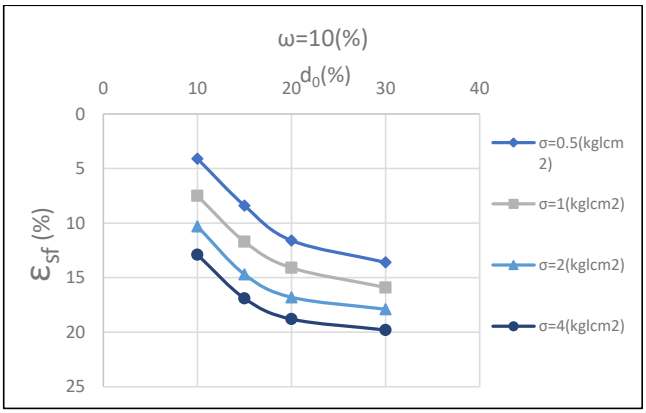
لإبراز تأثير رطوبة التربة على قيم الهبوط الانحلالي فقد أُجريت التجربة على عينات متباينة في رطوبتها الأولية وكذلك بمحتوى الجبس ومن أجل إجهاد ثابت وتم الحصول على النتائج المبينة في الشكل (11).



الشكل (11) تغير الهبوط الانحلالي مع الرطوبة الأولية من أجل إجهاد $\sigma = 1\ kg/cm^2$

يبدو من الشكل (11) أنه يتناقص مقدار الهبوط الانحلالي بزيادة الرطوبة الأولية، ومن الجدير بالذكر أن جزءاً من الجبس يبدأ بالانحلال من أجل الرطوبة المشكلة بها وتزداد نسبة الجبس المحلولة بزيادة الرطوبة المشكلة بها مما يفسر انخفاض قيمة الهبوط الانحلالي مع زيادة الرطوبة الأولية للعينات.

يُظهر الشكل (12) تأثير محتوى الجبس على قيم الهبوط الانحلالي من أجل محتوى رطوبة (10%).



الشكل (12) تأثير محتوى التربة من الجبس على قيم الهبوط الانحلالي من أجل رطوبة أولية (10%)

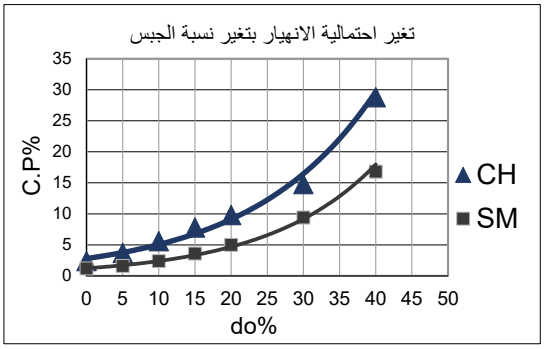
تبين من الشكل السابق أن الهبوط الانحلالي يزداد بزيادة نسبة الجبس في التربة حيث إن الجبس عند خلطه مع التربة وبمحتوى رطوبة محدد يأخذ حجماً معيناً ويزداد هذا الحجم مع زيادة نسبة الجبس في التربة وعند غسل التربة ينحل الجبس تاركاً فراغاً في التربة مما يؤدي إلى زيادة الهبوط الانحلالي.

تأثير محتوى التربة من الجبس على قابلية الانهيار:

لحساب قابلية التربة للانهيار لكلتا التربتين تم استخدام الطريقة المقدمة من قبل [9] حيث شُكلت العينات بالوزن الحجمي الجاف الأعظمي والرطوبة الأصولية مع إضافة نسب مختلفة من الجبس ووُضعت في جهاز الانضغاط (الآدومتر)، بعدها تم تطبيق حمولات متدرجة وصولاً إلى إجهاد يساوي $\boldsymbol{\sigma_w = 2kg/cm^2}$ وعند هذا الإجهاد غُمرت العينة بالماء وتُركت لمدة 24h. علماً أنه تم حساب معامل الفراغات عند هذا الإجهاد قبل الغمر وبعد الغمر وتعطى قابلية التربة للانهيار بالعلاقة التالية:

$$\boldsymbol{C.p\% = \varepsilon_{sl}\% = \frac{e_1 - e_2}{1 + e_0} * 100\%}$$

يبين الشكل (13) قيم احتمالية الانهيار للتربتين بتغير نسبة الجبس المضافة حيث تزداد قابلية التربة للانهيار بزيادة نسبة الجبس المضافة وتكون الزيادة أكبر في الترب الغضارية عالية اللدونة.



الشكل (13) تغير احتمالية الانهيار بتغير نسبة الجبس للتربتين

المجموعة الثانية: إظهار تأثير الإسفلت على الخصائص الهندسية للتربة الجبسية:

تحضير العينات:

تم تحضير العينات المراد دراستها من الترب الأساسية وخلطها بنسب مختلفة من الإسفلت السائل مع زمن معالجة (72 hours) لضمان تبخر الكيروسين وبدرجة حرارة المختبر، بحيث أُخذت عينات جافة من كل تربة وتم ترطيبها بالرطوبة الأصولية الموافقة لكل تربة لنحصل بذلك على عينات مشكلة بالوزن الحجمي الجاف الأعظمي والرطوبة الأصولية الموافقة لكل نوع من التربة، بعدها تم إضافة لكل عينة نسبة محددة من الإسفلت السائل ($\boldsymbol{E.A = 0 - 2 - 4 - 6 - 8 - 10 - 12}$ %)، تم خلط التربة مع الإسفلت السائل بشكل جيد حتى تجانس القوام لنحصل بذلك على عينات مشكلة بالوزن الحجمي الجاف الأعظمي والرطوبة الأصولية من أجل كل نسبة من الإسفلت السائل المضافة مع العلم أنه تم اتخاذ زمن معالجة وقدره (72 hours) لضمان تبخر مادة الكيروسين.

تأثير إضافة الإسفلت السائل على مقاومة الضغط غير المحصور:

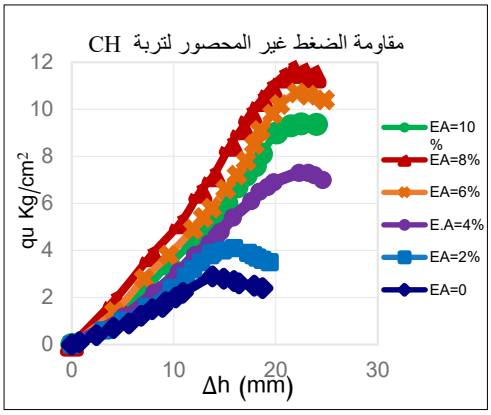
أُخذت عينتان جافتان من كلتا التربتين ونُخلت على المنخل ($\boldsymbol{N_{10} = 2mm}$) وبعدها تم تشكيل العينات كما هو وارد في الفقرة السابقة (4.6). تم إجراء تجربة الضغط غير المحصور للعينات المعالجة بالإسفلت ذات النسب ($\boldsymbol{E.A = 0 - 2 - 4 - 6 - 8 - 10}$ %)، وبسرعة تحميل ($\boldsymbol{0.8\ mm/min}$)، تم تسجيل قراءة التشوه الموافقة لمؤشر القوة.

يُظهر الشكل (14) تغير مقاومة الضغط غير المحصور تبعاً لمحتوى التربة من الإسفلت السائل والانتقال الموافق لبلوغ المقاومة القصوى، حيث يبدو بوضوح أن مقاومة الضغط غير المحصور ($\boldsymbol{q_u}$) تزداد كلما زاد محتوى التربة من الإسفلت السائل حتى نسبة معينة، بعدها تنخفض المقاومة مع زيادة محتوى التربة من الإسفلت السائل.

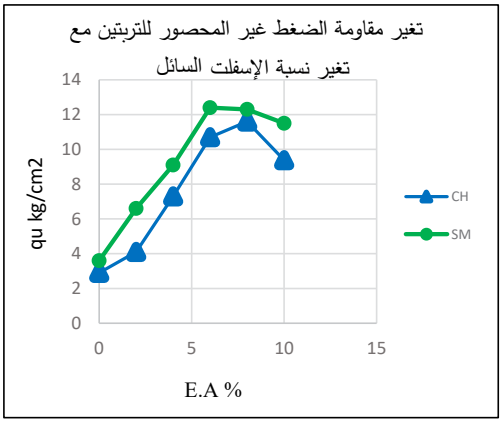
إنَّ الزيادة في مقاومة الضغط غير المحصور مع إضافة الإسفلت السائل تعود إلى زيادة قوة التماسك بين جزيئات التربة من خلال توفر طبقات رقيقة متواصلة من الإسفلت السائل الذي يُغلف ذرات التربة حتى قيمة مثالية من نسبة الإسفلت السائل مما يؤمن زيادة في التماسك، بعدها تنخفض مقاومة

الضغط غير المحصور مع زيادة محتوى التربة من الإسفلت السائل، يعود ذلك إلى زيادة في سماكة طبقة الإسفلت السائل المغلف لذرات التربة حيث ينخفض التماسك وتقل زاوية الاحتكاك الداخلي بين ذرات التربة بزيادة نسبة الإسفلت السائل عن تلك القيمة.

أما الشكل (15) فيظهر تغير مقاومة الضغط غير المحصور للتربتين بتغير نسبة الإسفلت السائل المضاف، حيث يبدو بوضوح أن مقاومة الضغط غير المحصور (q_u) بالنسبة لتربة (CH) تزداد كلما زاد محتوى التربة من الإسفلت السائل حتى نسبة معينة وهي (8%)، بعدها تنخفض المقاومة مع زيادة محتوى التربة من الإسفلت السائل، أما بالنسبة للتربة (SM) فقد بلغت مقاومة الضغط غير المحصور قيمتها العظمى عند محتوى (6%) وعند زيادة محتوى الإسفلت السائل عن هذه النسبة بدأ مقاومة الضغط غير المحصور بالانخفاض. أي نستطيع القول إنَّ التحسن يكون أكبر للترب الخشنة (SM) كما أن النسبة المثالية للإسفلت السائل المضاف للتربة تتعلق بنوع التربة المراد معالجته فكلما زادت نعومة التربة تحتاج التربة لنسبة أكبر من الإسفلت السائل والتحسن يكون أقل مقارنةً مع التربة الخشنة مما يجعلنا نستنتج ملاءمة هذا الأسلوب في تقوية الترب الجبسية للترب الخشنة.



الشكل (14) مقاومة الضغط غير المحصور للعينات المشكلة بنسب مختلفة من الإسفلت السائل لتربة CH



الشكل (15) تغير مقاومة الضغط غير المحصور للتربتين مع تغير نسبة الإسفلت السائل

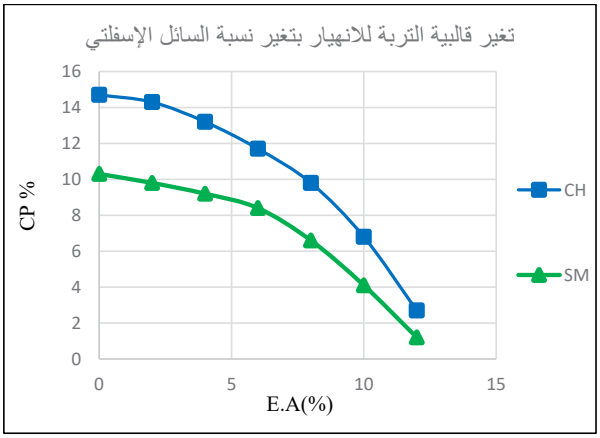
تأثير إضافة الإسفلت السائل على قابلية التربة للانهيار:

لدراسة تأثير الإسفلت السائل على قابلية التربة للانهيار لكل من التربتين السابقتين تم استخدام تجربة الآدومتر ذات حلقة تشديد مساحة مقطعها ($A = 40cm^2$) وارتفاع ($H = 2cm$) حيث شُكلت العينات بالوزن الحجمي الجاف الأعظمي والرطوبة الأصولية وبعدها تم إضافة الإسفلت بالنسب التالية ($E.A = 0 - 2 - 4 - 6 - 8 - 10 - 12\%$) كما هو وارد في الفقرة السابقة (4-1).

بعد تشكيل العينات ووضعها في حلقة التشديد تم تحميل العينات بحمولة تدريجية وصولاً إلى إجهاد قدره ($\sigma = 2kg/cm^2$) وعند هذا الإجهاد تم غمر العينات بالماء لإشباعها وتُركت لمدة 24 ساعة مع العلم أنه تم حساب معامل الفراغات e_1 قبل الغمر وe_2 بعد الغمر وتم حساب قابلية التربة للانهيار وفقاً للمعادلة التالية:

$$C.P = \frac{e_1 - e_2}{1 + e_0}$$

يُظهر الشكل (16) تغير قيم قابلية التربة للانهيار بتغير نسبة الإسفلت حيث تتناقص قابلية التربة للانهيار بزيادة نسبة الإسفلت وكلما زادت نسبة الإسفلت تنخفض قابلية التربة للانهيار ويعود ذلك لأن الإسفلت السائل يُغلف ذرات الجبس بطبقة رقيقة وبالتالي يقلل من انحلالية الجبس الموجود بالتربة وبالتالي تقليل من قابلية التربة للانهيار.

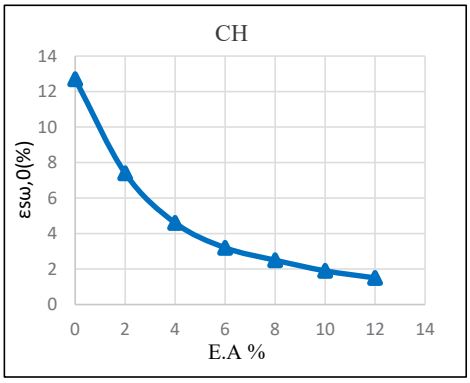


الشكل (16) تغير قيم قابلية التربة للانهيار بتغير نسبة الإسفلت السائل

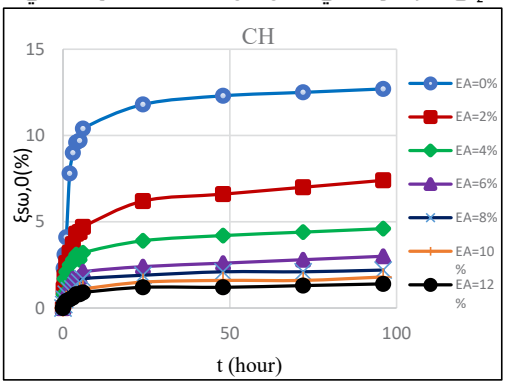
تأثير إضافة الإسفلت السائل على خصائص الانتفاخ للتربة:

أُجريت تجارب الانتفاخ وفقاً لمواصفات (ASTM, 1993) باستخدام تجربة الآدومتر بحلقة تشديد مساحة مقطعها ($A = 40cm^2$) وارتفاع ($H = 2cm$). أُجريت التجارب على التربة المأخوذة من منطقة السخنة (CH). شُكلت العينات برطوبة مساوية للرطوبة الأصولية وبوزن حجمي جاف مساوٍ للوزن الحجمي الجاف الأعظمي وبنسب مختلفة من الإسفلت السائل ($E.A = 0 - 2 - 4 - 6 - 8 - 10 - 12$ 14%)، بعد تشكيل العينات أُجريت تجارب التشديد بوضع العينات في جهاز الآدومتر وغُمرت بالماء، وبعدها تم قياس الانتفاخ النسبي الحر لجميع العينات، بعد الحصول على قيمة الانتفاخ النسبي الحر تم تحميل العينات بحمولات متدرجة للحصول على قيمة الانتفاخ لكل نسبة من الإسفلت السائل المضاف إلى التربة. (تم إشباع التربة بالماء بعد مضي 3 أيام على إضافة الإسفلت السائل).

الشكلان (17)، (18) يوضحان تغير الانتفاخ النسبي الحر تبعاً لنسبة الإسفلت السائل المضاف إلى التربة، الشكل (17) يوضح انخفاض قيمة الانتفاخ النسبي الحر بزيادة نسبة الإسفلت المضافة للتربة. ويُفسر هذا الانخفاض بأن السائل الإسفلتي يملأ فراغات التربة ويغلف حبيبات التربة بغشاء رقيق يمنع دخول الماء إلى التربة وبالتالي يقلل من قيمة الانتفاخ النسبي الحر.

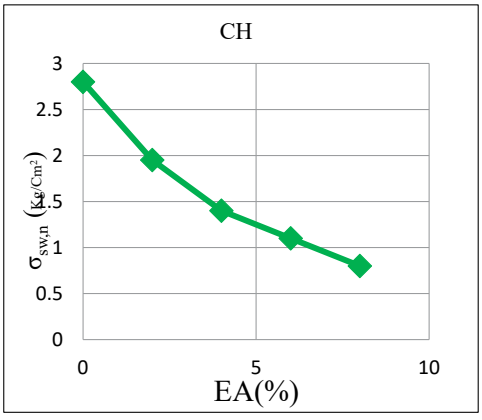


الشكل (17) تغير الانتفاخ النسبي الحر تبعاً لمحتوى التربة من الإسفلت السائل

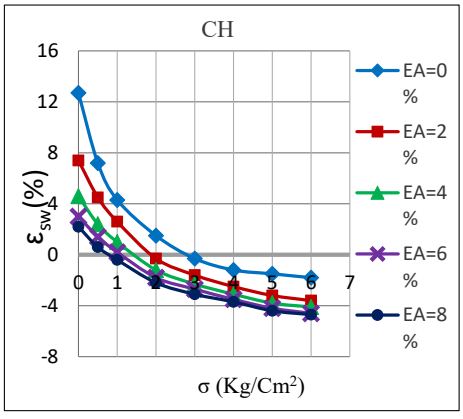


الشكل (18) تغير الانتفاخ النسبي مع الزمن تبعاً لمحتوى التربة من الإسفلت السائل

لإظهار تغير تشوهات الانتفاخ للتربة المعالجة بالإسفلت السائل تحت تأثير الإجهادات أجرينا تجربة التشديد حيث طُبقت حمولات متدرجة وقد حصلنا على النتائج الموضحة في الأشكال (19)، (20). نلاحظ أن ضغط الانتفاخ يتناقص مع زيادة نسبة الإسفلت إلى التربة.



الشكل (20) تغير ضغط الانتفاخ تبعاً لمحتوى التربة من الإسفلت السائل

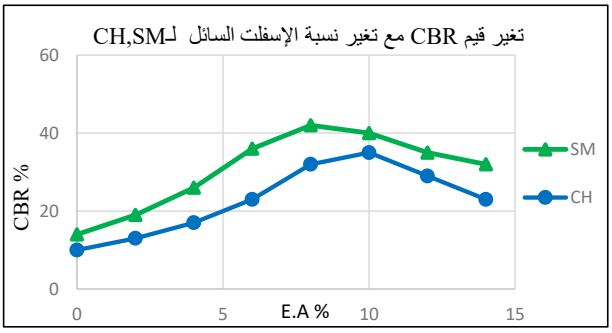


الشكل (19) تغير الانتفاخ النسبي مع الإجهاد من أجل نسبة محددة من الإسفلت

تأثير إضافة الإسفلت السائل على مقاومة CBR:

أُخذت عينتان جافتان من كلتا التربتين، بعدها قُسمت كل عينة إلى ثمانية أجزاء متساوية وبعدها شُكلت العينات كما هو وارد في الفقرة السابقة (3-3) ومن أجل النسب التالية من السائل الإسفلتي ($\boldsymbol{E.A = 0 - 2 - 4 - 6 - 8 - 10 - 12 - 14}$ %).

أظهرت نتائج التجارب التي أُجريت على كلتا التربتين كما هو مبين في الشكل (5) أن قيم CBR% تزداد بزيادة محتوى التربة من الإسفلت السائل المضاف إلى التربة حتى قيمة (8%) بالنسبة للترب الخشنة (SM) وحتى قيمة (10%) بالنسبة للتربة الناعمة (CH) أي أن التربة (CH) تحتاج إلى قيمة أكبر من الإسفلت السائل لبلوغ القيمة القصوى لـ CBR% في حين أن التربة (SM) تحتاج إلى قيمة أدنى من الإسفلت السائل، أما نقصان قيم CBR% بزيادة نسبة الإسفلت السائل عن هذه القيم لكلتا التربتين فيُعزى لزيادة اللدونة في التربة مما يؤدي إلى زيادة تغلغل المكبس في تجربة CBR.



الشكل (20) تغير قيم CBRمع تغير نسبة الإسفلت السائل لـ SM, CH

النتائج الرئيسية للبحث:

تأثير الجبس على خصائص التربة:

الخصائص الفيزيائية – انخفاض الوزن الحجمي للتربة وزيادة الرطوبة الأصولية مع زيادة نسبة الجبس:

الخاصية	بدون الجبس	نسبة الجبس 30%	نسبة التغير
الوزن الحجمي الجاف Kg/cm^3	1.79	1.63	انخفاض 9%
الرطوبة الأصولية ω_{opt}%	%5	%11	زيادة 120%

ويعد ذلك تدني قيمة الوزن الحجمي الجاف للجبس طبيعته الهيغروسكوبية "شره جداً للماء وبالتالي شديد الامتصاص".

خصائص اللدونة – تحسين في القوام ولكن هشاشة تحت التشبع:

الخاصية	بدون الجبس	نسبة الجبس 30%	نسبة التغير
حد السيولة (% WL)	%88.5	%62.3	انخفاض 30%
حد السيولة (% PI)	%46.3	%31	انخفاض 33.3%

وذلك بسبب التبادل الأيوني للشوارد Ca^{+2} الذي يعمل على تجميع حبيبات الغضار مما يقلل السطح النوعي ويخفض كمية الماء المطلوبة للتشبع وهذا يبدو إيجابياً لكنه يخفي هشاشة بنيوية تظهر عند التشبع الكامل.

قابلية الانهيار – تهديد مباشر لاستقرار المنشآت:

نوع التربة	بدون الجبس	نسبة الجبس 30%	نسبة التغير
الترب الرملية (SM)	2.1%	10.31%	زيادة 391%
الترب الرملية (CH)	3.5%	14.7%	زيادة 320%

يشكل الجبس هيكلاً مسامياً غير مستقر في الحالة الجافة وعند التشبع يذوب الجبس تاركاً فراغات هيكلية تؤدي إلى انهيار مفاجئ تحت الحمل.

الانتفاخ – تناقص طفيف لكن غير كاف:

الخاصية	بدون الجبس	نسبة الجبس 40%	نسبة التغير
الانتفاخ النسبي الحر (%)	%12	%5	انخفاض 58%

تنخفض قابلية الانتفاخ للترب الغضارية بزيادة نسبة الجبس، يعود السبب إلى استبدال الجزء النشط (الغضار) بجزء خامل (الجبس المشبع)، لكن هذه الميزة تُلغى أمام خطر الذوبان والانهيار الذي يسببه الجبس.

الهبوط الانحلالي – تهديد طويل الأمد:

حالة العينة	بدون الجبس	نسبة الجبس 30%	نسبة التغير
تحت إجهاد ($\sigma = 1kg/cm^2$)	%2	%7.8	زيادة 280%

يزيد الجبس من مسامية التربة ونفاذيتها مما يسهل عملية غسل وذوبان الجبس مع مرور الوقت مسبباً هبوطاً تراكمياً يهدد استقرار المنشآت على المدى البعيد.

- يظهر الجبس تحسناً ظاهرياً في بعض الخصائص (اللدونة والانتفاخ) لكنه يُخفي مخاطر كارثية عند التشبع كما أن الجبس يجمع بين خاصيتين وهما الذوبان السريع والانهيار الكلي مما يجعله من أخطر التحديات الجيوتكنيكية ولا سيما أن محاولات التحكم بالرطوبة وحدها غير كافية بسبب طبيعة الجبس الهيغروسكوبية وقابليته العالية للذوبان.

تأثير الإسفلت على الخصائص الهندسية للترب:

تحسن ملحوظ في مقاومة التربة "تجربة الضغط غير المحصور" Unconfined Compressive Strength UCS:

نوع التربة	النسبة المثالية للإسفلت	نسبة الجبس 30%
الترب الرملية (SM)	6%	زيادة قدرها 255% مقارنة بالعينة غير المعالجة
الترب الرملية (CH)	8%	زيادة قدرها 286% مقارنة بالعينة غير المعالجة

- تعمل طبقة الإسفلت كمادة رابطة تعزز التماسك بين حبيبات التربة مما يزيد من قدرتها على تحمل الأحمال الشاقولية دون انهيار.

انخفاض مخاطر الانهيار (Collapse Potential):

- الترب الرملية (SM): تنخفض قابلية التربة للانهيار من 10.31% إلى 1.2% بنسبة تحسن قدرها 88.4%.
- الترب الغضارية (CH): تنخفض قابلية الترب للانهيار من 14.7% إلى 2.8% بنسبة تحسن 82%.

الغشاء الإسفلتي يشكل عازلاً فعالاً يمنع وصول الماء إلى حبيبات الجبس مما يقلل عملية الذوبان ويحافظ على استقرار بنية التربة.

التحكم في الانتفاخ (Swelling Potential):

- **الترب الغضارية (CH):** انخفاض الانتفاخ النسبي الحر من 12.7% إلى 2.2% بنسبة تحسن 82%.
- **ضغط الانتفاخ:** انخفض من 2.5 kg/cm^2 إلى 0.5 kg/cm^2 بنسبة تحسن 80%.

الإسفلت السائل يعمل على ملء الفراغات بين الحبيبات ويقلل من مساحة السطح النشط مما يحد من قدرة التربة على امتصاص الماء والانتفاخ.

أثبتت تقنية الإسفلت السائل كفاءة عالية في تحسين خصائص الترب الجبسية بنسب تتراوح بين 200% و250% في الخصائص الأساسية، كما أن نوع التربة له دور أساسي في تحديد النسبة المثالية لإضافة الإسفلت السائل حيث تعتبر نسب (8-10)% مناسبة للترب الغضارية ونسبة (6-8)% مناسبة للترب الرملية، كما يمكن لتقنية المعالجة هذه زيادة العمر الافتراضي لمنشآت الري بنسبة قد تصل إلى أكثر من 50% وفقاً للتقديرات الأولية.

التوصيات:

- تطبيق هذه التقنية في مشاريع الري والسدود في المناطق الجافة مثل الإمارات والسعودية والعراق.
- إجراء تحليل للتكلفة والعائد لمعالجة التربة بالإسفلت مقارنة مع الطرق التقليدية.
- إمكانية دمج الإسفلت مع مواد بوليمرية لتعزيز الفعالية وتقليل الكميات المستخدمة.

- استخدام مستشعرات رطوبة التربة وطرق الرصد الذكية لمراقبة أداء الترب المعالجة.

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Innovation in Treating Gypsum Soils to Enhance the Durability of Irrigation Infrastructure Using Modern Techniques

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Abstract:

Gypsum soils present a significant geotechnical challenge, particularly in arid and semi-arid regions dependent on irrigation projects. Although they possess favorable mechanical properties in their dry state, they lose their strength and become prone to collapse upon wetting, threatening the sustainability of hydraulic structures such as irrigation canals and dams. This research proposes an innovative solution to this problem using a modern technique based on Cutback Asphalt, aiming to enhance the soil's bearing capacity and prevent collapse.

Soil samples from two different gypsum regions in Syria were studied. Their physical and mechanical properties were analyzed by systematically varying the gypsum content. As an innovative part of the study, Cutback Asphalt treatment was applied to the soil with its natural gypsum content, and its effect on key properties was evaluated, including Unconfined Compressive Strength (UCS), California Bearing Ratio (CBR), and collapse and swelling potential.

The results indicated that the addition of Cutback Asphalt led to a significant improvement in soil properties. The Unconfined Compressive Strength peaked at an optimal content of 6% for sandy soil (SM) and 8% for clayey soil (CH). The CBR value also improved substantially, reaching optimal values at 8% for sandy soil and 10% for clayey soil. Furthermore, the collapse potential and swelling susceptibility decreased markedly with increasing Cutback Asphalt content, confirming the effectiveness of this technique in enhancing soil durability.

This research highlights the potential of Cutback Asphalt as an innovative and effective solution for stabilizing gypsum soils. Its application can contribute to enhancing the durability and load-bearing capacity of irrigation infrastructure, extending its service life. We recommend implementing this technique in agricultural and hydraulic projects in arid regions. We also hope this study will serve as a foundation for future research exploring other treatment methods and comparing them with our findings.

Keywords:

Gypsum soils, Soil stabilization, Cutback Asphalt, Collapse potential, Agricultural innovation, Sustainable irrigation technologies.

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دراسة كيميائية حيوية لأوراق السدر(*Ziziphus spina-christi*) كمصدر طبيعي لمضادات الأكسدة وداعم للاستدامة الصحية بالمملكة العربية السعودية

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ملخص البحث:

يأتي هذا البحث ليعيد قراءة الإعجاز النبوي في ضوء التحليل العلمي الحديث، من خلال دراسة شجرة السدر (*Ziziphus spina-christi*)بوصفها نموذجًا يجمع بين الطابع الإيماني والابتكار العلمي في خدمة صحة الإنسان واستدامة البيئة. بدأت الدراسة من رؤية تستلهم من التراث الإسلامي النبوي في استثمار موارد الطبيعة، بالتالي قدمت تفسيرًا علميًا للخصائص العلاجية التي نُسبت إلى هذه الشجرة المباركة عبر العصور.

كشفت الدراسة عن غنى أوراق السدر التي جُمعت من منطقة الليث بالمملكة العربية السعودية بمركبات فعالة مثل الفينولات والفلافونويدات والتربينويدات، التي لها قدرة عالية على تثبيط الجذور الحرة ومقاومة الالتهابات وتقوية المناعة الطبيعية للجسم بشكل ملحوظ وفعّال. كما بيّنت الدراسة أن المستخلص الإيثانولي يتميز بأعلى فعالية مضادة للأكسدة، مما يجعله مرشحًا مناسبًا لتطوير منتجات دوائية وتجميلية طبيعية.

كما تم تحليل أوراق السدر باستخدام تقنيات كيميائية متقدمة من أبرزها التحليل الكروماتوغرافي الغازي المقترن بمطياف الكتلة .(GC–MS) يتفرد هذا البحث في قدرته على الربط بين الهدي النبوي والابتكار العلمي المعاصر، حيث يقدّم دليلًا علميًا واضحًا على بركة السدر من خلال معرفة وفهم مكوناته الكيميائية الحيوية، ثم توظيفها في تحقيق الاستدامة الصحية توافقًا مع رؤية المملكة 2030 وأهداف التنمية المستدامة للأمم المتحدة، مع إبراز دور البحث في دعم الاقتصاد الحيوي وتعزيز استخدام الموارد النباتية المحلية بصورة مستدامة.

الكلمات المفتاحية: نبات السدر، مضادات الأكسدة، الاستدامة الصحية، مركبات نشطة بيولوجيًا.

المقدمة:

يُعدّ التداوي بالنباتات الطبية من أقدم مجالات المعرفة التي ارتبطت بالإنسان منذ نشأة الحضارات الأولى، وقد شكّل هذا المجال أساسًا مهمًا لتطوّر الطب الحديث والصيدلة المعاصرة .ومع التقدم الكبير في تقنيات التحليل الكيميائي والحيوي، أصبح من الممكن إعادة دراسة كثير من النباتات التي استُخدمت تقليديًا في العلاج والتحقق من فعاليتها بأساليب علمية دقيقة.

تُعد شجرة السدر من أبرز النباتات التي حظيت بمكانة خاصة في التراث الإسلامي والطب الشعبي على حدّ سواء حيث ارتبط اسمها بالطهارة والشفاء واستُخدمت أجزاؤها المختلفة في معالجة العديد من الاضطرابات الصحية .ولم يكن هذا الاستخدام عبر العصور قائمًا على التجربة العشوائية وحدها، بل تشير الدراسات الحديثة إلى أن هذه الشجرة تحتوي على مجموعة متنوعة من المركبات الكيميائية الفعالة التي تمنحها خواص علاجية متعددة.

ومع ازدياد الاهتمام العالمي بالطب البديل والمنتجات الطبيعية برزت الحاجة إلى دراسة النباتات الطبية المحلية دراسة علمية منهجية بهدف الاستفادة منها في تطوير منتجات دوائية وغذائية وتجميلية آمنة، تسهم في تعزيز مفهوم الاستدامة الصحية وتقليل الاعتماد على المركبات الكيميائية الصناعية . ويأتي نبات السدر في مقدمة هذه النباتات لما يتميز به من وفرة في البيئات الجافة وشبه الجافة، ومقاومة طبيعية للظروف القاسية.

وانطلاقًا من هذا الإطار، تهدف هذه الدراسة إلى توصيف المكونات الكيميائية الحيوية لأوراق السدر المزروع في محافظة الليث بالمملكة العربية السعودية وتقييم نشاطه المضاد للأكسدة باستخدام اختبارات معملية دقيقة، من أبرزها اختبار القدرة على تثبيط الأكسدة إلى جانب تحليل المركبات الفعالة باستخدام تقنية الكروماتوغرافيا الغازية المقترنة بمطياف .كما تسعى الدراسة إلى ربط النتائج المخبرية الحديثة بما ورد في الهدي النبوي من إشارات إلى فضل السدر، في إطار علمي رصين يجمع بين الدلالة الإيمانية والبرهان التجريبي [1-3].

وتظهر أهمية هذه الدراسة من كونها تسهم في إبراز القيمة العلمية للنباتات الطبية المذكورة في السنة النبوية وتفتح آفاقًا جديدة لتوظيفها في مجالات الصحة الوقائية والصناعات الدوائية الطبيعية، بما ينسجم مع توجهات التنمية المستدامة ومع رؤية المملكة2030 .

مع التقدم السريع في علوم الكيمياء الحيوية والصيدلانية، ازدادت الحاجة إلى إعادة دراسة هذا الإرث النباتي بدقة علمية عالية بالاعتماد على التقنيات التحليلية الحديثة مثل الكروماتوغرافيا الغازية المقترنة بمطياف الكتلة (GC–MS) لتحديد المركبات الفعالة بيولوجيًا وفهم آليات تأثيرها على الجسم البشري. وقد أظهرت الدراسات الأولية أن نبات السدر غني بمجموعة متنوعة من المركبات الحيوية، بما في ذلك الفينولات والفلافونويدات والزيوت العطرية الطيارة التي ترتبط بقدرات قوية مضادة للأكسدة، ما يجعله خط الدفاع الأول ضد الإجهاد التأكسدي والأمراض المزمنة مثل السرطان وأمراض القلب، ويسهم في مكافحة الشيخوخة المبكرة وتعزيز الصحة العامة [1-3].

ولا يقتصر أهمية هذه الدراسة على الجوانب الكيميائية فحسب، بل تمتد لتشمل البعد البيئي والجغرافي، إذ تم جمع أوراق السدر من محافظة الليث في المملكة العربية السعودية، وهي منطقة تتميز بخصائص بيئية فريدة قد تؤثر على التركيب الكيميائي للنبات، ما قد يمنحها تفوقًا نوعيًا مقارنة بمناطق أخرى. ويُعد هذا الجانب مهمًا، إذ يربط بين تنوع البيئة المحلية وجودة المركبات النشطة في النبات، مما يعزز قيمة البحث من منظور الاستدامة والابتكار البيولوجي[4].

تهدف هذه الدراسة إلى تحقيق توازن متكامل بين التراث والإعجاز النبوي من جهة والابتكار العلمي الحديث من جهة أخرى من خلال توصيف المكونات الكيميائية الحيوية لأوراق السدر، وتقييم فعاليتها كمصدر طبيعي لمضادات الأكسدة، مع التركيز على التطبيقات العملية في الصناعات الدوائية والغذائية والتجميلية. كما تسعى الدراسة إلى تعزيز مفهوم الاستدامة الصحية من خلال الاستفادة المثلى من الموارد النباتية المحلية، وربط المعرفة التقليدية بالأسس العلمية الحديثة بما يفتح آفاقًا جديدة للابتكار الطبي والصيدلاني ويبرز القيمة العالمية للنباتات الطبية الموروثة.

من خلال هذه الدراسة، نسعى إلى تقديم نموذج علمي يجمع بين الإرث التراثي والابتكار العلمي مع ربطها بالاستدامة البيئية والصحية حتى تكون مساهمة نوعية في دعم البحث العلمي في المملكة العربية السعودية على المستوى الدولي، ويوضح قدرة النباتات التقليدية على إيجاد حلول طبيعية مبتكرة للتحديات الطبية المعاصرة بما يعزز مكانة المعرفة المحلية على الخريطة العلمية العالمية.

الدراسات السابقة:

أظهرت الدراسات السابقة أن نبات السدر (*Ziziphus spina-christi*) يمتلك قيمة طبية وكيميائية عالية حيث أوضحت الدراسات التراثية والطبية التقليدية أن استخدامه الطبي له أساس علمي واضح، حيث يحتوي النبات على تاريخ طويل من الاستخدام في الطب الشعبي لعلاج العديد من الحالات مثل السكري، الملاريا، مشاكل الجهاز الهضمي والتيفوئيد وأمراض الكبد وضعف الطاقة والالتهابات الجلدية أيضًا، اضطرابات التبول والسمنة والإسهال[5-6].

يوجد دراسة تمت على أوراق شجرة السدر المزروعة في منطقة اليمن، حيث أظهرت هذه الدراسة أن المستخلص الإيثانولي أعطى نشاطًا جيدًا مضادًا للبكتيريا من النوع *Staphylococcus aureus*, *Pseudomonas aeruginosa*, *Bacillus cereus* [7]. وفي دراسة أجريت في منطقة الرياض بالمملكة العربية السعودية حيث أفادت هذه الدراسة أن المستخلص الكحولي يحتوي على مركبات فينولية وفلافونويدات وتانينات، هذه المركبات قادرة على تثبيط الطفيليات أو إفساد بيئتها داخل الخلايا وتقليل الإجهاد التأكسدي الذي تسببه العدوى، ممّا يفسر انخفاض الطفيليات وتحسن وظائف الكبد والحالة الدموية[8].

أظهرت عدة دراسات وأطروحات في جامعات عراقية، مثل المستنصرية والكوفة، أن مستخلصات أوراق *Ziziphus spina-christi* تمتلك نشاطًا مضادًا لمجموعة من الممرضات الشائعة، بما في ذلك *S. aureus, Klebsiella, Proteus, Pseudomonas* و*E. coli*. وقد أظهرت النتائج أن المستخلصات

الكحولية (الميثانول أو الإيثانول) أعطت فعالية أكبر من المستخلصات المائية في تثبيط نمو البكتيريا، حيث لوحظت مناطق تثبيط أكبر وأدنى قيم MIC و MBCفي العديد من التجارب المخبرية (MIC = الحد الأدنى من التركيز المثبط؛ MBC = الحد الأدنى من التركيز القاتل). وأيضًا بعض الدراسات[9-14]قارنت أيضًا بين تأثير الأوراق واللحاء أو مزيج الاثنين، فتبين أن المزيج غالبًا يعطي أفضل نشاط مضاد للبكتيريا. هذه النتائج تدعم الاستخدام التقليدي للسدر في الطب الشعبي وتؤكد أن المذيبات العضوية تعزز استخلاص المركبات الفعالة مثل الفلافونويدات والتانينات، مما يزيد من القدرة المثبطة للبكتيريا. ورغم تقدم هذه الدراسات، تبقى هناك حاجة لإجراء تجارب شاملة تشمل جميع الممرضات البكتيرية الشائعة وتحليل المركبات الفعالة لتحديد الفعالية الدقيقة لكل مستخلص ومذيب[9-14.]

في دراسة أجريت على أوراق السدر التي تم جمعها من شمال كردفان في السودان، تمَّ استخراجها مبدئيًّا باستخدام جهاز Soxhlet ثم تحليلها عبرGC-MS ، حيث كشفت النتائج عن وجود سبعة عشر مركباً كيميائياً فعّالاً من بينها **erythritol** و**hydroquinone** و**decanal** و**benzofuran**، وبالإضافة إلى مركّبات أخرى تُعرف بقدرتها المضادة للأكسدة والمضادة للميكروبات. وقد أظهرت المستخلصات نشاطاً عالياً على عدد من البكتيريا مثل Escherichia coli و Pseudomonas aeruginosaو Bacillus subtilisبالإضافة إلى نشاط مضادّ للأكسدة مقارن باستخدام(2,2-diphenyl-1-picrylhydrazyl) DPPH . إن هذه النتائج تدعم الاستخدام التقليدي للنبات كمضاد للميكروبات ومصدر لمضادات الأكسدة، وتُظهر أن تركيبة الأوراق النباتية تحتوي على مركّبات تُستخلص بفعالية وتساهم في التأثير البيولوجي المُلاحَظ[15]. بالإضافة إلى ذلك آخرون من إحدى محافظات جنوب مصر (محافظة المينا) أجروا دراسة على أوراق *Ziziphus spina-christi*، تمكنوا من عزل مركبين جديدين من الصابونينات من نوع dammaraneأُطلق عليهما christinin E وchristinin F.أظهرت اختبارات السمية الخلوية أن هذين المركبين يمتلكان نشاطًا قويًا مضادًا لعدة خطوط خلوية سرطانية، بما في ذلك A 49 وU87 وMDA-MB-231وCT-26، مع تأثير ملحوظ حتى عند تركيزات منخفضة. تُشير هذه النتائج إلى أن مركبات السدر الجديدة قد تشكل مصدرًا واعدًا لتطوير أدوية مضادة للسرطان، كما تدعم القيمة البيولوجية العالية للنبات في التطبيقات الطبية الحديثة[16].

في دراسة على أوراق السدر المزروعة في شمال المملكة العربية السعودية ضمن بيئة جافة جدًا وبرد شديد، أظهر الباحثون عبر تحليل GC-MS وجود 38مركبًا كيميائيًا مهمًا، من بينها حمض الأوكتاديكانويك (Octadecanoic acid, 2-hydroxy-1-(hydroxymethyl)-ethyl ester) بنسبة 18.80% من المجموع. كما شملت الفئات الكيميائية المكتشفة الصابونينات والفينولات والتانينات، ما يبرّر خصائصها المضادة للأكسدة والمضادة للفطريات. هذه التركيبة الكيميائية تعكس القيمة البيولوجية العالية للنبات المزروع محليًا، وتوحي بإمكانية استخدامه في تطبيقات دوائية وطبية متنوعة[17].

تمت دراسات محدودة على أشجار هذه النبتة المزروعة في المناطق الجبلية بشمال المملكة العربية السعودية، حيث أظهرت التحاليل الكيميائية وجود فئات رئيسية من المركبات مثل الصابونينات والفينولات والتانينات. أظهرت هذه المستخلصات نشاطًا مضادًا للأكسدة، وتم قياسه جزئيًا باستخدام اختبارDPPH ، مع قيم IC_{50} تشير إلى تأثير ملحوظ في تثبيط الجذور الحرة. ورغم ذلك، لا توجد دراسات منشورة تفحص عينات من مناطق جبلية محددة مثل مكة المكرمة باستخدام مستخلصات متعددة القطبية أو اختبار DPPH. هذه النتائج توضح القيمة البيولوجية للنبات المزروع محليًا وتبرز الحاجة لإجراء

دراسات أكثر تفصيلاً على مختلف المناطق السعودية لتقييم تأثير البيئة على تركيبته الكيميائية والنشاط الحيوي[18]. على الرغم من الدراسات المتعددة التي أُجريت على أشجار *Ziziphus spina-christi* المزروعة في المناطق الجبلية والجافة في المملكة العربية السعودية، لم تُنشر أي دراسة تقييمية لعينات من أشجار السدر المزروعة في المناطق الساحلية مثل منطقة الليث التي تتميز بالجفاف والملوحة العالية. الدراسات الحالية ركّزت بشكل أساسي على تقييم التركيب الكيميائي للنبات باستخدام تحاليل مثل GC-MS، وكذلك النشاط البيولوجي للمستخلصات من حيث مضادات الأكسدة باستخدام اختبار .DPPH غياب هذه البيانات عن المناطق الساحلية يوضح وجود فراغ بحثي مهم، حيث من المحتمل أن تؤثر الظروف البيئية الساحلية، مثل الرطوبة والملوحة ودرجة الحرارة، على تركيب المركبات الكيميائية والنشاط الحيوي للنبات. لذلك، تمثل منطقة الليث موقعًا مناسبًا لإجراء دراسة جديدة لتقييم تأثير البيئة الساحلية على القيمة البيولوجية والكيميائية لأشجار السدر المزروعة فيها.

المواد والطرق :(Materials and Methods)

جمع العينات وتحضيرها:

تم جمع أوراق نبات السدر *(Ziziphus spina-christi)* خلال شهر أبريل من عام 2025 من محافظة الليث التابعة لمنطقة مكة المكرمة بالمملكة العربية السعودية (شكل 1). بعد الجمع، تُركت الأوراق لتجف في الظل تحت درجة حرارة الغرفة لمدة أسبوعين. وتم التأكد من اكتمال التجفيف بالوصول إلى وزن ثابت. بعد ذلك، طُحنت الأوراق المجففة وخُزِّنت في حاويات معتمة ومحكمة الإغلاق في مكان جاف وبارد وذلك لاستخدامها في الاستخلاص والتحليل الكيميائي.

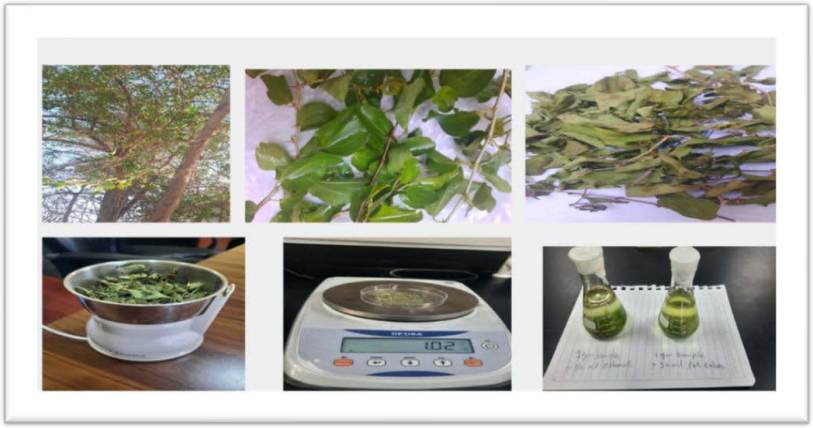


شكل 1: خريطة المملكة العربية السعودية موضحة موقع محافظة الليث

تجهيز المحاليل والقياسات:

تم تنفيذ هذه التجارب في معامل قسم الكيمياء بالكلية الجامعية في الليث – جامعة أم القرى – المملكة العربية السعودية، حيث تم وزن 1 جرام من أوراق السدر المجففة ثم طحنها ووضعها مع 50 مل من كل من مذيب الميثانول (قطبي) ومذيب الإيثر البترولي (غير قطبي). ثم وضعهما في عبوات محكمة الإغلاق

ووضعهما على جهاز orbital shakerلمدة ليلة كاملة Overnight. ثم بعد ذلك تم ترشيح المحاليل للحصول على المستخلص الرائق وهو الذي يستخدم بعد ذلك للتقديرات العملية في هذا البحث (شكل 2).



شكل 2: خطوات تجهيز عينات أوراق السدر

الفحص الكيميائي النباتي الأولي:

تم إجراء الفحص الكيميائي النباتي الأوّلي (النوعي) بهدف تحديد وجود أو غياب المجموعات الرئيسة من المركبات الثانوية في المستخلصين الإيثانولي والمائي لأوراق النبات. وقد تم تنفيذ الاختبارات باستخدام إجراءات قياسية معتمدة، وذلك وفقًا لما ورد في المراجع[19,20].

الكشف عن الفينولات:

أُجري اختبار كلوريد الحديديك (Ferric Chloride Test) لتحديد وجود المركبات الفينولية، حيث أُضيفت بضع قطرات من محلول كلوريد الحديديك ($FeCl_3$) بتركيز 1% إلى 2 مل من المستخلص. يشير ظهور لون أخضر مزرق أو أخضر مسود إلى وجود الفينولات والتانينات في العينة[19].

الكشف عن الفلافونويدات:

تم الكشف عن الفلافونويدات باستخدام الكاشف القلوي(Alkaline Reagent Test) ، حيث أُضيفت بضع قطرات من محلول هيدروكسيد الصوديوم (NaOH) بتركيز 1% إلى 2 مل من المستخلص. أدى ذلك إلى ظهور لون أصفر كثيف، يختفي عند إضافة حمض الهيدروكلوريك المخفف، مما يدل على وجود الفلافونويدات[19].

الكشف عن الستيرويدات:

تم الكشف عن الستيرويدات باستخدام اختبار ليبرمان–بوشارد(Liebermann–Burchard Test) ، وذلك بإضافة 2 مل من حمض الخليك اللامائي إلى 0.5 مل من المستخلص الميثانولي، ثم إضافة 2 مل من

حمض الكبريتيك المركز (H_2SO_4) بحذر على جدار الأنبوب. يُشير ظهور لون أخضر مزرق أو أخضر زمردي إلى وجود مركبات ستيرويدية[19].

الكشف عن الصابونينات:

تم تحديد وجود الصابونينات باستخدام اختبار الرغوة .(Foam Test) أُضيف 10 مل من الماء المقطر إلى 5 مل من المستخلص (المائي أو الإيثانولي المخفف)، ثم رُجّ الأنبوب بقوة لمدة دقيقتين. يُعتبر تكوين طبقة رغوية ثابتة بارتفاع يقارب 1 سم واستمرارها لمدة لا تقل عن 15 دقيقة دليلاً على وجود الصابونينات[21].

الكشف عن التربينويدات:

تم الكشف عن التربينويدات باستخدام اختبار سالكوفسكي(Salkowski Test) ، حيث أُضيف 2 مل من الكلوروفورم ($CHCl_3$) إلى 0.5 مل من المستخلص الإيثانولي، ثم أُضيف بحذر 3 مل من حمض الكبريتيك المركز (H_2SO_4) على طول جدار الأنبوب لتكوين طبقتين. يشير ظهور حلقة بنية مائلة إلى الحمرة عند السطح البيني إلى وجود التربينويدات[21](شكل 3).



شكل 3: اختبار الكشف اللوني الكيفي للمركبات النباتية النشطة في أوراق نبات السدر (الفينولات – الفلافونويدات –الستيرويدات – الصابونينات –التربينات) من اليسار لليمين بالترتيب

التقديرات الكمية:

تقدير الفينولات بطريقة فولن

تم تقدير المحتوى الكلي من الفينولات في المستخلص الإيثانولي (القطبي) ومستخلص الإيثر البترولي (غير القطبي) لأوراق *Ziziphus spina-christi* باستخدام كاشف فولن–سيوكالتيو(Folin–Ciocalteu) ، وذلك بالاعتماد على الطريقة القياسية المذكورة في المرجع [22]مع إجراء بعض التعديلات البسيطة بما يلائم طبيعة العينات. تم أخذ 300 ميكروليتر من المستخلص الخام وإضافة 3 مل من الماء المقطر إليه، ثم أضيف 0.5 مل من كاشف فولن–سيوكالتيو، وتُرك الخليط لمدة 3 دقائق في درجة حرارة الغرفة. بعد ذلك تمت إضافة 2 مل من محلول كربونات الصوديوم (Na_2CO_3) بتركيز 10%، ثم وُضعت العينات في الظلام لمدة ساعة لاستكمال التفاعل. تم قياس الامتصاصية عند طول موجي 750 نانومتر باستخدام جهاز المطيافية الضوئية. كما جرى إعداد جدول معايرة باستخدام تركيزات مختلفة من حمض الجاليك Gallic) (Acid (شكل 4).



شكل 4: طريقة فولن لتقدير الفينولات

تقدير الفلافونويدات الكلية بطريقة كلوريد الألومنيوم

تم قياس المحتوى الكلي للفلافونويدات في كل من المستخلص الإيثانولي (القطبي) ومستخلص الإيثر البترولي (غير القطبي) لأوراق السدر باستخدام طريقة كلوريد الألومنيوم($AlCl_3$) ، وذلك بالاستناد إلى الطريقة المنشورة في المرجع [23].

في بداية الإجراء، تم أخذ كمية مناسبة من كل مستخلص، ثم تم إكمال حجم العينة إلى 2 مل بواسطة الميثانول. بعد ذلك، أضيف محلول كلوريد الألومنيوم ($AlCl_3$) بتركيز 10% متبوعًا بإضافة محلول خلات الصوديوم.

تُركت العينات لتتفاعل خلال فترة محددة، ثم قيس الامتصاص الناتج عن ظهور اللون الأصفر المميز عند طول موجي 415 نانومتر باستخدام جهاز المطيافية الضوئية. ولغرض حساب كمية الفلافونويدات، جرى تحضير سلسلة من المحاليل القياسية لمركب الكويرسيتين (Quercetin) بتراكيز مختلفة لبناء منحنى المعايرة، والذي استُخدم في تقدير إجمالي الفلافونويدات بوحدة ملغم مكافئ كويرسيتين لكل غرام من الوزن الجاف للعينة.

طريقة DPPH لتقدير القدرة المضادة للأكسدة :

تم تقييم النشاط المضاد للأكسدة لمستخلصات أوراق السدر باستخدام اختبار الجذر الحر-2,2) DPPH (diphenyl-1-picrylhydrazyl، وذلك بالاعتماد على الطريقة القياسية الموصوفة في المرجع [24]. تقوم هذه الطريقة على مبدأ قدرة المركبات المضادة للأكسدة على اختزال الجذر الحرDPPH ، مما يؤدي إلى انخفاض تدريجي في اللون البنفسجي المميز للمحلول. ولأداء الاختبار، تم أخذ 1 مل من محلول DPPH في أنبوب اختبار، وأضيف إليه 3 مل من كل مستخلص بتركيزات مختلفة (25، 50، 100 ميكروغرام/مل) (شكل 5). كما تم تحضير أنبوب بلانك خالٍ من المستخلصات لاستخدامه كمرجع. بعد الخلط، تُركت الأنابيب في الظلام لمدة 30 دقيقة في درجة حرارة الغرفة لضمان اكتمال التفاعل بين مضادات الأكسدة والجذر الحر. عقب ذلك، قيس الامتصاص عند الطول الموجي 517 نانومتر باستخدام جهاز المطيافية الضوئية، وتم حساب النسبة المئوية للنشاط المضاد للأكسدة اعتمادًا على التغير في الامتصاصية مقارنةً بالبلانك، وذلك وفقاً للمعادلة التالية:

$$\text{التثبيط } \% = \frac{A_{DPPH} - A_S}{A_{DPPH}} \times 100$$

حيث :A_{DPPH}الامتصاص الضوئي لعينة البلانك.

A_S :الامتصاص الضوئي للعينة المحتوية على المستخلص.





شكل 5: طريقة DPPH لتقدير القدرة المضادة للأكسدة

استخلاص المركبات النشطة للتحليل الكروماتوغرافي الغازي (GC–MS)

تم استخلاص المركبات الكيميائية من 50 غرامًا من مسحوق أوراق السدر باستخدام 250 مل من الهكسان (95%) بطريقة النقع المستمر لمدة 72 ساعة مع التحريك الدوري، ثم تم ترشيح المستخلص وتركيزه تحت ضغط منخفض باستخدام المبخر الدوار عند درجة حرارة 40 °C للحصول على المستخلص الخام. حُفظ المستخلص في درجة حرارة 4 °C لحين إجراء.

تم إجراء التحليل باستخدام جهاز GC–MS من نوع Agilent Technologies 7890B/5977Aمزود بعمود شعري من نوع HP-5MSالطول 30 م، القطر الداخلي 0.25 مم، سمك الطبقة الثابتة 0.25 ميكرومتر. تمت برمجة درجة حرارة الفرن من 60 °C إلى 280 °C بمعدل زيادة 10°C/دقيقة. استُخدم غاز الهيليوم كغاز

ناقل بمعدل تدفق 1 مل/دقيقة. تم تحديد المركبات من خلال مقارنة أطياف الكتلة الناتجة بقاعدة بيانات NISTلتحديد المركبات النشطة بيولوجيًا.

التحليل الإحصائي:

تم تنفيذ جميع التجارب بثلاثة مكررات، وتم تحليل البيانات باستخدام تحليل mean SD ± لتحديد الانحراف المعياري، وذلك وفق الأسس البحثية الحديثة المبينة في المرجع [25].

النتائج والمناقشة(Results and Discussion) :

المركبات الأولية في كل من المستخلص الإيثانولي والمستخلص الإيثري أظهرت النتائج ما يلي:

- الفينولات :تظهر بشكل واضح في المستخلص القطبي بسبب ذوبانها العالي في الماء والكحول.
- الفلافونويدات :موجودة بقوة في المستخلص القطبي، وهي مضادات أكسدة مهمة.
- الستيرويدات :تتركز بدرجة أكبر في المستخلص غير القطبي بسبب طبيعتها غير القطبية.
- الصابونينات :موجودة بشكل ملحوظ في المستخلص القطبي، مع وجود ضعيف في المستخلص غير القطبي.
- التربينويدات :غالباً ما توجد في المستخلص غير القطبي، مع وجود ضعيف أو شبه غائب في المستخلص القطبي .وتم عرض النتائج في (جدول 1).

جدول 1: نتائج الفحص الأولي النوعي للمركبات الكيميائية في مستخلصات نبات السدر

المركبات	مستخلص قطبي (إيثانولي)	مستخلص غير قطبي (بترواليم إيثر)
الفينولات	++ (وجود قوي)	± (وجود ضعيف جداً)
الفلافونويدات	++ (وجود قوي)	± (وجود ضعيف)
الستيرويدات	± (وجود ضعيف)	++ (وجود قوي)
الصابونينات	++ (وجود قوي)	± (وجود ضعيف)
التربينويدات	± (وجود ضعيف)	++ (وجود قوي)

وجود الفينولات والفلافونويدات والصابونينات بوضوح في المستخلص القطبي يعود إلى قابلية ذوبانها في الماء والكحول، مما يدعم الدراسات التي أظهرت احتواء مستخلصات السدر الكحولية على هذه المركبات بكميات كبيرة، ما يفسر النشاط المضاد للأكسدة[26]. يتميّز المستخلص غير القطبي بمحتواه العالي من الستيرويدات والتربينويدات، ويُعزى ذلك إلى الطبيعة غير القطبية لهذه المركّبات. وقد دعمت دراسات عدّة على أوراق السدر (*Ziziphus spina-christi*) هذا الاتجاه، حيث أكّدت وجود هذه المركّبات بكميات ملحوظة في المستخلصات غير القطبية. كما أشارت الأبحاث إلى الدور الحيوي المهم لهذه

المركّبات بوصفها مكوّنات فعّالة تُسهم في العديد من الأنشطة البيولوجية للنبات، بما في ذلك النشاطات المضادة للأكسدة والمضادة للميكروبات.[27,28]

المحتوى الكلي من الفينولات والفلافونويدات والنشاط المضاد للأكسدة (DPPH) في مستخلصات السدر

تم تقييم النشاط المضاد للأكسدة باستخدام اختبار DPPH، الذي يعتمد على قدرة المستخلصات على تثبيط الجذور الحرة في كل من المستخلصين الرئيسيين: مذيبات قطبية (الإيثانول) ومذيبات غير قطبية (الإيثر).

حيث أعطى تقدير فولن أن مستخلص الإيثانول غني بمحتوى الفينولات، حيث بلغ متوسط محتوى الفينولات الكلية 0.13 ± 39.74 بينما بلغ محتوى الفلافونويدات 0.21 ± 18.5. أما مستخلص الإيثر البترولي فقد أظهر محتوى منخفضاً من الفينولات والفلافونويدات حيث بلغ 0.15 ± 8.16 و4.42 ± 0.17 على التوالي، بسبب طبيعة المذيب غير القطبي الذي يقلل من استخلاص المركبات القطبية الفعالة.

وبالنسبة للنشاط المضاد للأكسدة DPPH فقد سجل مستخلص الإيثانول نشاطاً مضاداً قوياً للأكسدة، حيث حقق نسبة تثبيط لجذور DPPH الحرة بلغت % عند تركيز 2.14 ملغ/مل، ويُعزى ذلك إلى ثراء المستخلص بالمركبات الفينولية والفلافونويدية التي تعمل كمانحي إلكترون وتثبط النشاط التأكسدي. وفي المقابل، أظهر مستخلص الإيثر نشاطاً أقل بكثير من تثبيط DPPH، مما يعكس انخفاض محتواه من مركبات الفينولات والفلافونويدات وفعاليتها المضادة للأكسدة (جدول 2).

جدول 2: نتائج التقدير الكمي للمركبات الكيميائية في مستخلصات نبات السدر

التقدير	مستخلص الإيثانول (قطبى)	مستخلص الإيثر (غير قطبى)
محتوى الفينولات الكلية (ملغ غ/جم)	0.13 ± 39.74	0.15 ± 8.16
محتوى الفلافونويدات الكلية (ملغ غ/جم)	0.21 ± 18.5	0.17 ± 4.42
النشاط المضاد للأكسدة(%) DPPH	2.14	1.84

ترتبط القوة المضادة للأكسدة لمستخلصات نبات السدر بشكل مباشر بمستوى الفينولات والفلافونويدات الموجودة فيها، إذ تُعتبر هذه المركّبات من مضادات الأكسدة الطبيعية الفعّالة التي تمنح المستخلصات القدرة على القضاء على الجذور الحرة الضارة وتثبيط عملية الأكسدة الذاتية. استخدام مذيبات قطبية مثل الإيثانول يزيد من استخلاص هذه المركّبات الفعّالة، مما يعزز النشاط المضاد للأكسدة كما يظهر في نتائج اختبار DPPH.

حيث تشير القيم المذكورة في الجدول 3 إلى ظهور ارتفاع واضح في فعالية تثبيط جذر DPPH عند زيادة تركيز المستخلصات المختلفة للنبات ويُلاحظ أن هذا الارتفاع له علاقة بالتركيز في كل من

المستخلصات القطبية وغير القطبية، وهذا يعكس قدرة هذه المستخلصات على التخلص من الجذور الحرة تدريجيًا عند زيادة الجرعة.

وقد أظهر المستخلص الإيثانولي أعلى نشاط مضاد للأكسدة عند جميع التراكيز، حيث أعطت نسبة التثبيط 89% عند تركيز 100 ملغم/مل، وهي أعلى بكثير من المستخلص الإيثري ويدل هذا النشاط المرتفع على المحتوى الكبير من المركبات الفينولية والفلافونويدية المعروفة بقدرتها الفعالة على اصطياد الجذور الحرة .

وهذا ما تدعمه دراسات متعددة تحدثت عن دور الفينولات والفلافونويدات كمضادات أكسدة طبيعية ذات فوائد صحية كبيرة. على سبيل المثال، مراجعة شاملة وصفت كيف تُسهم الفلافونويدات ضمن عائلة العديد الفينولات في إزالة الجذور الحرة والتبرير الميكانيكي لنشاطها المضاد للأكسدة [30,29]. أما الانخفاض الملحوظ في النشاط المضاد للأكسدة في مستخلص الإيثر فيعود إلى قلة المركبات الفينولية والفلافونويدية فيه نتيجة لطبيعة الذوبان في المذيبات غير القطبية .هذه النتائج تؤكد أهمية اختيار المذيب المناسب لاستخلاص المركبات النباتية الفعالة عند دراسة الخصائص المضادة للأكسدة لنبات السدر.

جدول 3: نسبة تثبيط جذر (%) DPPH لمستخلصات نبات السدر ومادة بيوتيل-4-هيدروكسي أنيزول (BHA)عند تراكيز مختلفة

التركيز (ملغم/مل)	تثبيط DPPH بواسطة المستخلص الإيثانولي(%)	تثبيط DPPH بواسطة مستخلص البترول إيثر(%)	تثبيط DPPH بواسطة BHA(السيطرة الموجبة) (%)
25	45 ± 0.25	18 ± 0.24	87 ± 0.23
50	72 ± 0.11	33 ± 0.19	90 ± 0.11
100	89 ± 0.24	53 ± 0.17	90 ± 0.29

المتوسط ± الانحراف المعياري

المركبات النشطة للتحليل الكروماتوغرافي الغازي (GC–MS):

جدول 4: أسماء ونسب المواد ذات الحصيلة الكبيرة في المستخلص الإيثانولي:

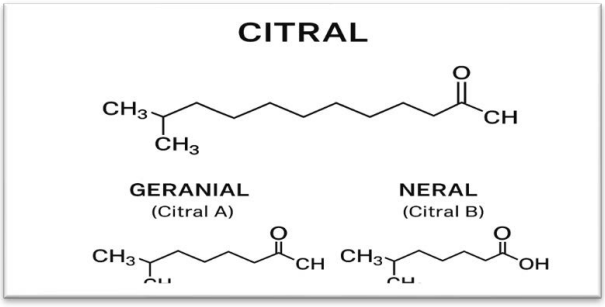
م	اسم المركب	زمن الإبقاء RT /دقيقة	نسبة المساحة تحت القمة Peak area %
1	α-Farnesene	18.6	4.0
2	Linalool	18.75	9.00
3	Zingerone	22.1	3.6
4	Citral	21.50	10.32
5	Terpineol	22.6	13.96
6	Palmitic acid	27.3	3.0
7	Farnesol	30.8	1.0
8	Methyleugenol	31.90	1.5
	Ethyl benzoate	32.75	14.0

أظهر تحليل كروماتوغرافي الغاز المقترن بمطياف الكتلة (GC–MS) لمستخلص أوراق السدر (Ziziphus spina-christi) التي تم جمعها من محافظة الليث بالمملكة العربية السعودية، احتواء المستخلص الإيثانولي على مجموعة متنوعة من المركبات النشطة بيولوجيًا التي تنتمي إلى فئات كيميائية متعددة، شملت المركبات الفينولية، والفلافونويدية، والمركبات التربينية، والأحماض الدهنية. ويُعزى هذا التنوع الكيميائي إلى طبيعة البيئة المحلية للنبات في محافظة الليث، إذ تسهم الظروف المناخية الساحلية الرطبة والتربة الغنية بالأملاح والمعادن في تحفيز إنتاج المركبات الثانوية (Secondary metabolites) المسؤولة عن النشاط الحيوي العالي للنبات. من أبرز المركبات التي تم تحديدها في المستخلص الإيثانولي لأوراق السدر: الستترال (6) citral، وهو مركب ألدهيدي عطري يمتاز بخصائص قوية مضادة للبكتيريا والفطريات، مما يجعله مكونًا فعّالًا في المستحضرات المطهّرة والعلاجية.

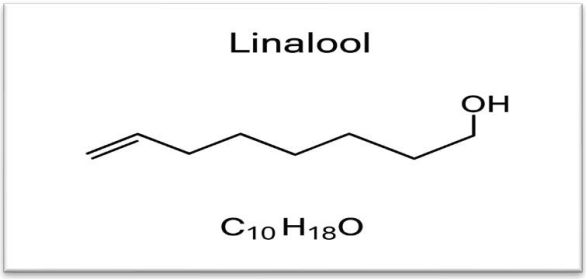
كذلك وُجد اللينالول (7) linalool، وهو مركب تربيني عطري واسع الانتشار في النباتات الطبية، وله تأثيرات مهدئة ومضادة للأكسدة، كما يساهم في حماية الخلايا من الإجهاد التأكسدي. أما التربينول (8) terpineol فهو مركب أحادي التربين يتميز بقدرته على مقاومة الميكروبات وتثبيط الجذور الحرة، إضافة إلى دوره في دعم الأنشطة المضادة للالتهابات.

كما تم الكشف عن حمض البالميتك (Palmitic acid)، وهو أحد الأحماض الدهنية المشبعة الأساسية التي تدخل في تكوين الأغشية الخلوية، وتسهم في استقرارها وتحسين الخصائص الفيزيولوجية للأنسجة.

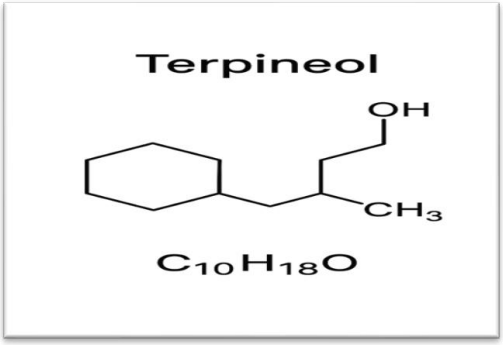
وأخيرًا، تم تحديد بنزوات الإيثيل (Ethyl benzoate) بنسبة عالية، وهو مركب عطري يمتلك خواص مضادة للالتهابات والبكتيريا، ويُستخدم في الصناعات الدوائية والعطرية بفضل رائحته المميزة واستقراره الكيميائي (جدول 4).



شكل 6: الصيغة الكيميائية لمركب الستترال ووجوده على هيئة متشابهين



شكل 7: الصيغة الكيميائية لمركب اللينالول



شكل 8: الصيغة الكيميائية لمركب التربينول

تُظهر هذه النتائج أن أوراق السدر في محافظة الليث تحتوي على مزيج متكامل من المركبات الفعالة ذات التأثيرات الحيوية المتعددة، مما يعزز مكانتها كمصدر طبيعي واعد لتطوير العقاقير النباتية ومضادات الأكسدة.

كما تدعم هذه البيانات الفهم العلمي لما ورد في الهدي النبوي الشريف حول بركة شجرة السدر، إذ تكشف التحاليل الحديثة عن الأساس الكيميائي للخصائص العلاجية التي أُشير إليها قديمًا، مما يفتح المجال أمام تطبيقات دوائية وتجميلية وصحية مستدامة تعتمد على الموارد النباتية المحلية.

وعند مقارنة هذه النتائج بدراسات أُجريت على نبات السدر في مناطق أخرى من المملكة العربية السعودية وبلدان مجاورة، تتضح اختلافات واضحة في التركيب الكيميائي والنشاط الحيوي تبعًا لاختلاف العوامل البيئية والجغرافية.

ففي منطقة المدينة المنورة، وُجد أن أوراق السدر تحتوي على نسب مرتفعة من الفلافونويدات مثل الكويرسيتين (Quercetin) والروتين (Rutin)، والتي تمنحها قدرة عالية على مقاومة الأكسدة والالتهابات.

أما في منطقة جازان، فقد تميزت العينات بارتفاع محتواها من الأحماض الدهنية غير المشبعة مثل الأوليك (Oleic acid) واللينوليك (Linoleic acid)، ما يجعلها أكثر ملاءمة للتطبيقات الغذائية والجلدية.

وفي المقابل، أظهرت دراسات أُجريت في مصر واليمن والسودان أن أوراق السدر في تلك المناطق تتفوق في محتواها من المركبات القلوية والعفصية (Alkaloids & Tannins)، وهي مركبات دفاعية تنتجها النباتات المتأقلمة مع البيئات الجافة أو شبه الجافة، وتمنحها خصائص قابضة ومطهّرة قوية.

وبذلك، يمكن القول إن الإعجاز النبوي في الإشارة إلى السدر يتجلى اليوم من خلال الكشف عن أسس علمية دقيقة توضّح سبب بركته وفوائده، وإن هذا النبات المبارك يشكّل نموذجًا فريدًا يجمع بين التراث الروحي والمعرفة العلمية. كما تمثل نتائجه دعوة إلى توظيف العلم الحديث في فهم الطب النبوي، لا بوصفه موروثًا تقليديًا فحسب، بل كمنظومة علمية متكاملة تحترم الطبيعة وتستمد من الوحي منهجًا في البحث والاكتشاف.

الدلالة الإعجازية لشجرة السدر في ضوء النص النبوي والتحليل الكيميائي الحيوي الحديث

يُعدّ الربط بين النصوص النبوية الشريفة والحقائق العلمية المكتشفة حديثًا من أعظم مظاهر الإعجاز العلمي في السنة النبوية، حيث تأتي التوجيهات النبوية موجزة في ألفاظها، عميقة في دلالاتها، سابقة لعصرها في إشاراتها العلمية. ومن بين هذه التوجيهات المباركة يبرز ذكر شجرة السدر بوصفها نموذجًا فريدًا يجمع بين الطهارة، والشفاء، والبركة.

وقد ورد ذكر السدر في القرآن الكريم في سياق عظيم، قال تعالى:

﴿عِندَ سِدرَةِ المُنتَهى﴾ سورة النجم: 14، كما ورد في السنة النبوية في مواضع متعددة، من أشهرها قول النبي ﷺ في غسل الميت:

اغسلنها ثلاثًا أو خمسًا أو أكثر من ذلك إن رأيتن، بماء وسدر (رواه البخاري ومسلم).

ويمثل هذا النص النبوي توجيهًا تشريعيًا دقيقًا لاختيار نبات بعينه في موضع يتطلب أعلى درجات الطهارة والتعقيم، وهو ما يفتح باب التساؤل العلمي عن السر الكامن وراء هذا الاختيار.

وقد جاءت نتائج هذه الدراسة الكيميائية الحيوية لتكشف جانبًا مهمًا من هذا الإعجاز النبوي، حيث أظهرت التحاليل المخبرية أن أوراق السدر تحتوي على منظومة متكاملة من المركبات النشطة بيولوجيًا، في مقدمتها المركبات الفينولية والفلافونويدات والتربينويدات والأحماض الدهنية، وهي مركبات ثبت عالميًا دورها الأساسي في مقاومة الأكسدة، وتثبيط الالتهابات، ومحاربة الميكروبات، وتعزيز مناعة الجسم.

وأظهر اختبار النشاط المضاد للأكسدة (DPPH) أن المستخلص الإيثانولي لأوراق السدر يمتلك قدرة عالية جدًا على تثبيط الجذور الحرة، حيث بلغت نسبة التثبيط نحو **89%عند تركيز 100 ملغم/مل**، وهي نسبة مرتفعة تعكس قوة النشاط الوقائي للمستخلص ضد الإجهاد التأكسدي الذي يُعد أحد الأسباب

الرئيسة في تلف الخلايا وظهور الأمراض المزمنة، مثل السرطان وأمراض القلب والشيخوخة المبكرة. ويُفسَّر هذا النشاط المرتفع علميًا باحتواء الأوراق على تركيزات عالية من الفينولات والفلافونويدات، التي تعمل كمانحات إلكترون فعّالة في تحييد الجذور الحرة.

كما كشف التحليل باستخدام الكروماتوغرافيا الغازية المقترنة بمطياف الكتلة (GC–MS) عن وجود عدد من المركبات ذات التأثيرات العلاجية المتعددة في مستخلص أوراق السدر، من أبرزها:
السترال (Citral) المعروف بنشاطه القوي المضاد للبكتيريا والفطريات،
و**اللينالول (Linalool)** الذي يتميز بخواصه المهدئة والمضادة للأكسدة،
و**التربينول (Terpineol)** الذي يجمع بين النشاط المضاد للالتهابات والمضاد للأكسدة،
إضافة إلى **حمض البالميتيك (Palmitic acid)** الداعم لاستقرار الأغشية الخلوية، و**بنزوات الإيثيل (Ethyl benzoate)** ذات الخواص المطهرة.

ويُعد اجتماع هذا العدد من المركبات المتعددة الوظائف في نبات واحد ظاهرة كيميائية نادرة، إذ إن كثيرًا من النباتات الطبية تمتلك نشاطًا بيولوجيًا واحدًا أو نشاطين فقط، في حين يتميز السدر باتساع طيفه الحيوي، وهو ما يفسّر من الناحية العلمية مفهوم **البركة** الوارد في النصوص الشرعية، باعتبارها اجتماع المنافع وتعدد آثارها مع الأمان وقلة السمية.

ويتجلى الإعجاز العلمي كذلك في **التطابق الدقيق بين الاستخدام النبوي والخواص الكيميائية الحيوية المثبتة حديثًا**؛ فالسدر استُخدم في الهدي النبوي في الغسل والتطهير، وأثبت العلم الحديث أن أوراقه تمتلك نشاطًا قويًا مضادًا للبكتيريا والفطريات، فضلًا عن خواصه المضادة للالتهابات والمجددة لخلايا الجلد، وهو ما يفسر استخدامه التقليدي في تنظيف الجلد وتسريع التئام الجروح ومعالجة الالتهابات الجلدية.

ولا يقتصر الإعجاز في السدر على الجوانب الطبية فحسب، بل يمتد إلى البعد البيئي والاستدامة الصحية؛ إذ تُعد شجرة السدر من النباتات المقاومة للجفاف والملوحة والحرارة المرتفعة، وتنمو في البيئات الصحراوية القاسية دون الحاجة إلى موارد مائية كثيفة، ومع ذلك تنتج مركبات علاجية عالية القيمة. وهذا يفتح بابًا مهمًا في مجال **الإعجاز البيئي للنباتات المذكورة في النصوص الشرعية**، ويجعل من السدر موردًا استراتيجيًا داعمًا للصناعات الدوائية والغذائية والتجميلية المستدامة، بما ينسجم مع مستهدفات رؤية المملكة 2030 في تعزيز الأمن الصحي والاستدامة البيئية.

وبناءً على ما تقدّم، فإن هذه الدراسة تمثل نموذجًا تطبيقيًا واضحًا للإعجاز العلمي في السنة النبوية، حيث انتقلت الإشارة النبوية إلى شجرة السدر من كونها توجيهًا تعبديًا وإرشادًا صحيًا عامًا، إلى حقيقة علمية مدعومة بالتحليل الكيميائي الحيوي والاختبارات المخبرية الدقيقة. ويؤكد هذا التطابق أن الهدي النبوي سبق الاكتشافات العلمية الحديثة بقرون طويلة، وأن دراسة الطب النبوي في ضوء مناهج البحث العلمي المعاصر تمثل مدخلًا أصيلًا لفهم أعمق لعلاقة الوحي بالكون والإنسان.

الاستنتاجات والتوصيات:

تُظهر نتائج هذه الدراسة أن شجرة السدر (*Ziziphus spina-christi*) ليست مجرد نبات ورد ذكره في السنة النبوية لفضله وبركته، بل هو ثروة طبيعية غنية بالمركبات الفعالة التي تفسر كثيرًا من الفوائد الصحية التي أشار إليها الإعجاز النبوي قبل قرون. لقد بيّن التحليل الكيميائي أن أوراق السدر تحتوي على مجموعة من المركبات الحيوية المهمة، مثل السترال واللينالول والتربينول، وهي مواد معروفة بقدرتها على مقاومة الأكسدة والالتهابات، ودعم الجهاز المناعي. كما أظهر اختبار مضادات الأكسدة (DPPH) أن مستخلص الأوراق يمتلك فعالية عالية في تثبيط الجذور الحرة، وهي الجزيئات التي تسبب تلف الخلايا وتسهم في حدوث الأمراض المزمنة. بالإضافة إلى احتواء هذه النبتة على نسبة مرتفعة من الفينولات والفلافونويدات والمركبات الأخرى مثل الصابونينات والستيرويدات.

هذه النتائج تؤكد أن للسدر أساسًا علميًا يبرر مكانته في الطب النبوي، وأن الرجوع إلى دراسة مثل هذه النباتات المحلية يُعتبر خطوة مهمة نحو تفعيل الاستدامة الصحية، وذلك من خلال الاعتماد على موارد طبيعية آمنة يمكنها أن تدعم الصناعات الدوائية والغذائية والتجميلية. إذن، فإن هذه الدراسة توصي بالتالي:

- من المهم القيام بالمزيد من الدراسات الكيميائية التفصيلية حول كل ما يتعلق بعمل المركبات النشطة في نبات السدر على المستوى الخلوي والجيني، وذلك لفهم دورها في مقاومة الأكسدة والالتهابات.
- يُنصح بالقيام بدراسة مرجعية وذلك لمقارنة عينات السدر المزروعة في مناطق مختلفة من العالم لمعرفة تأثير البيئة والمناخ على تركيبه الكيميائي وجودة المركبات الفعالة.
- يمكن أن يشكّل السدر أساسًا لتطوير منتجات طبيعية محلية مثل المكملات الغذائية والمستخلصات العطرية، التي تدعم صحة الإنسان وتقلل من الاعتماد على المركبات الصناعية.
- توصي الدراسة بدعم مشروعات زراعة السدر في المناطق الصحراوية وشبه الجافة، لما لذلك من أثر في حفظ التنوع النباتي ومكافحة التصحر وتحقيق عوائد اقتصادية مستدامة.
- وأخيرًا، من الضروري نشر الوعي المجتمعي بأهمية النباتات المذكورة في القرآن والسنة، ليس فقط من منظور ديني، بل أيضًا من أجل دعم الحلول العلمية الحديثة للحفاظ على الصحة والبيئة.

تُظهر هذه الدراسة أن ما جاء في الهدي النبوي بخصوص شجرة السدر لا يقتصر على جانب ديني، بل له اتجاه علمي يشير إلى نبات يحمل خصائص طبية مثبتة علميًا. ومن خلال فهم هذا الارتباط بين الإيمان والعلم، يتضح أن استثمار موارد الطبيعة ليس مجرد بحث علمي، بل رسالة إنسانية تهدف إلى تحقيق التوازن بين صحة الإنسان وسلامة البيئة، وهو جوهر مفهوم الاستدامة الصحية الذي تسعى إليه رؤية المملكة 2030.

يساهم البحث في تعزيز الاستدامة الصحية من خلال التركيز على أوراق السدر (*Ziziphus spina-christi*) كمصدر طبيعي لكثير من المركبات الهامة ومضادات الأكسدة. إذ تبين أن المركبات الكيميائية الحيوية الموجودة في الأوراق تساهم في الحد من الشوارد الحرة بالتالي يقلل من الإجهاد التأكسدي، مما يعزز الصحة الوقائية ويقلل من الاعتماد على الأدوية الكيميائية المصنعة. كما أن استخدام نبات محلي مثل

السدر يدعم الاستغلال المستدام للموارد الطبيعية، ويربط بين الصحة والحفاظ على البيئة. وأيضًا يربط بين الإعجاز النبوي والتركيب الكيميائي للنبات وبالتالي يشجع على اعتماد ممارسات علاجية تقليدية مدعومة بالأدلة، مما يعزز نموذجًا مستدامًا للصحة على المستويين الفردي والمجتمعي.

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A Biochemical Study of Sidr (Ziziphus spina-christi) Leaves as a Natural Source of Antioxidants and a Promoter of Health Sustainability in the Kingdom of Saudi Arabia

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Abstract:

This research revisits the concept of Prophetic miracles considering modern scientific analysis, through the study of the Sidr tree (*Ziziphus spina-christi*) as a model that combines a spiritual dimension with scientific innovation in serving human health and environmental sustainability. The study is based on a vision inspired by Islamic prophetic heritage in the utilization of natural resources, thereby providing a scientific interpretation of the therapeutic properties attributed to this blessed tree throughout history.

The study revealed that Sidr leaves collected from the Al-Leith region in the Kingdom of Saudi Arabia are rich in active compounds such as phenols, flavonoids, and terpenoids, which exhibit strong capabilities in inhibiting free radicals, combating inflammation, and enhancing the body's natural immune response in a noticeable and effective manner. It also demonstrated that the ethanolic extract shows the highest antioxidant activity, making it a promising candidate for the development of natural pharmaceutical and cosmetic products.

Sidr leaves were also analyzed using advanced chemical techniques, most notably Gas Chromatography–Mass Spectrometry (GC–MS). This research is distinguished by its ability to bridge Prophetic guidance with contemporary scientific innovation, presenting clear scientific evidence of the blessing of the Sidr tree through understanding its biochemical constituents and utilizing them to achieve health sustainability in alignment with Saudi Vision 2030 and the United Nations Sustainable Development Goals, while highlighting its role in supporting the bioeconomy and promoting the sustainable use of local plant resources.

Keywords: *Ziziphus spina-christi*, Antioxidants, Health sustainability, Bioactive compounds.

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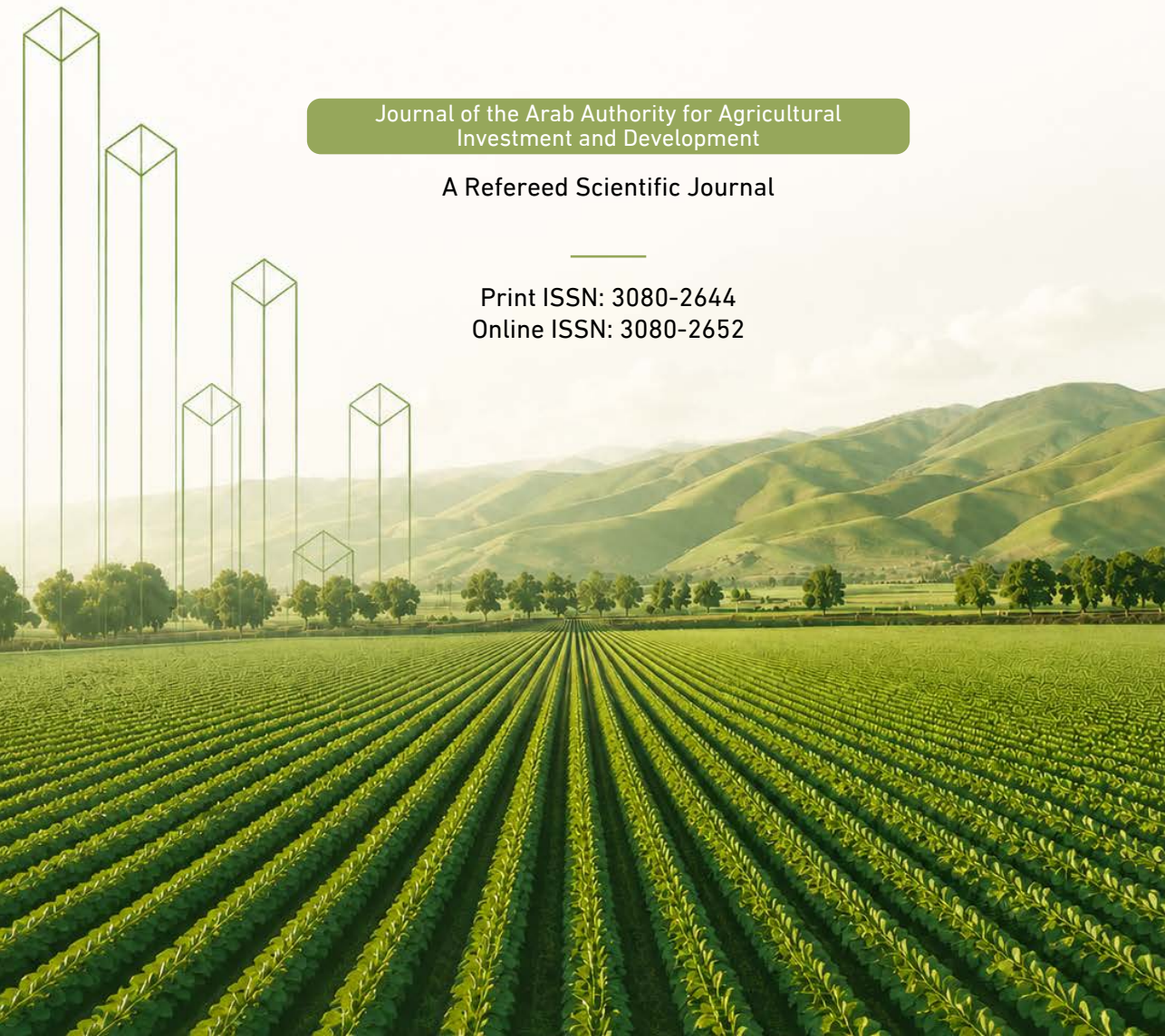
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An Innovative System Study for Sustainable Agriculture in the Salinized Lands in Central and Southern Iraq without Reclamation or Drainage Processes

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Abstract:

Agricultural production in central and southern Iraq faces a serious challenge due to soil salinity, which arises from a combination of environmental and hydrological factors. A major cause is the rise of saline groundwater to shallow depths, restricting proper root development of crops. Conventional reclamation through large-scale drainage projects is constrained by diverse terrain, extremely high costs, and the shortage of fresh water required for extensive leaching operations.

To address these limitations, this study introduces an alternative farming system designed for long-term sustainability. The approach involves cultivating plants in sealed containers with a lifespan of no less than ten years, ensuring root growth beyond the direct influence of salinity. Shallow groundwater (0.5–1.5 m depth) is utilized after being desalinated through an evaporation–condensation cycle powered by flared gas from oil refineries, thereby converting a wasted by-product into a useful source of irrigation water.

The research included soil sampling from several locations, estimation of water volumes required for leaching, evaluation of salinity levels before and after treatment, and determination of field capacity across soil types. Findings indicate that this system effectively mitigates the primary obstacles of saline land management, namely the scarcity of fresh water, high reclamation costs, and the proximity of saline groundwater to the surface. Moreover, continuous withdrawal of groundwater throughout the system's operational period is expected to gradually lower its level, removing it from the active root zone and enhancing soil productivity on a sustainable basis.

Keywords: salinity, soil leaching, field capacity, Shura soils, Sabakh soils.

Introduction:

Global Water Scarcity and Soil Salinization: To meet the rising global food demand, agricultural production must increase by roughly 60% by 2050 [FAO. 2012]. The global population, currently near 7 billion, is projected to reach 10 billion within the next fifty years [Goswami et al. 2016]. This rapid population growth, combined with diminishing arable land, constitutes one of the most critical challenges limiting agricultural productivity and sustainability [Saghafi et al. 2019]. Within this framework, water availability emerges as a key determinant in meeting these challenges [FAO. 2017]. Therefore, improving agricultural output remains the most feasible strategy to ensure future food security [Vaishnav et al. 2016].

The surge in population, alongside expanding industrial and agricultural activities, has intensified the demand for irrigation, worsening water scarcity, particularly in arid and semi-arid regions [Ma et al. 2020]. Limited rainfall and elevated evaporation rates have further widened the gap between water supply and demand [Mohamed et al. 2020], [Gupta & Kumar. 2018]. Water resources in these regions are scarce, and competition with other sectors restricts the volume of freshwater available for agriculture. Consequently, water scarcity has become a major constraint on economic development and human well-being, affecting approximately 40% of the global population and numerous ecosystems [Oki & Kanae. 2006]. In semi-arid regions, agriculture accounts for around 80% of current freshwater usage [UN Environment. 2019]. Population growth, rising food demand, and climate change have collectively increased water demand by elevating temperatures and reducing availability [IPCC. 2013]. As a result, groundwater development and utilization have become common strategies to address the imbalance between supply and agricultural demand [Huang et al. 2012].

Soil salinity constitutes a major limitation to crop productivity worldwide. Salt accumulation in soils arises from primary causes, such as rock weathering, and secondary causes including excessive fertilizer use, irrigation with low-quality water, waterlogging, and discharge of industrial saline solutions [Sahab et al. 2021]. Climate change accelerates soil salinization through altered rainfall patterns, higher temperatures, and increased evaporation rates [Bannari & Al-Ali. 2020, Corwin. 2021].

Currently, over 50% of irrigated lands globally are affected by salinity, which impairs plant growth, development, and survival [Guo et al. 2022]. This situation threatens global food security, with climate change intensifying the problem [Mukhopadhyay et al. 2021]. The expansion of intensive orchard irrigation in recent decades, coupled with declining water quality, has worsened soil salinity. By 2050, more than half of arable lands may be affected by salinization [Jamil et al. 2011]. Anthropogenic activities have already impacted around 76 million hectares of productive land due to excessive salt accumulation [Nurbekova et al. 2024].

Soil salinity is closely linked to global issues such as climate change, food security, and the United Nations Sustainable Development Goals (SDGs). Addressing salinity is crucial for achieving the SDGs, particularly Goal 2 ("Zero Hunger"), Goal 3 ("Good Health and Well-being"), and Goal 15 ("Life on Land") [Lal et al. 2021]. Therefore, enhancing crop productivity on saline lands requires adopting effective management strategies [Du et al. 2023].

Local Salinization in Central and Southern Iraq: The President of Iraq emphasized that addressing land degradation and water scarcity requires $13 billion for land reclamation, $12 billion for dam construction, and $3 billion for water resource development [Abdul Latif 2022] (Climate Conference 2022). Nevertheless, financial limitations and water scarcity remain significant obstacles to implementing reclamation initiatives.

Iraq's Salinity Crisis: Irrigating large tracts of reclaimed land along the Tigris and Euphrates rivers presents serious challenges, particularly in preventing saline groundwater from contaminating the Shatt al-Arab waterway. Flood irrigation, poor soil management, and insufficient drainage have contributed to high salinity levels in Iraqi soils.

Classification of Saline Soils in Iraq: Iraqi saline soils are generally classified into two main types:

Al-Shura Soil: Exhibits a white, crystalline, non-soluble surface layer that swells upon wetting.

Sabkha Soils: Dark brown soils with high concentrations of calcium and magnesium chlorides.

Typical soil profiles include a dark brown surface layer, a middle layer at approximately 60 cm depth with sodium chloride accumulation, and a lower moist layer below the groundwater level [Khalaf & Alrijabo. 2006].

Geographic Distribution: The first Iraqi distribution map [Alrijabo. 1991] revealed concentrated salinization in central and southern Iraq, particularly within the Tigris and Euphrates river basins (Figure 1).

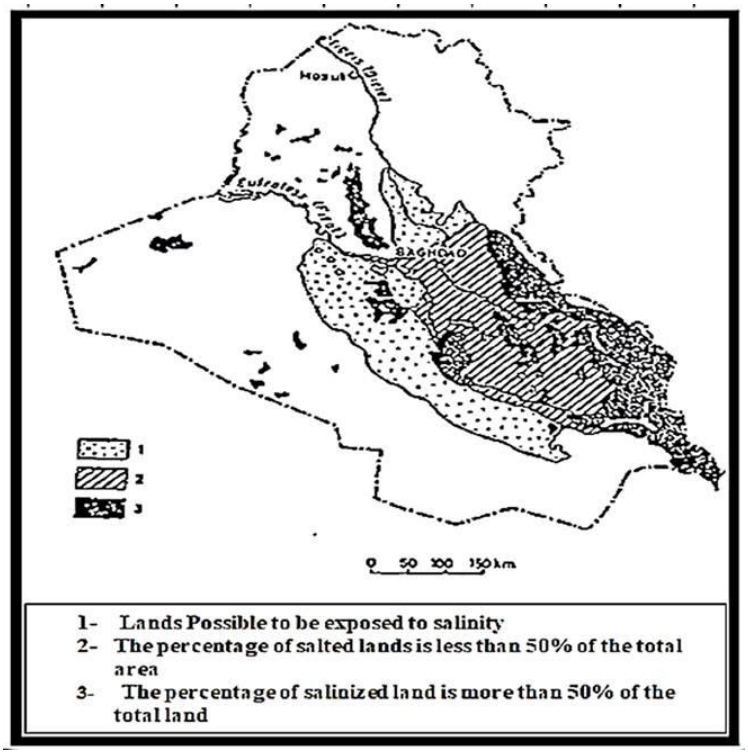


Figure 1: Salinized Land Distribution in Central and Southern Iraq

The Food and Agriculture Organization's map (Figure 2) Soil Salinity Map (FAO, [FAO. 2012]) illustrates Iraq's soil salinity levels:

Salinity Classification: **S1**: Moderate salinity (4-15 $ds.m^{-1}$), and **S2**: High salinity (>15 $ds.m^{-1}$).

Salinization Trends: **R1**: Moderate increase (2-3 $ds.m^{-1}.year^{-1}$), and **R2**: Rapid increase (3-5 $ds.m^{-1}.year^{-1}$).

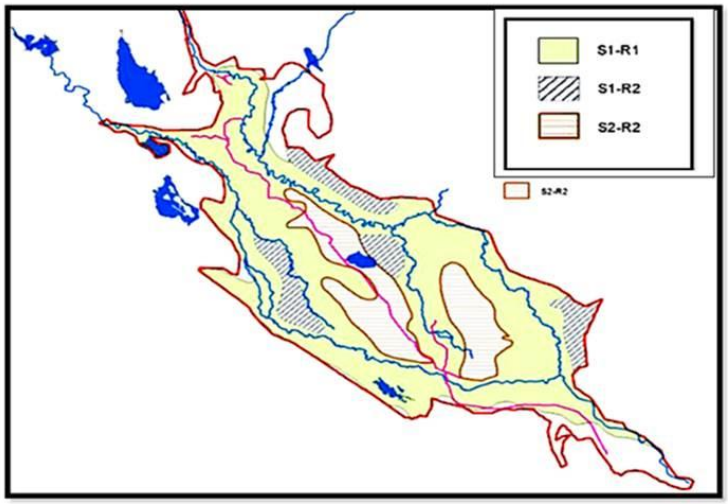


Figure 2: Soil Salinity and Degradation in the Mesopotamian Valley

Recent Soil Salinity Assessment (Ministry of Water Resources, [Al-Mashhadani. 2016]). The map illustrates soil salinity levels in central and southern Iraq: Salinity Zones: Red: Extremely saline (>25 $ds.m^{-1}$), and Orange: Moderately saline (16-25 $ds.m^{-1}$).

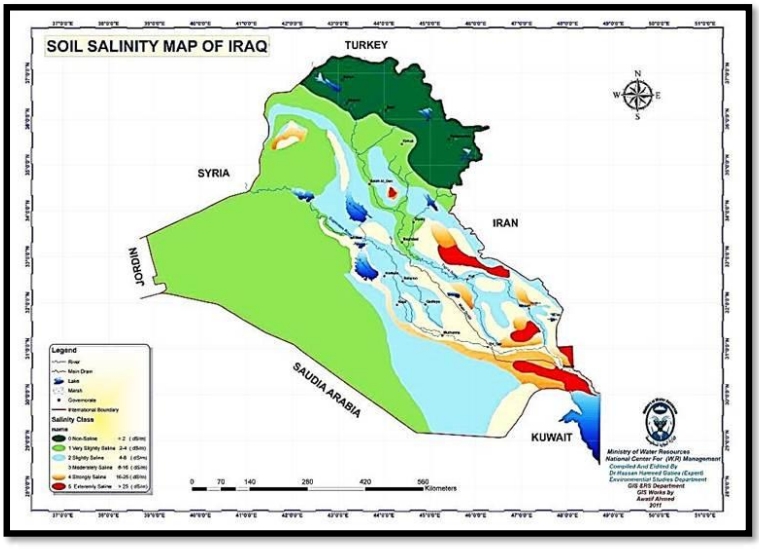


Figure 3: Salinity Levels in the Iraqi Plain

Factors Contributing to Iraqi Soil Salinity

- First, Low elevation (e.g., Baghdad: 33 m above sea level, 600 km from the sea)
- Second, Excessive irrigation water waste by farmers
- Third, Inadequate drainage systems
- Fourth, Seasonal groundwater level rise due to lack of natural drainage
- Fifth, High temperatures, evaporation, and low precipitation.

  These factors cause groundwater to rise to the soil surface, accumulating dissolved salts and leading to salinity issues [Asaad & Adnan. 2015].

Groundwater Depth and Quality:

Soil salinization in central and southern Iraq is directly related to the depth and quality of groundwater. In central Iraq, the depth of the groundwater level ranged from 100 to 200 cm during different months of the year, and in southern Iraq, the groundwater level ranged between 45 cm in February and 200 cm in August, and the salinity of groundwater in the unreclaimed soil was very high, ranging from 42 to 44 $ds.m^{-1}$, while the groundwater of the semi-reclaimed and reclaimed soils was medium saline, and ranged from 8.2 to 10 $ds.m^{-1}$.

The salinity of the groundwater in the low Mesopotamian plain ranged from 10,000 to 60,000 ppm [Qureshi et al. 2013].

Reclamation Challenges: Saline soil reclamation requires substantial water resources for leaching. Iraq's water resources have significantly declined:

Euphrates River: from 30 billion cubic meters (1933) to 9.5 billion cubic meters (2021).

Tigris River: from 20.5 billion cubic meters (1933) to 9.7 billion cubic meters (2021) [Al-Jubouri. 2022].

Project Goals and Features:

This innovative project transforms the curse of highly saline groundwater in central and southern Iraq into a blessing, leveraging vast groundwater resources for agricultural irrigation.

The key objectives are: Utilize purified groundwater for irrigation, to eliminate drainage and leaching needs.

Lower groundwater levels over 10+ years, facilitating negotiation with river source countries in this period.

Implement sustainable agriculture using natural Iraqi resources. Foster self-sufficiency, minimizing imports.

Project Highlights:

Water scarcity has emerged as a global maritime issue, with population growth, industrialization, and pollution all contributing to its challenges. Only 0.014% of the Earth's total water is available for human use, with 97.5% being saltwater and the remaining 2.5% consisting of freshwater. Unfortunately, access to this freshwater remains a challenge, as most of it is trapped in glacial ice and vast forests [Masoud et al. 2023].

For this reason, approximately one-third of the world's population suffers from freshwater scarcity, particularly in areas experiencing severe freshwater impacts [Masoud et al. 2019].

Access to clean water is a critical challenge in areas with limited energy resources. Solar distillation systems have emerged as a popular and sustainable option for obtaining clean water in these regions. This method utilizes solar energy for heating, which is then condensed into potable water. This study presents a distillation system that is cost-effective and energy-efficient, while also ensuring its sustainability.

The average daily production of the proposed distillation system was presented as 1.14 liters/m^2, resulting in an annual production rate of 416.54 liters/year. The estimated cost of producing one liter of distilled water was $0.023 [Jakub et al. 2024].

There are several methods for desalinating seawater, including thermal methods (such as multi-stage flash distillation and multi-effect distillation) and membrane methods (such as reverse osmosis and electrolysis) [Taghavian et al. 2022], [Taghavian et al. 2023].

However, most common desalination methods cannot remove all the purified water from a saline or polluted source and must discard up to 50% of the incoming water.

This can be harmful to the environment and is also costly [Kandeal. 2021].

Solar distillers are a simpler and more efficient method for small-scale projects due to their lower cost. Solar water treatment is a practical solution for purifying various water sources, including seawater, groundwater, surface water, and different types of wastewater, such as pharmaceutical, industrial, and municipal effluents. There are three main types of solar desalination and purification systems: solar distillers, solar water disinfection systems (SODIS), and humidification and dehumidification (HDH) systems.

Among these systems, solar water disinfection systems (SODIS) are considered one of the simplest and most cost-effective methods for treating contaminated water, particularly in developing countries where biological contamination is a significant problem [Masoud et al. 2020].

Desalination via water evaporation/condensation using refinery gas. Legalizing the burning of natural gas in oil refineries, which is currently being done without benefit, and using it to evaporate salty groundwater. In addition to the possibility of relying on solar energy to evaporate and condense groundwater. Locally manufactured plastic containers and drip irrigation systems. Conservation agriculture using containerized tree planting. Reduced water scarcity impacts.

Environmental benefits:

Desalinated saline groundwater will be utilized for irrigation, gradually lowering groundwater levels over 10+ years. This allows many key benefits such as negotiation opportunities with river source countries for restored Tigris and Euphrates River flows. Natural soil drainage through rainfall will eliminate the need for drainage projects for saline soil in the future. In 10 years mature, productive trees with optimized economic returns.

Iraq's sustainable agriculture project aims to utilize saline groundwater for irrigation, reducing reliance on river imports. This innovative approach leverages natural resources, specifically refinery gas, to desalinate water through evaporation and condensation. Approximately 17 billion cubic meters of refinery gas are available annually, with less than a third required for nationwide desalination efforts.

Key Project Components

Desalination Technology: Utilizes refinery gas for water evaporation and condensation. Conservation Agriculture: It employs locally manufactured containerized tree planting resistant to physical pressure and saline groundwater. It can be locally manufactured through the Ministry of Industry's production of polyethylene, which has been re-produced, according to the statements of the Minister of Industry on 11/15/2022 [Khaled. 2022].

Materials and Methods:

This research represents a design study of a pioneering system for coexisting with salinity in difficult-to-reclaim soils. These difficulties are due to the interaction of several factors, such as the scarcity of leaching and irrigation water, the high level of saline groundwater reaching the plant root zone, and the impact of high temperatures and low rainfall on the fluctuating groundwater level throughout the year.

Therefore, analytical laboratory studies for some soil traits were conducted on numerous samples of saline soils, both before and after leaching, including determining their field capacity. The complete system will be implemented with the plant parts in subsequent seasons on a continuous and ongoing basis.

The research plan comprised the following components:

- Soil Analysis
- Sampling: Collected soil samples (0-50 cm depth) from Baghdad to Nasiriya.
- Physical and Chemical Properties: Analysed texture, salinity, and chemical characteristics.
- Saline Soil Leaching Study
- Soil Selection: Used dry soil samples with low, medium, and high salinity. Study of the leaching of saline soils: one kilogram of selected dry soil (low, mid, and high soil salinity compared with control soil) was placed in pots perforated from the bottom to drain the water. The soil was leached with two levels of tap water: (A) half a liter of water. 1 kg of soil. (B) A liter of water. 1 kg of soil. Soil salinity was analysed after that, and the salinity of the drained water was tested for each sample.
- The water used for salty soil leaching was tap water, whose electrical conductivity EC ($ds.m^{-1}$) was (0.23) and its pH was (7.3). Tap water is better than the Tigris

River in Mosul, whose electrical conductivity EC ($ds.m^{-1}$) was (0.43) and its pH was (7.3), and better than the AlKhuser River in Mosul, whose electrical conductivity EC ($ds.m^{-1}$) was (1.61) and its pH was (7.1) [Al-Jubouri. 2009].

- Determining the field capacity: The field capacity of each sample was determined by immersing one kilogram of dried soil in a liter of water and leaving the sample for 48 hours until the gravity water exuded from it. Then measuring the weight of the wet soil to determine the maximum capacity of the soil to hold. Moisture retention 48 hours after immersion.
- Evaluating the results and presenting a cultivation plan within the data of the soil and water analysis results.
- As part of the methodology, the academic search engine Google Scholar was used to identify some relevant studies and peer-reviewed research that support the objectives of this research.

Results and Discussion:

Soil Physical and Chemical Traits Results

The majority of soil samples tended to be clayey in texture, according to the values shown in Table (1). Soil values varied in their content of cations and anions, with a general increase in the index as a result of the effect of the presence of salts in it (Tables 2, 3). The salinity values in the soil varied from the lowest value (10.90 $ds.m^{-1}$) to the highest value (16.10 $ds.m^{-1}$).

Table 1. Soil texture analysis.

Sample No.	Sand %	Silt %	Clay %	Soil Texture
1	17.05	45.75	37.2	Silt-Clay Loam
2	19.55	48.25	32.2	Silt-Clay Loam
3	26.3	29.0	44.7	Clay
4	12.05	38.25	49.7	Clay
5	17.05	35.75	47.2	Clay
6	52.05	15.75	32.2	Sandy Clay
7	51.3	11.5	37.2	Sandy Clay
8	27.05	33.25	39.7	Clay Loam
9	31.3	29.0	39.7	Clay Loam
10	29.55	38.25	32.2	Clay Loam

Table 2. Analysis of cations and anions in some soil samples.

Sample No.	Mg %	K %	Na %	N %	P %	Cl %	Hco3 %	So4 %
1	0.081	0.0019	0.0053	0.015	0.00026	0.81	0.23	0.061
2	0.068	0.0022	0.0072	0.047	0.00050	1.88	0.024	0.056
3	0.042	0.0019	0.0045	0.023	0.00050	0.71	0.041	0.078
4	0.067	0.0020	0.0049	0.015	0.00042	0.75	0.25	0.109
5	0.032	0.0024	0.0044	0.039	0.00026	0.80	0.036	0.104
6	0.016	0.0015	0.0051	0.008	0.00036	0.86	0.053	0.050
7	0.032	0.0014	0.0051	0.054	0.00042	0.90	1.03	0.069
8	0.024	0.0019	0.0048	0.031	0.00079	1.04	0.029	0.083
9	0.008	0.0020	0.0022	0.015	0.00079	0.34	0.014	0.021
10	0.015	0.0024	0.0051	0.023	0.00026	0.88	0.12	0.062

The pH values ranged from (7.1 to 8.0), and organic matter was between (2.62 and 4.03) as shown in Table (3).

Table 3. Soil salinity, pH, and percentage of OM. for some soil samples.

Sample No.	EC ($ds.m^{-1}$)	pH	$CaCo_3$ %	O. M. %
1	11.30	8.0	49	3.82
2	16.10	7.1	46.5	3.69
3	10.90	7.5	48	2.79
4	11.30	7.3	49	3.31
5	11.60	7.2	47	3.38
6	12.30	7.3	49.5	4.00
7	13.01	7.7	47	3.48
8	13.70	7.2	46.5	2.62
9	13.70	7.5	44.5	4.03
10	13.40	7.3	48.5	3.48

The Results of the Salty Soil Leaching Study

It is clear from Table (4) that leaching the soil samples with a volume of 500 ml of water led to a decrease in salinity in the three samples (10.9, 12.3, 16.1 $ds.m^{-1}$) to a very low degree (1.90, 2.60 and 2.70 $ds.m^{-1}$), respectively. The salinity decreased in the same samples when washed with a volume of 1000 ml of water to percentages (1.30, 0.90, and 1.00 $ds.m^{-1}$), respectively.

Reducing soil salinity to 2.7 ds.m^{-1}, which is the higher limit in soil salinity after leaching with a volume of 500 ml, means that this degree of soil salinity is suitable for growing all types of trees [Kumar et al. 2020], grain crops, and vegetable crops [Michael & Khalid. 2015].

Therefore, the leaching process was very efficient in reducing soil salinity. Repeating irrigation with tap water will make the soil salinity decrease until it is equal to the Ec. of irrigation water.

Table 4. Soil salinity (ds.m^{-1}) after leaching of (1000 gm.) soil weight.

Soil Samples	Soil salinity Before leaching	After leaching with 500 ml water	After leaching with 1000 ml water
control	1.20 fg	0.60 i	0.50 i
A	10.90 c	1.90 e	1.30 f
B	12.30 b	2.60 d	0.90 h
C	16.10 a	2.70 d	1.00 gh
Mean	**10.13 a**	**1.95 b**	**0.93 c**

Similar letters have no significant difference according to Duncan's significance test.

Determination of Field Capacity:

Determine the amount of water required to reach 80% of the field capacity of the soil container per tree: The average field capacity of 100% for four samples of saline soil with a weight of 1000 gm. for each sample is very close to = 27.6 + 24.4 + 23.5 + 22.6 = 98.1/4 = 24.5% = 245 ml is sufficient to achieve 100% field capacity for one kilogram of dry soil.

Volume weight of 1 kg of dry soil = approximately 700 ml (cm3).

Weight of a liter of soil = 1000 x 1000 / 700 = approximately 1430 grams of soil.

100% of the field capacity for the weight of 1000 grams of soil is equivalent to 245 grams of water; 80% of the field capacity for the weight of 1000 grams of soil is equivalent to 196 grams of water.

That is, 1000 grams of soil + 196 grams of water = 1196 grams, which represents 80% of the field capacity per kilogram of soil.

Mathematically, a liter of dry soil (1430 gm) would need (280 gm water) to reach (80% field capacity).

This means that the water required per one container of 200 liters of soil to reach 80% of its field capacity is about 56 liters from the multiplying of 200 liters by 280 grams of water.

It seems that the soil texture controls the field capacity values of the four soil samples; the results of [Datta et al. 2017] showed that field capacity values that are very close to the results of this study have a similar soil texture.

The volume of water required to reach 80% of the field capacity of the first irrigation for an area of one hectare (600 trees) = 56 liters x 600 trees per hectare = 33,600 liters, which means only 34 cubic meters for (the first irrigation).

The need for traditional irrigation (the irrigation canals 4 X 4 m. distances) for an area of a hectare is not less than ten times what is consumed per hectare by drip irrigation in plant containers.

That means: 33,600 * 10 = 330,000 liters of water per one hectare, or 330 cubic meters, for the first irrigation only.

The evapotranspiration rate of trees in general = 10% in winter and 30% in summer. Due to the sealing of the upper barrel nozzle, evaporation will be very limited, and only transpiration will remain, so the loss rate will decrease to 5% in winter and 15% in summer, approximately.

Irrigation is done until the field capacity reaches 80%. Then it is stopped.

When the field capacity falls below 50%, irrigation is repeated, and so on.

Table 5. Determination of the field capacity of the four sites.

Sample	Dry soil weight gm.	Soil weight (gm.) after 36 hours of immersion	Soil weight difference gm.	Field Capacity %
Control	1000	1276	276	%27.6
A	1000	1244	244	%24.4
B	1000	1235	235	%23.5
C	1000	1226	226	%22.6

Conclusions and Recommendations:

Through the foregoing, it is clear to us the seriousness of salinity on Iraqi soils and how most of the soils of central and southern Iraq were salinized as a result of irrigation and turned into salty soils and therefore need reclamation (Figure 4(.

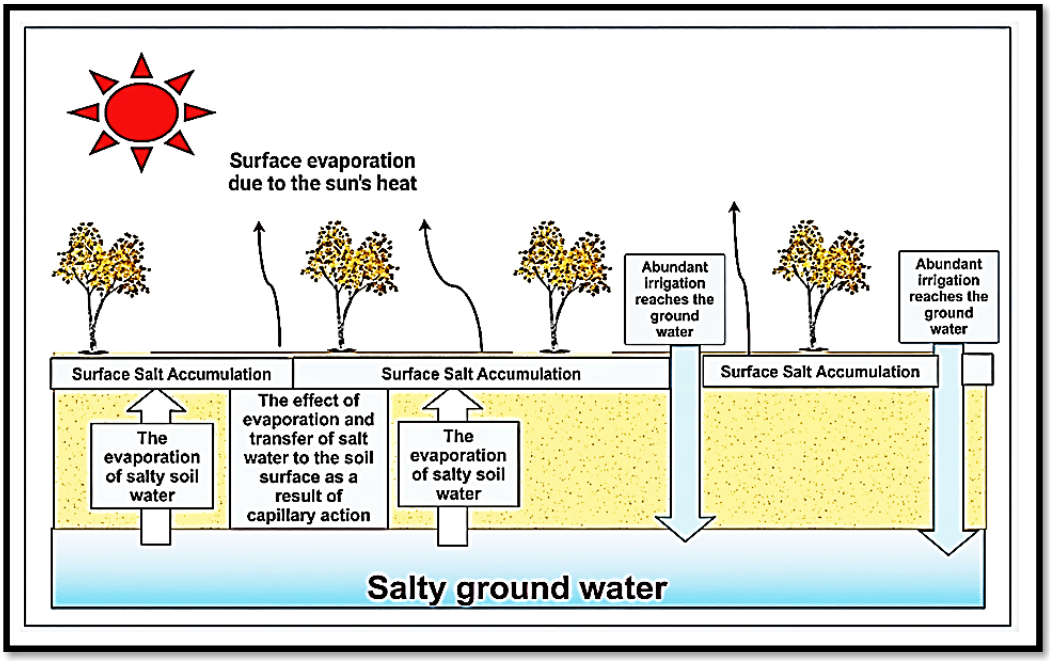


Figure 4. Shows how Iraqi soils are salinized and transformed into Shura salt.

Agricultural lands require a great effort in planning and implementing reclamation projects that the government may not be able to implement; in addition, any reclamation process requires the establishment of a comprehensive drainage network for central and southern Iraq to reduce the level of saline groundwater, as well as filtering the soil with fresh water.

Through the foregoing, it is clear to us that it is impossible to cultivate in such soil due to the scarcity of water required in the filtration process, in addition to the establishing of the drainage network that may cost the government its total budget.

The question now: How can we restore life to these vast lands without opening a comprehensive network of drains, and without sufficient fresh water for leaching and reclamation and then for cultivation, and even how to plant the streets and orchards again without the presence of the most important components of agriculture, which are water for leaching and irrigation, in addition to drains to lower the level of groundwater below the level of crop roots or tree roots?

Through the foregoing, and after analysing many soil samples that were brought from the implementation site, it became clear through the results of testing the samples that these soils can be leached with small quantities of water according to the degree of their salinity, but in the end, they turn into suitable soil for planting all kinds of trees and shrubs, whether pastoral or horticultural plants and, most importantly, this cultivation will take place in the same salinized sites and will not be affected by soil salinity or groundwater level according to the idea presented in the following diagrams.

Accordingly, the curse of salty water and the rise in the groundwater level will turn into a blessing and a water treasure that will enrich Iraq for decades, until the water returns to the Tigris and Euphrates rivers, and then there will be no concern about return rising of groundwater level because much of it will have been used in irrigation after treatment.

The results of the study conducted on the many soil samples of the implementation site in central Iraq succeeded in reducing the level of salinity in it from 10-16 $ds.m^{-1}$ to about 1-1.3 $ds.m^{-1}$ only, and the planning and implementation of this project will be through sustainable agriculture that manages itself, preserves the environment from pollution, and restores life to Iraqi orchards and villages that were abandoned decades ago.

Summary of Action Steps

- Digging a small pond or well 6 meters deep, connecting an anti-salt water pump and electrical connection to the pump. The location of the well is chosen in the middle of the project so that it turns into an outlet for salty groundwater.
- Installing a water desalination plant on these ponds to convert this relatively salty water into fresh water through an evaporation and condensation system that

relies on Iraqi resources only by using refinery gas exhausted by burning, as well as using evaporation technology by heating with direct sunlight or generating electricity through solar energy when needed (Proposed Figure 5).

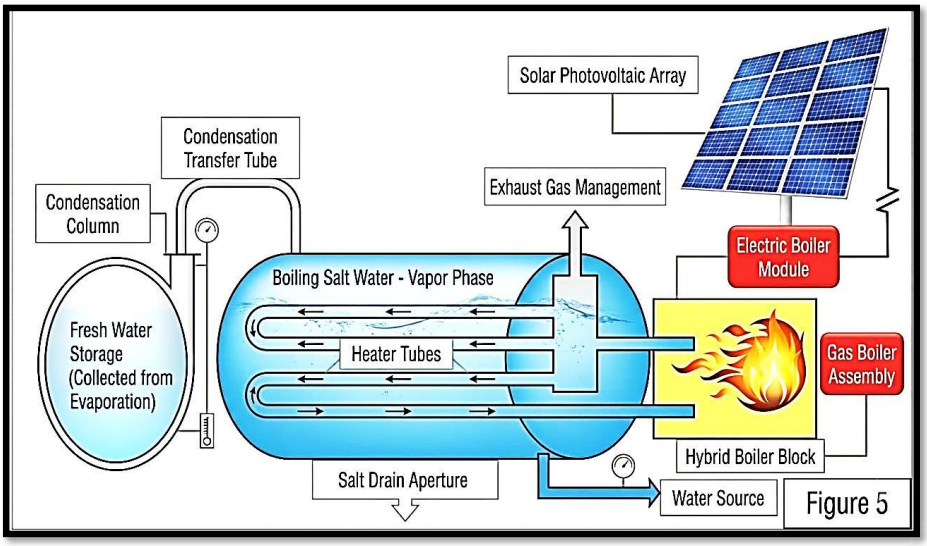


Fig. 5: Water desalination by gas or solar energy. Illustration chart

- After obtaining fresh water (relatively limited and sufficient for sure), sufficient salty soil blocks will be leached in limited and studied quantities of fresh water according to the results of the study and prior analysis of soil and water samples.
- Tree seedlings will be planted in resistant plastic containers (drums) with an expiration date of not less than 10 years and a volume of 220 liters. This period is sufficient to eliminate the risk of salinity from the Iraqi soil if the Iraqi plain turns to the adoption of the drip irrigation technique, and this volume will be sufficient for the roots of the trees and shrubs whose species will be carefully selected (Fig. 6).

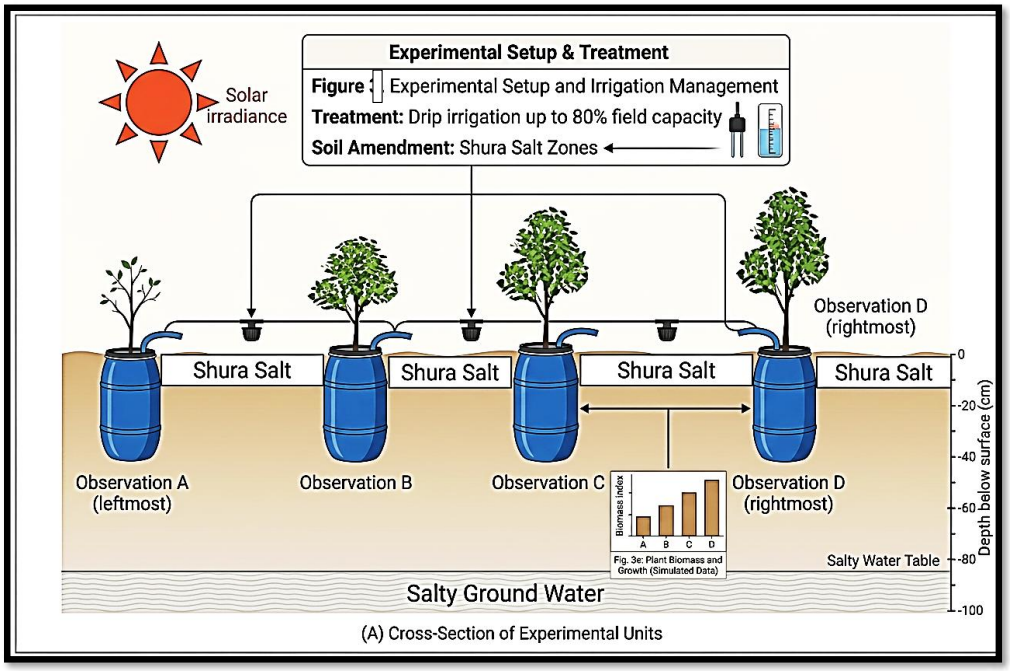


Figure 6. Container cultivation technique with drip irrigation.

- All planting containers will be connected to a drip irrigation network, and irrigation will be done with extreme precision after determining the field capacity of all the soil samples that have been studied.
- Irrigating will be done at a constant rate that does not exceed 80% of the field capacity of the soil. Then the pumping is resumed for irrigation when the soil loses 30% of its moisture when it reaches 50% field capacity, and the pumping continues until the moisture returns to 80% field capacity; this irrigation management is controlled in a standard and weighing manner by preparing a field container (or two containers) to determine the field capacity by a field capacity sensor.

A field capacity sensor was placed in it, and the pointer delivered an electrical signal to the water pump to operate when the soil moisture reached 50% and to turn off when it reached 80% (Fig. 7).

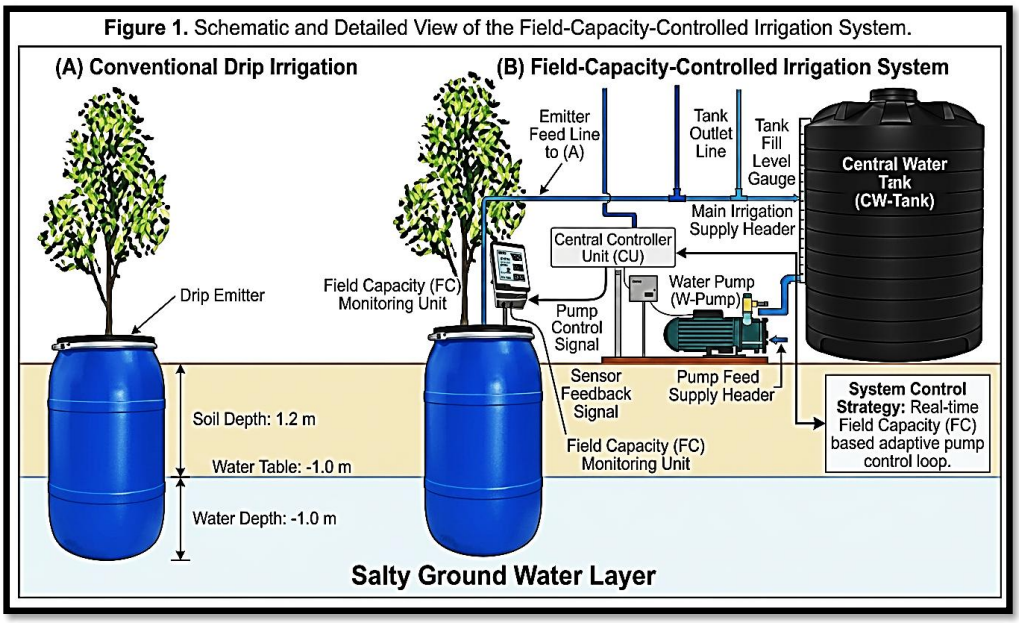


Figure 7. The field capacity sensor for irrigation determines the field capacity.

The method of determining the amount of irrigation is based on measuring the field capacity by a specific field capacity sensor or using a wireless moisture meter (Figure 7) to determine soil moisture, and according to its data, the amount of water is determined for each container to reach the required field capacity.

The device can transmit moisture meter data wirelessly and display it using an application on the farmer's mobile phone. The watering can be operated remotely using the same app based on hygrometer readings.

- After burying these containers in the fields at a depth of more than 1.25 meters, there will be no concern about the problem of the salt water level rising in the winter to about half a meter from the soil surface, because the containers of trees are completely impermeable to water. No matter how high the salt column rises to the surface of the soil to turn into Shura, it will not reach the soil of the seedlings, since the mouth of the container is slightly higher than the surface of the soil, as shown in the attached figure (Fig. 7).

- When we deal with a project to grow trees in agricultural containers, we must understand the mechanisms by which environmental factors control root traits within the root zone is crucial for improving fruit tree productivity by regulating root structure with irrigation [Li et al. 2024].
- Fine roots, the primary organs for water and nutrient absorption in fruit trees, are densest in the 0–100 cm soil layer (Li et al., 2024). Therefore, choosing a container depth of more than 120 cm is ideal for planting trees [Li et al. 2024].
- The irrigation water will be controlled so that it does not cause soil waterlogging through the control system shown in the previous figure. However, if a defect occurs and the soil of one of the containers becomes waterlogged, the excess water can be withdrawn through the excess water intake pipe shown in Figure (8) below.
- This innovation can be used in the implementation of the afforestation of the roadsides, as this method will be beneficial for all farmers to implement it in their fields and with the help of the government, as all farmers' requests for containers can be met by operating the production line for these containers in the petrochemical plant in Basra.
- This application will provide great job opportunities for unemployed youth and will restore life to the Iraqi villages again, with decent and easy means of living.
- Several pastoral shrubs will be planted, the most important of which is the saltbush to cover plant and animal production.
- The period of ten years, which is the period of container life, is sufficient to leach salinity by seasonal rainwater from the soil surface to deeper than the root zone; ten years of rainwater is sufficient for natural leaching of soil salinity, accompanied by a sharp drop in the groundwater level due to withdrawing groundwater in high quantities by farmers to purify it and use it to irrigate all cultivated lands in central and southern Iraq.

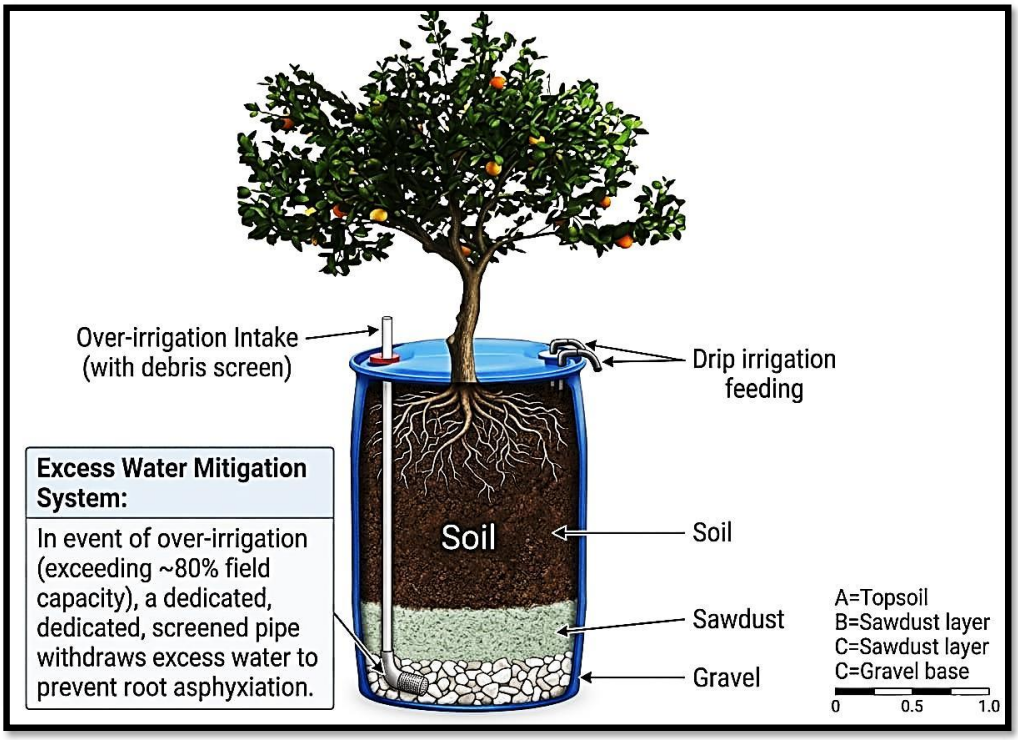


Figure 8. Controlled Container Agriculture System for Citrus Trees

The estimated cost of intensive tree cultivation per Iraqi donum (2500 m^2) is (150 trees / donum): its cost is between 9,000 and 10,000 $ in the event that the government provides desalinated water through a central groundwater desalination project.

Costs include the cost of purchasing 150 tree containers with a capacity of 220 liters through import now (and the ambition is to locally manufacture containers with a size of 300 liters), the cost of leaching the soil of the container and preparing it for cultivation, the cost of digging the positions of the containers and filling them with leached soil, the cost of purchasing tree seedlings and planting them, the cost of the drip irrigation system for an area of Iraqi donums with installation and operation, the cost of the technique of determining the field capacity by the electronic sensor to control the irrigation system, in addition to the cost of establishing small stations for desalination of groundwater to cover their irrigation water needs.

Acknowledgment and Approval:

The study was approved by the Iraqi Prime Minister, and His Excellency instructed it to be implemented in an experimental field. It is currently under implementation, and the study will continue for several years (Appendix).

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دراسة نظام مبتكر لتحقيق الزراعة المستدامة في الأراضي المتملحة بوسط وجنوب العراق دون الحاجة لعمليات الاستصلاح أو البزل. (مشروع استثماري في مجال الأمن الغذائي).

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الملخص:

تواجه الزراعة في مناطق وسط وجنوب العراق تحديات كبيرة بسبب ملوحة التربة، والتي تنشأ نتيجة تفاعل عوامل بيئية وهيدرولوجية متعددة. ومن أبرز هذه التحديات ارتفاع مستوى المياه الجوفية المالحة إلى قرب منطقة الجذور للأشجار والنباتات، مما يحد من نمو جذور النباتات. كما أن الاستصلاح التقليدي عبر مشاريع بزل واسعة النطاق يواجه صعوبات نتيجة للتنوع التضاريسي، وارتفاع التكاليف، ونقص المياه العذبة اللازمة لعمليات الغسل الشامل.

تسعى هذه الدراسة إلى تقديم نظام زراعي بديل يدعم الاستدامة طويلة المدى، ويعتمد على زراعة النباتات في حاويات مغلقة ومقاومة بعمر افتراضي لا يقل عن عشر سنوات، ما يتيح للجذور النمو داخلها خارج نطاق تأثير الملوحة المباشر. ويتم استخدام المياه الجوفية الضحلة (بعمق 0.5–1.5 متر) بعد تحليتها بواسطة دورة تبخير–تكثيف تعمل بطاقة الغاز المحترق الناتج عن مصافي النفط، فضلًا عن إمكانية دعم منظومة طاقة شمسية.

شملت منهجية البحث جمع عينات من التربة من مواقع مختلفة، وتقدير حجم المياه المطلوبة للغسل، وقياس مستويات الملوحة قبل وبعد المعالجة، بالإضافة إلى تحديد السعة الحقلية للتربة عبر أنواعها المختلفة. وأظهرت النتائج قدرة هذا النظام على معالجة أبرز التحديات المرتبطة بالأراضي المالحة، بما فيها محدودية المياه العذبة، وارتفاع تكاليف الاستصلاح، وارتفاع مستوى المياه الجوفية بالقرب من سطح التربة. كما يُتوقع أن يؤدي السحب المستمر للمياه الجوفية خلال فترة تشغيل النظام إلى خفض مستوى المياه الأرضية تدريجيًا، وإبعادها عن منطقة الجذور الفعّالة، مما يعزز إنتاجية التربة بشكل مستدام.

الكلمات المفتاحية: الملوحة، غسل التربة، السعة الحقلية، ترب الشورة، ترب السبخ.

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Financing Resilience: Closing the Arab Food Gap through Innovation and Policy

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Abstract:

Achieving sustainable food security in the Arab world requires mobilizing financial resources, advancing agricultural innovation and creating resilient market structures that reduce the region's dependence on imports. Despite agriculture's role in employment and rural livelihoods, the sector remains underfinanced, with SMEs, which are critical actors in production, processing and distribution, facing systemic barriers to capital access. Our paper aims to demonstrate that identifying and scaling innovative financial models, channeling investment into high-impact technologies, and fostering enabling policies are important steps toward closing the Arab food gap and securing sustainable agricultural development.

Our paper is structured around three interrelated pillars. First, an examination of high-impact innovations that can be financed and scaled across Arab economies. These include strategies and technologies to overcome land and water scarcity, manage pests, and improve productivity for key commodities in the Arab region. We focus on solutions where capital deployment can drive both regional food security and broader economic gains, from employment to trade balance improvements.

Second, an overview of innovative financial models that can unlock agricultural investment, including blended finance, digital financial tools, and outcome-linked financing that ties financial characteristics to measurable improvements in agricultural

production. Such instruments can de-risk investment and align incentives across key stakeholders, including businesses, policymakers, and investors.

Third, an analysis of enabling systems that encourage adoption and scale. This involves regulatory frameworks, shock-responsive financing models to mitigate climate and geopolitical disruptions and public-private partnerships that pool resources while reducing risk exposure. Comparative lessons, such as Asia's food security crisis response framework, highlight how strategic reserves and coordinated supply management can stabilize prices and supply in times of crisis.

By integrating financial innovation with agricultural modernization, we outline a pathway that Arab policymakers and financiers can adopt to build resilient food systems, support SME growth and ensure agriculture becomes a driver of long-term economic resilience.

Key Words: Food Security, Agricultural Innovation, Climate Resilience, Policy Reform, Public-Private Partnerships

Introduction:

Food security in the Arab region is increasingly under strain from structural vulnerabilities, climate change, and global market volatility. The region exhibits structurally high dependence on imports to meet its dietary needs, with imported grains representing roughly 40% of dietary energy and 63% of protein (Rahimi et al., 2023). Long-term empirical evidence confirms that import dependence is not cyclical but structural, with demand for imported food in Arab economies remaining inelastic to price and income shocks, reinforcing vulnerability to external supply disruptions (Mohammed & Almojel, 2025). The human impact of these vulnerabilities is stark. In 2021, an estimated 53.9 million people in the Arab region experienced severe food insecurity, representing a 55% increase since 2010, while more than half the population, approximately 162.7 million people, could not afford a healthy diet (FAO, 2024).

Despite these challenges, agriculture remains a cornerstone of rural livelihoods and employment. Small and medium-sized enterprises (SMEs) account for over 90% of businesses in the Arab world, serving as a major source of job creation and income generation (ANND, 2021). Yet the sector is chronically underfinanced. In the Gulf

Cooperation Council (GCC), SME lending averages just 3% of total bank lending, with an estimated credit gap of USD 250 billion, while in other emerging markets SME lending typically accounts for 15–20% of bank portfolios (OECD, 2025; Deloitte, 2022). This financing shortfall constrains investment in productivity-enhancing technologies and limits the sector's ability to adapt to climate and market risks.

The Arab region therefore faces a dual challenge: reducing its structural dependence on food imports while modernizing agricultural systems to withstand climate and geopolitical shocks. Climate-driven water scarcity is expected to materially constrain agricultural productivity, with rising temperatures and shifting precipitation patterns increasing the incidence of water stress across cropping systems (He & Rosa, 2023). Land degradation compounds these risks, with approximately 46 million hectares of agricultural land, or two-thirds of the region's degraded land, affected by salinization, erosion, and unsustainable farming practices (FAO, 2017).

Addressing these challenges requires an integrated approach that accelerates the adoption of innovative agricultural technologies, mobilizes both public and private finance, and strengthens enabling policy and market systems. This paper argues that aligning capital flows with transformative agricultural solutions, supported by robust governance, can reduce import dependency, enhance resilience, and unlock broader socio-economic benefits for the Arab region.

Literature Review

Food security challenges in the Arab region

Historically, the Arab region's food security has been shaped by structural constraints like limited arable land, chronic water scarcity, and rapid urbanization, combined with policy choices that favored food import reliance over domestic production. Studies consistently link the region's limited natural resources and high import dependence to heightened exposure to external shocks, particularly in grain markets central to caloric intake (Rahimi et al., 2023; Le Mouël et al., 2023). The 2007–2008 food price crisis and subsequent volatility exemplified this vulnerability to external forces, causing a deterioration in household welfare and fiscal balances. The United Nations Economic and Social Commission for Western Asia (ESCWA) underscores that

these long-standing constraints, coupled with fragmented value chains and weak storage and logistics, have kept the region off track on food security and nutrition targets despite periods of strong economic growth (ESCWA, 2023). Climate stressors, including heat, drought and erratic rainfall, contribute to reducing yields and straining groundwater, while salinization and land degradation hinder productivity gains (FAO, 2017; ESCWA, 2019). Recent global shocks, including COVID-19 and the war in Ukraine, exposed the limits of the import-reliant model, tightening cereal supplies and raising prices, with measurable impacts on affordability and diet quality across the region (FAO, 2024; ESCWA, 2023).

The cumulative effect is a persistent vulnerability where global market volatility translates quickly into domestic food stress, with disproportionate impacts on low-income communities given the inelastic nature of food demand. Despite policy efforts such as subsidy reforms, targeted safety nets, and investments in irrigation, progress has been uneven, and nutrition outcomes have stagnated or worsened for many populations (FAO, 2024). The literature converges on the need for systemic reforms: diversified import sources and regional reserves, climate-smart production and water-saving technologies, stronger storage and logistics, and social protection that cushions shocks while enabling dietary adequacy (FAO, 2017; ESCWA, 2023).

Agricultural Innovation and Climate Resilience

Technological innovation in the Arab region has largely focused on water efficiency, climate-smart production, and post-harvest management, reflecting structural constraints of scarce arable land and chronic water stress. Policy frameworks such as the Arab Strategy for Sustainable Agricultural Development (2020–2030) have emphasized precision irrigation, drought-tolerant varieties, protected agriculture, and improved storage and logistics (AOAD, 2020; FAO, 2017). Regional initiatives and knowledge programs such as webinars, capacity-building, and toolkits have aimed to create awareness about climate-resilient practices and share best-fit technologies across contexts (FAO, 2023; ESCWA, 2019). In parallel, global literature on climate-smart agriculture (CSA) highlights integrated solutions (soil health, water management, pest control, and digital advisory) as more effective than single interventions, a principle increasingly reflected in Arab policy discourse (World Bank, 2022; FAO, 2017).

Several efforts show measurable success when finance, extension, and market linkages are aligned. Morocco's Green Plan paired subsidies for drip irrigation with concessional finance, expanding micro-irrigation adoption, improving water-use efficiency, and raising yields in horticulture (FAO, 2017). Jordan, Egypt, and Morocco have advanced PPPs that improved water efficiency, piloted wastewater reuse for agriculture, and reduced post-harvest loss through logistics and cold-chain investments, illustrating the role of private capital and operational know-how in scaling innovation (IWMI, 2024). More broadly, targeted adoption of protected agriculture (greenhouses and net-houses), solar-powered pumping, and improved storage has reduced vulnerability to heat and erratic rainfall, with knock-on benefits for income stability and food availability (FAO, 2017; ESCWA, 2019).

Yet the literature also documents a pattern of partial or unsustainable adoption when enabling systems are weak. Financing constraints, high upfront costs, limited collateral, and banks' risk perceptions slow uptake of CSA technologies, especially among SMEs and smallholders (ESCWA, 2023). Fragmented extension services and insufficient data (weather, soils, market prices) undermine the return on precision tools, while energy and maintenance costs limit the viability of greenhouse and irrigation investments without reliable infrastructure or subsidies (FAO, 2017; ESCWA, 2019). Climate shocks and conflict disrupt supply chains and service provision, causing projects to stall once donor support ends, echoing findings that innovation must be bundled with training, infrastructure, and coherent policy incentives to be durable (World Bank, 2022; FAO, 2024). Overall, the evidence points to a clear conclusion: successful innovation in the Arab region depends on integrated packages and long-term financing mechanisms that de-risk adoption, rather than standalone technologies introduced in isolation (ESCWA, 2023).

Financing Gaps and Agricultural Investment

Although the financing gap for agricultural SMEs in the Arab region has been well documented, efforts to address it through targeted investments have produced mixed results. Donor-backed and multilateral programs have played a central role in attempting to expand access to credit and strengthen rural livelihoods. For instance, the International Fund for Agricultural Development's (IFAD) rural development projects in

Morocco, Sudan, and Yemen combined microfinance with technical assistance, improving household incomes and women's participation, though their benefits often diminished once external funding ended (IFAD, 2022). Similarly, World Bank credit lines in Egypt and Tunisia improved access to irrigation and mechanization but faced uneven repayment rates, reflecting the high-risk nature of agricultural lending (World Bank, 2020). UNDP's blended finance pilots further demonstrated the potential to mobilize private capital, though their success depended heavily on supportive regulatory frameworks (UNDP, 2025).

Complementary mechanisms such as credit guarantees have also been introduced to reduce banks' exposure to agricultural lending. The African Guarantee Fund and regional development banks piloted such schemes in North Africa, modestly expanding SME loan portfolios. However, uptake was slower than anticipated, as financial institutions continued to perceive agriculture as a high-risk sector despite the presence of risk-sharing instruments (ESCWA, 2024). These experiences highlight the structural reluctance of banks to engage with agriculture, even when innovative financing tools are available.

The outcomes of these initiatives underscore a consistent lesson: finance alone is insufficient. Programs that integrated credit with training, infrastructure, and policy reform achieved more durable results, while credit-only schemes often collapsed once donor support ended. Morocco's *Green Plan* (2008–2020) is frequently cited as a successful example, combining subsidies for drip irrigation with concessional loans to significantly improve water-use efficiency and yields (FAO, 2020). By contrast, initiatives in fragile states that lacked complementary support mechanisms struggled to achieve lasting impact. Together, these findings suggest that closing the financing gap requires not only innovative financial models but also systemic reforms that strengthen the enabling environment for agricultural SMEs.

Methodology:

This study presents analysis of available research structured around a three-pillar framework:

1. High-Impact Agricultural Innovations – focusing on technologies and practices that address land and water scarcity, improve yields, and reduce post-harvest losses.
2. Innovative Financial Models – including blended finance, digital financial tools, and outcome-linked financing to de-risk investment and align incentives among stakeholders.
3. Enabling Policy and Market Systems – examining regulatory reforms, shock-responsive financing, and public-private partnerships to accelerate adoption and scale.

Through desk research, case studies, and comparative analysis, the paper provides policymakers, investors, and development actors with a practical roadmap for financing resilience in Arab agriculture.

Results:

This paper finds that closing the Arab food gap requires a multi-pronged strategy that integrates high-impact agricultural innovations, tailored financing, and enabling policy frameworks. Controlled Environment Agriculture (CEA), solar-powered greenhouses, and traditional irrigation techniques demonstrate strong potential for resource-efficient food production in arid climates, though scalability remains constrained by capital intensity and regulatory barriers. Financial instruments such as use-of-proceeds bonds, blended finance, and outcomes-linked credit show promise in mobilizing private investment, especially when paired with public guarantees and concessional capital. Policy reforms that reduce collateral requirements, promote strategic reserves, and expand public–private partnerships are essential to build resilient, inclusive, and climate-smart food systems across the Arab region.

Discussion:

High-Impact Agricultural Innovations

i) Agricultural Innovations for Arid Climates

A key solution to addressing food security challenges is to increase domestic agricultural production. Doing so would reduce price volatility driven by transit and foreign exchange costs, as well as decrease the risks associated with exogenous

geopolitical shocks involving exporting countries. However, the Arab world faces unique challenges in promoting domestic agricultural production. Paramount among those challenges is the region's arid climate. Water scarcity, extreme heat, and poor soil quality create barriers to food production endemic to the desert ecosystems of this region.

Over the past several years, technological advancements have unearthed promising solutions to these problems. Many of these solutions were incubated in the Arab region itself, demonstrating their viability in this specific environment. These solutions exist along a spectrum of technical maturity and commercial viability. Some are in nascent stages of development, requiring patient and often concessionary capital, while others have proven track records and are more suitable for institutional-grade or market-rate investors. Chart 1 presents a stylized representation of key agricultural innovations with potential to address Arab food insecurity mapped against these spectra.

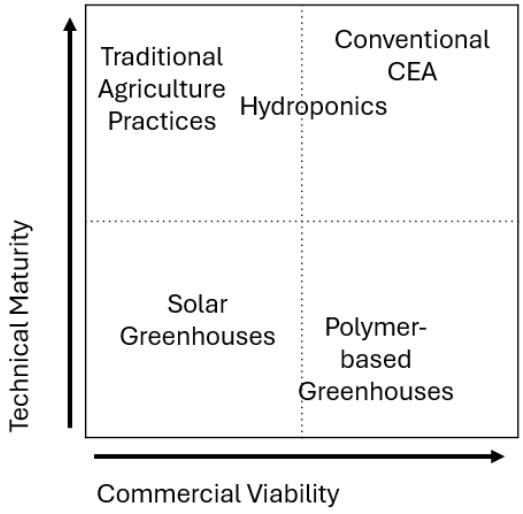


Chart 1: Spectrum of Agricultural Innovations

Source: TCW Research

ii) **Controlled Environment Agriculture (CEA)**

The most mature technologies are those associated with CEA, which refers to the use of enclosed structures such as greenhouses or glasshouses to create optimized growing conditions for plants. These systems allow for precise control over environmental

factors like temperature, humidity, light, and water, enabling cultivation in regions or seasons where traditional agriculture would be impractical or inefficient (Lefers, 2020).

Though CEA systems were originally developed for cold climates, they are showing increased applicability to hot and arid regions. Water conservation is particularly important in the Arab world, where 80% of the region's freshwater resources are used for agriculture. Hydroponic production systems, a subset of CEA in which plants are grown without soil in nutrient-rich water solutions, can reduce water usage by up to 90% relative to field agriculture depending on the system and crop (Regmi, 2024). In hydroponic systems, water use efficiency may be enabled by vertical farming techniques, in which plants are stacked on top of one another so excess water from one plant is used to water plants below it. Likewise, the ability to capture excess water enables a closed-loop system allowing for water reuse.

From an economic perspective, CEA's costs are front-loaded, requiring significant upfront investment outlays. Upfront costs are needed to build facilities and procure the technologies for calibrating the environment. Though, with appropriate operational modifications this agricultural technique not only enables cultivation of various crops, it also provides cost savings over time relative to traditional field agriculture, particularly in inhospitable climates.

At the operational stage, gains in water use efficiency are often counterbalanced by increased electricity and labor costs (Pomoni et al., 2023). Electricity and labor are the two greatest costs associated with CEA, driven by the need for round-the-clock temperature, humidity, and light regulation, as well as the technical skills needed to operate the facility (Wang, 2025). Though investments in CEA have proven to achieve positive NPVs and IRRs, their significant upfront costs and long payback periods are key barriers to scaling these techniques in regions heavily reliant on smallholder farmers.

A World Bank study of climate-smart agriculture (CSA) in Jordan found that investments to transform open-field cultivation of vegetables to hydroponic systems achieved an 11% IRR with a payback period of 10.3 years (World Bank, 2021). In the Jordanian context, initial investment to set up a hydroponic greenhouse with sophisticated sensors and ventilation cost JD 44 per square meter. Though this investment cost is a one-time outlay and enables profitability as soon as the second year

of operation, the initial cost is so high that it requires a decade to recover the initial investment (World Bank, 2021).

iii) Leveraging Desert Ecosystems for Agricultural Innovation

Reframing region-specific challenges, such as high solar irradiation and heat stress, as opportunities to adapt and advance proven agricultural innovations offers solutions unique to the Middle East and North Africa. For CEA to be successful in the desert ecosystem, operators must rely heavily on cooling, ventilation, and artificial lighting. These requirements directly conflict with the regional climate, and their energy intensiveness often increases the greenhouse gas (GHG) emissions associated with CEA relative to traditional agriculture practices.

iv) Solar Greenhouses

More nascent technologies in the renewable energy and materials sciences fields offer promising remedies that leverage the region's consistent and high solar irradiation to provide natural sunlight and energy to CEA facilities. Solar greenhouses, for example, use high-transparency photovoltaic modules mounted on rooftops and windows to capture sunlight for electricity generation while transmitting sufficient light for plant growth (Luo, 2025). These custom-designed panels redirect ultraviolet, violet-blue, and infrared radiation toward PV cells, while maintaining visible light transmission of around 60-70%.

A research-scale solar greenhouse constructed at Murdoch University in Australia using solar panels from ClearVue Technologies piloted this approach. The study found a reduction in energy and water consumption by 57% and 29%, respectively, relative to traditional greenhouses (Luo, 2025). Resource savings were enabled by both energy conservation from reduced reliance on artificial lighting and cooling, and energy generation from the solar panels. Yields for common horticulture crops, such as tomato, beans, lettuce, and bell pepper, were comparable in solar versus conventional rooms. Several crops showed increased productivity, and soil moisture content was higher in the solar greenhouse versus conventional greenhouses (Luo, 2025).

v) Materials Science Solutions

A lower-tech innovation developed by researchers at King Abdullah University of Science and Technology (KAUST) targets similar results with specialized greenhouse cover films

that reduce resource usage while maintaining or improving yields in arid environments. Use of nanoparticle-enhanced covers can reduce heat loads by blocking near-infrared radiation while maintaining photosynthetically active light, enabling passive cooling in arid climates. KAUST-supported field trials found that a combination of cover and ground film reduced soil temperatures by as much as 25.1 degrees Celsius (Tian et al., 2025).

While results show meaningful promise, these technologies are still commercially immature. One company, Iyris, was spun out of the KAUST research effort with backing from investors including the Dubai Future District Fund, Aramco, and Future Investment Initiative. Commercial success of innovative products across a spectrum of technological complexity requires incubation and patient capital.

Greenhouses with transparent solar panels have higher upfront investment costs than traditional CEA facilities, exacerbating economic barriers to scale. Over time, however, studies suggest that solar greenhouses can become 100% self-sustainable and achieve positive ROI (Luo, 2025). Nevertheless, the issues of high upfront costs and long payback periods persist, suggesting that scalability is dependent on significant public or venture investments.

Polymer-based greenhouse enclosures, for their part, require less upfront cost, but have a shorter lifespan than solar modules. Ultimately, farmers must conduct their own cost-benefit analyses to identify the most attractive solutions for their needs.

Traditional Agriculture Solutions

Any discussion of agricultural innovation in the Arab world would be incomplete without consideration of traditional techniques long practiced in the region. Ancient water channeling and irrigation practices like *qanats/aflaj, jessour systems,* and terrace irrigation provide lessons on low-technology sustainable water management (Hassen, 2025). These systems leverage gravity and the natural landscape to channel water from underground aquifers or fluvial or pluvial sources to farmlands. Though these practices are economical, sustainable, and engrained in cultural heritage, they face threats from urbanization, climate change, and policy decisions. Typically, the domain of smallholder and community farmers, these practices also lack the scale required to meaningfully address the region's food security challenges.

Urbanization has led to significant land use change, while climate change continues to alter rainfall patterns. Concurrently, public support for the widespread implementation of modern agricultural techniques, sometimes maladapted to arid ecosystems, has reduced the prominence of traditional practices within Arab agriculture and increased the agricultural sector's energy usage. Over time, generational knowledge of traditional techniques has waned, contributing to agricultural resource overuse, and land and water degradation.

Despite these challenges, beneficial features of traditional techniques can be found in some of the most promising new technologies. For example, gravity-based irrigation systems are reflected in vertical farming practices, which don't require energy-intensive sprinkler systems. Advanced sensing and soil nutrient monitoring, common in CEA, recognize the importance of soil health and moisture levels in maintaining and enhancing yields, while limiting resource depletion. Though industrial-scale agriculture is critical to Arab food security, sustainability tenets of ancient farming practices should be retained as the sector evolves.

Innovative Financial Models

Blended Finance

Mobilizing private capital at scale for climate-aligned agriculture in MENA remains difficult due to structural and policy barriers. Blended finance, strategically combining public and concessional capital to attract private investment, offers a pathway to advance agricultural finance solutions.

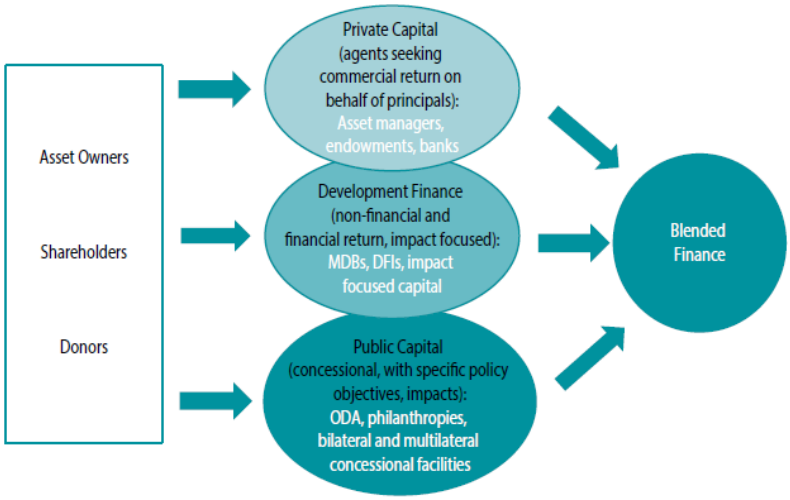


Chart 2: Blended Finance: Structure

Adapted from the Network for Greening the Financial System Technical Document on 'Scaling up Blended Finance for Climate Mitigation and Adaptation in Emerging Market and Developing Economies (EMDEs)', December 2023

To be effective, blended finance requires an integrated ecosystem: lending instruments, risk-sharing mechanisms, standardized frameworks, and project preparation facilities that help de-risk agricultural investments. The Arab region has a foundation upon which to build. Its track record of government collaboration with Development Finance Institutions (DFIs) and Multilateral Development Banks (MDBs) provides effective models of mobilizing capital for agriculture solutions.

Country-Specific Programs

Country-specific blended finance programs offer tailored solutions to unique national government, sectoral, environmental, and market ecosystems. These facilities involve a multilateral institution or provider of concessional capital that works in collaboration with national governments and relevant ministries to harmonize sectoral strategies at a national level. They deploy capital to crowd in private sector investment to fund implementation of these strategies.

The Green Climate Fund (GCF), for instance, was established in 2015 under the United Nations Framework Convention on Climate Change (UNFCCC). It is the largest multilateral climate fund dedicated to helping developing countries reduce greenhouse

gas emissions and adapt to climate change. The facility deploys a variety of financial instruments, including grants, concessional loans, equity investments, guarantees, and outcomes-based investments, to advance its objectives. It partners with national governments through its country platforms to adapt National Decarbonization and National Adaptation Plans into investment pipelines, ensuring that national priorities are centered in capital mobilization efforts.

The GCF's Private Sector Facility (PSF) has catalyzed billions of dollars in private sector investment to advance climate-smart agriculture alongside economic development.

For example, the Jordan Aqaba-Amman Water Desalination and Conveyance Project (AAWDCP) is a large-scale infrastructure project designed to address Jordan's acute water scarcity by desalinating seawater from the Red Sea and transporting it to Amman (Green Climate Fund, 2025). The project involves constructing a solar-powered desalination plant in Aqaba and conveyance infrastructure to transport the treated water over 300 km inland. By improving water security in the country, this project indirectly supports the agriculture sector by developing more extensive and effective water infrastructure with multiple possible end uses. While it is a government-led initiative, the AAWDCP is highly dependent on GCF concessional funding to improve the economics of the project.

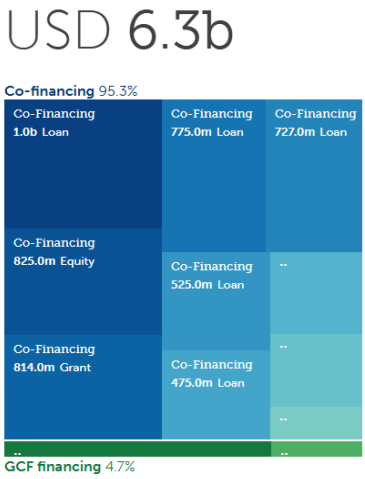


Chart 3: AAWDCP Financing Structure

Source: Green Climate Fund. https://www.greenclimate.fund/project/fp288.

Region-Specific Programs

Regional blended finance programs operate similarly to country-specific programs, but they are also able to leverage the diverse capabilities and resources within the region to support a more resilient multinational ecosystem. In addition, they provide common frameworks and measurement systems to enable more effective cross-boundary collaboration on shared challenges.

The Islamic Organization for Food Security (IOFS) epitomizes this type of regional program. The multinational funding mechanism is designed to mobilize capital for food security across Organization for Islamic Cooperation (OIC) member countries. Like country-specific blended finance facilities, the IOFS leverages concessional capital from MDBs and DFIs and public sector contributions from member countries to catalyze private co-investment. The facility segments member countries by food system maturity to tailor interventions and facilitate targeted knowledge sharing (Islamic Organization for Food Security, 2021).

OIC Member Country Segmentation by Level of Food System Stability

- Group A1 – Established agrifood processors (e.g., Turkey, Indonesia)
- Group B1 – Food secure, import dependent (e.g., Bahrain, Qatar, Saudi Arabia)
- Group A2 – Lagging, high-potential exports (e.g., Afghanistan, Kazakhstan, Niger)
- Group B2 – Least developed, food insecure (e.g., Yemen, Iraq, Somalia)

Green Financing

MDBs/DFIs have played an outsized role in channeling grants, loans, and concessionary capital to climate-resilient agriculture. The World Bank's Roadmap for Climate Action in the Middle East and North Africa plans to mobilize $10 billion in Bank and IFC funding to climate projects and aims to catalyze an additional $2 billion in private capital (Ezzeldin, 2023). Food systems, climate-smart agriculture, water security, and biodiversity are one of four pillars targeted under this plan, which runs from 2021 to 2025. Likewise, the European Bank for Reconstruction and Development (EBRD) and the French Development Agency (AFD) are each active players in the region with dedicated financing facilities for climate resilience and agriculture.

These multilateral and bilateral development banks have pioneered the use of green and 'climate resilience bonds' in the region. As with blended finance structures,

investment-grade issuances with proceeds allocated to emerging and frontier markets can catalyze private investment into sustainability projects that otherwise would have been too risky for participation from institutional investors. Not only do such development-oriented investments mobilize needed green financing, but they are often structured to include technical assistance to local banks, governments, and agriculture firms. Such capacity-building increases the investments' effectiveness in achieving agricultural productivity improvements.

Use-of-proceeds bonds, such as green bonds and novel 'climate resilience bonds', ensure that proceeds raised are allocated to projects with measurable non-financial outcomes. In the sustainable agriculture space, bond proceeds often target yield improvements alongside resource efficiency, training in regenerative farming practices, and ecological conservation efforts. For example, the EBRD issued the world's first climate resilience bond in 2019, with Morocco's Saiss water conservation project as one of its beneficiary projects.

Outcomes-Linked Instruments

Whereas development finance and blended mechanisms channel capital at scale to large agriculture projects, such as industrial vertical farming operations, outcomes-linked financing can be tailored for earlier-stage ventures. These financing mechanisms, well-established in impact investing and formalized more broadly with sustainability-linked loans and bonds, tie financial characteristics, such as interest rates, to contractual outcomes. In the agricultural sector, borrowers are rewarded based on their achievement of targets such as carbon footprint, adoption of cover crops, and soil and water health improvements.

These outcome-linked instruments can be tailored to the specific needs of borrowers based on the maturity of their business and capital requirements. For example, operating loans can include terms to support transition to regenerative agriculture practices, providing both needed bridge financing and technical support to support the adoption of climate-smart agriculture.

Likewise, sustainability-linked insurance products recognize the long-run risks, such as soil degradation and water depletion, related to many conventional agriculture practices. These products help farmers mitigate income volatility while encouraging

adoption of sustainable farming techniques by tying premium pricing or period extensions to eligible counterparties.

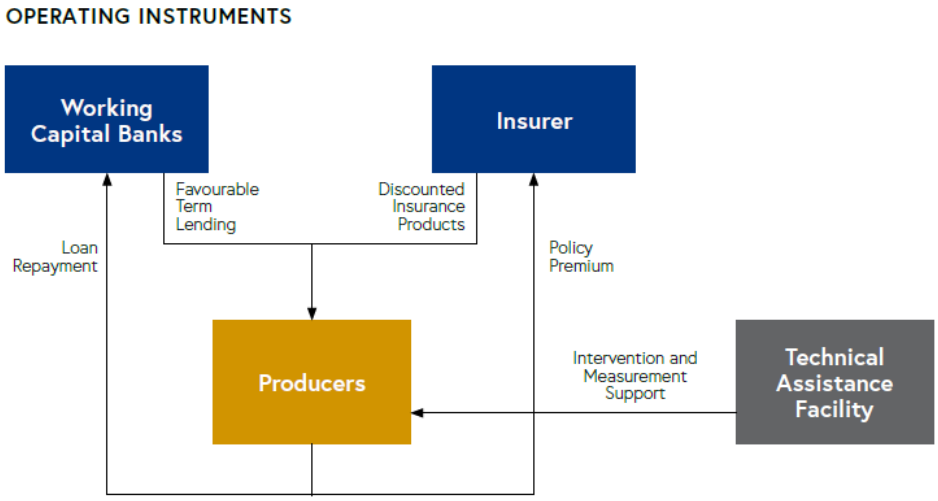


Chart 4: Outcomes-Linked Instruments: Structure

Adapted from Financing for Regenerative Agriculture supported by the Rockefeller Foundation, Transformational Investing in Food Systems, and Pollination. June 2024.

Enabling Policy and Market Systems

Achieving sustainable food security in the Arab region requires more than innovative financing and technological breakthroughs; it depends critically on the policy and market systems that determine whether such innovations can be adopted, scaled, and sustained. Policy frameworks, shock-responsive financing mechanisms, and effective public–private partnerships (PPPs) are essential to reduce systemic vulnerabilities and build resilience. Comparative lessons from Asia's food security crisis responses further highlight the importance of coordinated reserves, supply management, and price stabilization.

Policy Frameworks for Agricultural Resilience

The Arab region's agricultural sector is constrained by fragmented regulatory environments, limited incentives for sustainable practices, and weak institutional

capacity. Regulatory reforms are therefore central to enabling resilience**.** The Arab Monetary Fund and World Bank (2019) note that agricultural lending in the region averages only 7% of total bank lending, compared to 14% in other emerging markets, reflecting high perceived risks and a lack of tailored products. Reforms that reduce collateral requirements, expand the use of non-traditional collateral (e.g., warehouse receipts, crop insurance), and promote branchless banking could ease SME financing and technology adoption.

Incentives for sustainable practices are also critical. Morocco's *Green Morocco Plan* (2008–2020) demonstrated the effectiveness of targeted subsidies for drip irrigation. Empirical studies of Morocco's irrigation transition show that drip irrigation adoption improved farm-level yields and water productivity, although aggregate water savings may be offset by expanded irrigated area (Assouli et al., 2018). Similar incentive structures could be scaled across the region to encourage adoption of climate-smart technologies.

At the regional level, the Arab Strategy for Sustainable Agricultural Development 2020–2030 emphasizes harmonizing agricultural trade and investment policies, rural development, and knowledge sharing (AOAD, 2020). However, implementation remains uneven, underscoring the need for stronger governance and institutional alignment. ESCWA (2019) and FAO stress that secure land tenure, improved storage and logistics, and market-oriented agriculture are prerequisites for resilience. Without such reforms, financial and technological innovations will struggle to achieve scale.

Shock-Responsive Financing Models

The Arab region is highly vulnerable to climate shocks, geopolitical disruptions, and global commodity price volatility. Shock-responsive financing models are therefore essential to provide rapid liquidity and risk-sharing mechanisms. The African Risk Capacity (ARC) has pioneered sovereign insurance pools that disburse funds quickly after droughts, reducing reliance on slow humanitarian aid. Similar regional mechanisms could be developed for Arab states to insure against droughts, floods, or supply chain disruptions.

Emergency credit lines, preapproved by central or development banks, could prevent liquidity crises from cascading into bankruptcies and food shortages. Mobilizing climate finance is equally critical: ESCWA (2025) estimates that $127 billion is needed to address water scarcity alone, yet the Arab region receives only a small fraction of global climate finance. Accessing funds such as the Green Climate Fund and channeling them into agriculture and water management would strengthen resilience. Risk transfer instruments, including weather-indexed insurance and catastrophe bonds, could further diversify risks across global capital markets.

Public–Private Partnerships (PPPs)

PPPs are indispensable for mobilizing capital, sharing risks, and coordinating investments in agriculture. The Arab Authority for Agricultural Investment and Development (AAAID) provides a model, with investments in 45 agricultural companies across 12 Arab countries, generating over 107,000 jobs (AAAID, 2025). By pooling resources from member states and private investors, AAAID demonstrates how PPPs can scale agricultural production and processing.

PPPs have also supported infrastructure development. In Jordan and Egypt, partnerships with international donors and private firms have expanded solar-powered irrigation and cold-chain facilities, reducing post-harvest losses and improving export competitiveness (IWMI, 2024). Moreover, circular economy partnerships in Jordan, Egypt, and Morocco have improved water efficiency and soil health while creating new business opportunities. To maximize impact, PPPs should be structured with clear risk-sharing arrangements, transparent governance, and measurable performance indicators.

Comparative Lessons: Asia's Food Security Crisis Response

The Arab region can draw valuable lessons from Asia's experience in managing food security crises. During the 2008 global food crisis, Asian countries pursued strategies to enhance self-sufficiency while maintaining trade integration. Academic analyses of ASEAN+3's Emergency Rice Reserve (APTERR) identify regional stockpiling mechanisms as an effective institutional tool for crisis response and food security coordination (Kim, 2021). APTERR pooled rice reserves from member states to provide

emergency supplies during crises, stabilizing prices and ensuring availability. Indonesia's recent reforms, including a US$8.6 billion allocation for food security in its 2025 budget, highlight the importance of strategic reserves, diversified staples, and investments in irrigation and logistics (East Asia Forum, 2025).

For Arab economies, adapting these lessons could involve establishing regional grain reserves for wheat and barley, coordinating supply management policies to avoid export bans, investing in logistics networks, and embedding food security strategies into broader development and climate adaptation plans. Such measures would not eliminate import dependence but would reduce vulnerability to external shocks and stabilize domestic markets.

Conclusion and Policy Implications:

The Arab region's food security challenges are deeply rooted in structural vulnerabilities, climate stressors, and financial constraints. While technological innovations offer promising solutions, their success hinges on integrated approaches that combine finance, policy reform, and market development. The path to resilience lies in aligning capital flows with high-impact agricultural technologies, fostering enabling environments, and learning from global best practices. Only through coordinated efforts across public and private sectors can the Arab world reduce its import dependency and build sustainable, shock-resilient food systems. Effective initiatives will integrate the following policy recommendations that focus on strengthening existing resources, establishing new practices, and channeling capital flows to proven solutions.

Phase 1 (0-12 months): Policy alignment and capacity-building for local institutions

a. Embed food security into national development plans: Align agricultural modernization with climate adaptation strategies and broader economic goals.
b. Reform agricultural finance regulations: Remove barriers to financial access by lowering collateral requirements, expanding the use of warehouse receipts, and promoting branchless banking and fintech tools for rural SMEs.

c. Strengthen domestic institutions: Invest in data infrastructure, extension services, and technical training to support precision agriculture and durable adoption of climate-smart practices.

Phase 2 (12-36 months): Pilot blended finance models in priority countries

d. Mobilize climate finance: Tap MDB, DFI, and blended finance structures to attract institutional investments. Leverage mechanisms, such as green and climate resilience bonds, that offer accountability and reporting for sustainability outcomes.
e. Deploy outcomes-linked financing: Tailor financing to business maturity and sustainability objectives by linking financial terms and insurance premia to climate-smart practices and yield improvements.
f. Scale public-private partnerships: Employ PPPs to finance large-scale infrastructure, such as solar-powered irrigation, cold storage, and industrial-scale vertical farms.

Phase 3 (36+ months): Advance regional knowledge-sharing and monitoring frameworks

g. Establish regional monitoring frameworks: Track progress across countries using harmonized metrics and reporting systems to evaluate impact and guide future investment.
h. Preserve and integrate traditional practices: Leverage indigenous techniques like qanats and terrace irrigation to enhance sustainability and embed cultural heritage into modern systems.
i. Facilitate cross-border collaboration: Promote regional grain reserves, supply coordination, and shared logistics to stabilize markets and reduce vulnerability to external shocks.

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تمويل القدرة على الصمود: سدّ الفجوة الغذائية العربية من خلال الابتكار والسياسات

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الملخص:

يتطلب تحقيق الأمن الغذائي المستدام في العالم العربي تعبئة الموارد المالية، وتعزيز الابتكار الزراعي، وبناء هياكل سوقية قادرة على الصمود بما يسهم في الحد من اعتماد المنطقة على الواردات. وعلى الرغم من الدور الذي يؤديه القطاع الزراعي في توفير فرص العمل ودعم سبل العيش في المناطق الريفية، فإنه لا يزال يعاني نقصاً في التمويل، في حين تواجه المؤسسات الصغيرة والمتوسطة، التي تؤدي دوراً محورياً في الإنتاج والتصنيع والتوزيع، عوائق هيكلية تحد من قدرتها على الوصول إلى رأس المال. وتهدف هذه الورقة إلى بيان أن تحديد النماذج التمويلية المبتكرة وتوسيع نطاقها، وتوجيه الاستثمارات نحو التقنيات ذات الأثر المرتفع، وتهيئة السياسات الداعمة، تمثل خطوات مهمة نحو تقليص الفجوة الغذائية العربية وتحقيق تنمية زراعية مستدامة.

وتستند الورقة إلى ثلاث ركائز مترابطة .تتمثل الركيزة الأولى في دراسة الابتكارات ذات الأثر المرتفع التي يمكن تمويلها وتوسيع نطاق تطبيقها في الاقتصادات العربية. وتشمل هذه الابتكارات الاستراتيجيات والتقنيات الرامية إلى التغلب على تحديات ندرة الأراضي والمياه، وإدارة الآفات، وتحسين إنتاجية السلع الزراعية الرئيسة في المنطقة العربية. وتركز الورقة على الحلول التي يمكن من خلالها لتوجيه رأس المال أن يسهم في تعزيز الأمن الغذائي الإقليمي وتحقيق مكاسب اقتصادية أوسع نطاقاً، بدءاً من توفير فرص العمل ووصولاً إلى تحسين الميزان التجاري.

وتتناول الركيزة الثانية استعراض نماذج التمويل المبتكرة القادرة على تحفيز الاستثمارات الزراعية، بما في ذلك التمويل المختلط(Blended Finance) ، والأدوات المالية الرقمية، والتمويل المرتبط بالنتائج (Outcome-Linked Financing)، الذي يربط الخصائص المالية بتحسينات قابلة للقياس في الإنتاج الزراعي. ويمكن لهذه الأدوات أن تسهم في الحد من مخاطر الاستثمار ومواءمة الحوافز بين أصحاب المصلحة الرئيسيين، بما في ذلك مؤسسات الأعمال وصنّاع السياسات والمستثمرون.

أما الركيزة الثالثة، فتتناول تحليل الأنظمة التمكينية التي تشجع على تبني الحلول وتوسيع نطاق تطبيقها. ويشمل ذلك الأطر التنظيمية، ونماذج التمويل المستجيبة للصدمات للتخفيف من آثار الاضطرابات المناخية والجيوسياسية، فضلاً عن الشراكات بين القطاعين العام والخاص التي تتيح حشد الموارد المشتركة مع الحد من التعرض للمخاطر. وتبرز الدروس المستفادة من التجارب المقارنة، مثل إطار الاستجابة لأزمات الأمن

الغذائي في آسيا، كيف يمكن للاحتياطيات الاستراتيجية والإدارة المنسقة للإمدادات أن تسهما في استقرار الأسعار والإمدادات خلال فترات الأزمات.

ومن خلال التكامل بين الابتكار المالي والتحديث الزراعي، **ترسم الورقة** مساراً يمكن لصنّاع السياسات والجهات التمويلية في الدول العربية تبنيه لبناء نظم غذائية قادرة على الصمود، ودعم نمو المؤسسات الصغيرة والمتوسطة، وضمان تحول القطاع الزراعي إلى محرك لتعزيز القدرة الاقتصادية على الصمود على المدى الطويل.

الكلمات المفتاحية : الأمن الغذائي، الابتكار الزراعي، القدرة على الصمود في مواجهة تغير المناخ، إصلاح السياسات، الشراكات بين القطاعين العام والخاص.

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Sustainability Assessment at Farm Level Using the RISE Method (Baghdad Governorate Case Study)

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Abstract:

The research aimed to evaluate farm-level sustainability because decisions made at the farm level—such as specialization, resource allocation, and production process management—are crucial and essential for achieving sustainability. Fostering strong communities requires a balance between economic, environmental, and social aspects. A survey was conducted on 72 farms in Baghdad province for the year 2023, in addition to other data obtained from relevant authorities. The RISE (Response-Inducing Sustainability Evaluation) tool was used, which is a comprehensive tool for assessing the sustainability of agricultural production at the farm level. Eight indicators were calculated, with each indicator comprising more than four criteria, covering economic, environmental, and social aspects. These indicators include: energy consumption, water consumption, soil care, biodiversity, emission potential, plant protection, waste and residue production, cash flow, farm income, investments, contribution to the local economy, social status of farm families and farm employees, and farm management. The water use indicator achieved 56 points, which is a critical sustainability indicator, influenced by water supply, which scored 27 points, indicating a difficult situation. Performance was weak for air use and environmental protection, achieving only 25 points due to poor material supplies and fertilization. Meanwhile, working conditions indicators were unsustainable through labor management and the wage and income level, which scored 27 points and was critical in terms of working hours and work safety indicators. The economic viability indicator achieved 57 points, which is critical in terms

of sustainability and was weak in terms of liquidity (only 6 points) and livelihood security (18 points). However, it was sustainable through the profitability indicator. The farm management criterion was critical at 48 points, influenced by risk management, which was unsustainable. Other indicators within the sustainability polygon were also critical: animal husbandry achieved only 50 points and soil use 54 points. Overall, it can be concluded that sustainability at the farm level in Baghdad province was unsustainable and failed to balance economic, environmental, and social indicators. Sustainable agriculture is a challenging and highly complex undertaking, requiring individualized, farm-specific solutions. Therefore, farm sustainability analysis should contribute to capacity building.

Keywords: Sustainability Polygon, Water Supply, Environmental Protection, RISE (This is an acronym, so it remains the same), Farm Management

Introduction:

Sustainable agriculture is a strategic issue within the Sustainable Development Goals. Continuous population growth exacerbates food demand, placing pressure on the supply side. This has led to an expansion of measures to boost food production. Sometimes, agricultural development is perceived as solely focusing on increasing output without considering its impact on ecosystems and soil quality. Consequently, this could lead to future food scarcity and food insecurity, threatening the sustainability of food production. A sustainable food system, in particular, is one that "provides food and nutritional security for all, in a way that does not compromise the economic, social, and environmental bases required for achieving food security and nutrition for future generations." Therefore, the ability of socially equitable and resilient food systems to provide nutritious food without exceeding Earth's environmental capacity lies at the heart of sustainable development and is closely linked to all Sustainable Development Goals. Given that agriculture drives many global environmental and social challenges, farm-level decisions—such as specialization, resource allocation, and production process management—are crucial in determining the food system's impacts on communities and the environment (Foley et al., 2011).

Therefore, "sustainable agriculture" involves developing agricultural systems focused on advancing agricultural techniques and projects that: (a) do not negatively affect the environment (as the environment is a vital resource for agriculture); (b) are accessible and effective for farmers; and (c) lead to increased food productivity and have a positive impact on environmental goods and services. Sustainability in agricultural systems integrates the concepts of resilience (the system's ability to withstand shocks

and pressures) and sustainability (the system's ability to persist over time), and broadly discusses its impact on the economy, society, and environment. This ensures the presence of sustainable food production systems and the application of flexible agricultural practices that enhance productivity and output, help preserve ecosystems, and boost adaptive capacity to climate change, extreme weather, droughts, floods, and other disasters, while gradually improving land and soil quality.

Measuring sustainable agriculture through various indicators is essential for monitoring goal achievement, especially to determine if the currently implemented agricultural system is sustainable. This allows for identifying whether current agricultural practices truly reflect sustainable agriculture or if further efforts are needed to promote it. These indicators can also empower policymakers to identify

necessary policies for achieving the goal. As rural communities evolve, it has become more crucial than ever for agricultural industries, governments, and researchers to possess effective frameworks for sustainability assessment. This determines the feasibility of applying farm-level sustainability indicators to measure and identify societal issues in an agricultural area. While agricultural sustainability indicators exist to standardize and guide assessment, not all can be easily applied at a regional scale. As development extends into rural communities, practical sustainability assessments to evaluate the social, environmental, and economic impacts of development on local communities become increasingly important each year. Agriculture has always been the cornerstone of rural communities, and a robust agricultural sector is essential for achieving sustainability.

Fostering strong communities requires a balance among environment, culture, and development. Sustainability assessment for agriculture should include accessible indicators that monitor the interactions between society, environment, and development. As development expands the boundaries between rural and urban communities, tracking change is paramount. However, the necessary tools to track these changes are currently insufficient.

For tracking developments and supporting evidence-based policymaking, accurate measurement is the cornerstone of transitioning to a sustainable food system. To monitor progress toward this transition, adequate measurement is a critical research and policy priority for both the private and public agricultural and food sectors. Consequently, sustainability indicators have gained importance across all scales. Indicators that embody, enable, and provide transparency regarding sustainability's key characteristics are particularly significant in a context where perspectives on this

concept vary among different stakeholders. Thus, the use of indicators to measure sustainability in agriculture has become common practice, with numerous literature reviews conducted on the topic (Foley et al., 2011).

Sustainability indicator frameworks showcase a wide variety of approaches. Regardless of the chosen approach, the specific framework and indicators selected to represent aspects of sustainability strongly influence the outcomes of sustainability assessments. However, the basis for indicator selection is rarely explicit in research. Even when indicator selection criteria are explicitly defined, significant limitations often exist in indicator construction, such as measurability and practical applicability, particularly regarding data availability. Specifically, data-driven sustainability assessments require readily available, relevant, and reliable data for indicator construction, and a lack of appropriate data severely limits analysis. In the literature on sustainability indicators in agriculture, little attention has previously been given to the potential consequences of this fundamental role of data availability for indicator construction and sustainability assessment results. Since the selection of sustainability assessment indicators is inevitably based on available data, the data sources for indicator construction and their implications for the explanatory power of the indicators warrant further research (Latruffe et al., 2016). Sustainability is a fundamental element toward a profitable future for agriculture. Therefore, there is growing recognition of the need to establish procedures for measuring sustainability within an integrated farm-level framework. Farm-level sustainability indicators have been developed here, encompassing the four aspects of sustainability: economic, environmental, social, and innovative, within an integrated framework to measure the current sustainability of agriculture. Indicators were chosen based on their general relevance within the socio-economic context.

Indicators are quantitative measures that allow for the assessment of farm sustainability performance. According to the European Commission, sustainability indicators should help evaluate the extent to which sustainability concerns are integrated into the Common Agricultural Policy, and thus should meet specific criteria. The limitations of the production-focused agricultural model, based on simplifying production systems and intensive use of non-renewable resources, are observable worldwide. These environmental, economic, and social limitations challenge this model and necessitate a transition to more sustainable agriculture. For transitions to be effective, they must be adapted to farmers' motivations and their diverse operational contexts. To improve the economic and environmental performance of agricultural systems, it is essential to understand and account for how farmers perceive their operating context and transform it to better achieve sustainable development

(Fairweather et al., 2011). However, only a few studies have explored farmers' perceptions of their farms' sustainability or how they translate these perceptions into productive strategies. Studies generally focus on specific topics, such as soil degradation, plant health risk management, biodiversity management, or groundwater management. The few studies that holistically explore how farmers perceive sustainability examine farmers' values concerning the concept of sustainability, the impact of the socio-economic context on their perceptions, or what motivates farmers to integrate the concept into their practices. These studies have been conducted in contexts where farmers are generally aware of the concept of sustainability. Given that the concept of "sustainability" and the word itself can mean many different things, there is a widening gap between the discourse and actions of individuals (farmers, extension services, politicians, scientists) involved in sustainability discussions, programs, and policies. Therefore, many authors have chosen to focus on how farmers design and implement farm-level sustainability strategies to ensure their income and the continuity of their farms across generations in a changing context (Suess-Reyes, 2016). Despite all this, currently developing agricultural sustainability measurement tools tend not to involve farmers in their interpretation, focusing more on measurement at spatial and temporal levels (Frater, Poppy & Jeremy Franks, 2013). Simultaneously, farmers/farm households are a crucial element in achieving a sustainable agricultural system. Therefore, measuring sustainable agriculture indicators at the farm household level is vital.

Various methods for measuring farm-level sustainability have been developed in recent decades. Among the methods developed by the Food and Agriculture Organization (FAO) is the Sustainability Assessment of Food and Agriculture systems (SAFA), which can measure sustainable agriculture based on three or four hierarchical levels. Here, "dimensions" represent the core pillar, while the highest and most general level describes sustainability. Furthermore, global sustainability goals are translated into "themes" (and in some cases, more clearly formulated into "sub-themes"). The lowest level of sustainability measurement is an indicator in the form of a measurable variable to assess the sustainability performance of the relevant theme or "sub-theme" (FAO, 2014). The SAFA method uses three main dimensions to measure sustainability at the smallest scale (farm households): the economic dimension, the social dimension, and the environmental dimension.

Another method developed to measure sustainable agriculture at the farm/household level is the Indicators of Sustainable Agricultural Exploitations (IDEA). The IDEA method defines the concept of sustainable agriculture by (a) incorporating viability, in the economic sense, i.e., the efficiency of the production system and the

securing of income sources in the agricultural production system in the face of market changes and unstable funding sources; (b) livability, focusing on analyzing whether agricultural activities provide a decent life for farmers and their families; and (c) the environmental reproducibility of agricultural ecosystems, which can be analyzed using agro-environmental indicators, especially those that characterize the impact of agricultural practices on the environment (Zahm, Frederic & Lionel Vilain, 2008). The IDEA method uses three scales, ten components, and 41 indicators to address 16 objectives describing farm-level sustainability. Other methods used to measure agricultural sustainability at both macro (country, spatial) and micro (farm/household) levels include the Public Goods (PG) tool developed by Gerrard et al. (2012), and the Response-Inducing Sustainability Evaluation (RISE 2.0) developed by Häni et al. (2003).
RISE, an instrument known as "Response-Inducing Sustainability Evaluation," is an indicator-based method for assessing the sustainable economic, social, and environmental performance of agricultural production at the farm level. The purpose of RISE is to contribute to promoting the sustainability of agricultural production by supporting knowledge-based processes based on voluntary, confidential participation and capacity building. The steps of RISE analysis include defining the objective and scope, selecting and contacting farmers, collecting and interpreting data, discussing farmers' feedback, and preparing reports. The use of the RISE methodology contributes to achieving more sustainable agriculture by translating the sustainability model to the farm level, making sustainability more measurable, communicable, and tangible. By identifying deficiencies and potential related to sustainability, economically oriented farm management is complemented by environmental and social dimensions. It is also noted that RISE is neither a control method nor a certification protocol; rather, it is designed to contribute to education and advisory schemes aimed at knowledge-based and self-motivated sustainable development of agricultural production at the farm level. The questionnaire-based interview with the farm manager is the primary source of information, and the model relies on the Microsoft Access database management program. This database, which grows with each farm assessment, will allow for...

RISE aims to conduct a comprehensive assessment of the sustainability of agricultural production at the farm level. Its vision is to contribute to more sustainable agricultural production by helping to disseminate the philosophy and practice of sustainable agriculture. This will be achieved by making sustainability more measurable and communicable at the farm level. By identifying sustainability potential and deficits, farm management focused on classical economics is complemented by the environmental and social dimensions. Our target group includes all stakeholders in agriculture, society, management, and business who share this vision. Previous versions

(RISE 0.x, RISE 1.x, and RISE 2.0) have been applied in diverse contexts. From 2000 to the end of 2010, 750 farms were analyzed in 22 countries, including dairy, vegetable, arable, and mixed farms, as well as coffee, cocoa, tea, and smallholder farms. Figure 3 illustrates the countries where the indicator was used, and with the 2025 update, Iraq will be added to the program family after the completion of our study. The RISE model is based on twelve indicators of economic, environmental, and social status: energy consumption, water consumption, soil care, biodiversity, emission potential, plant protection, waste and residue production, cash flow, farm income, investments, contribution to the local economy, and social status of farm families and farm employees. Spatial analysis is determined by farm area and temporally by a one-year period. A key feature of the model is the evaluation of both "state" (S) and "driving force" (D) for each indicator. This allows for a combination of systems and analytical approaches: the calculated "sustainability score" (D–S = DS) considers both the actual state (S) and the pressure (D) on the specific indicator. A high D is likely to lead to a low S over time. D allows for long-term trends and risks to be considered, which are crucial for the concept of operational sustainability, while S can serve as an analytical database for the actual situation; DS also includes systemic trends (see Vester, 1983). The tool allows for the identification of strong and weak aspects of the farm and can thus prompt steps to improve sustainability (a decision-oriented and response-inducing approach). The research aims to assess sustainability at the farm level in Baghdad province for the year 2024 using the RISE method and to measure the sustainability polygon.

Materials and Methods:

Response-Inducing Sustainability Evaluation (RISE) was utilized for this assessment, following communication and collaboration with Bern University of Applied Sciences, School of Agricultural, Forest and Food Sciences (HAFL). We obtained the RISE 3.0 program with a student account under the name RuaEsk2025. We were the first to use RISE in Iraq and the region, necessitating the creation of a new, previously non-existent regional designation within the program, and our inclusion in the RISE family. Our sample farm was assigned the number 33615. The program and the analysis process required a significant amount of data and calculations. Over 390 complex and diverse questions and items were entered, covering all environmental, economic, and social aspects. These included, for example, the nature and quality of water, soil details,

animal life and health, feed, lighting, grazing, various types of labor, consumption, living conditions, air quality, pollution, wages, income, irrigation, costs, revenues, and more.

The analysis required some data obtained from various sources. For instance, data related to humidity, temperature, and rainfall were acquired from Al-Raid station. Data concerning inflation and exchange rates were obtained from the Ministry of Planning. Information related to the nature of agriculture in the governorate and biodiversity was procured from the Ministry of Agriculture. Additionally, some technical data specific to cattle farming and methane emissions were added in consultation with the Animal Production Department at the College of Agricultural Engineering Sciences (Prof. Dr. Hussam Hussein Bananah, Dr. Huda Qasim Al-Hamdani). Some questions related to the security and political situation of the region were answered with estimations. It should be noted that some questions or items were not answered, either because they did not serve the objectives of our study or due to the difficulty of data availability. We strived to maintain a good balance between a set of universally applicable sustainability topics and indicators on one hand, and a sufficiently specific analysis on the other, which presented a significant challenge. A total of 72 survey forms were collected from farms in Baghdad province for the year 2024.

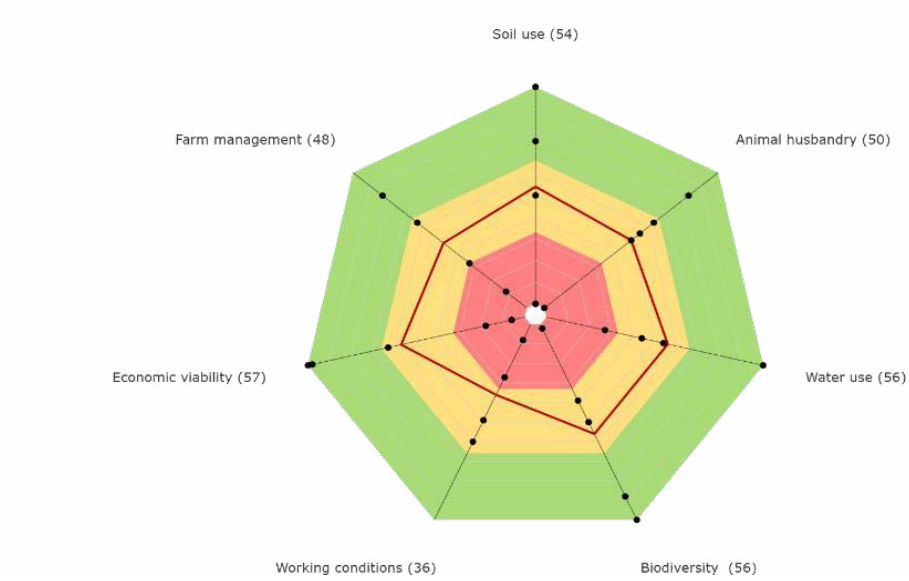
Results and Discussion:

After data input, sorting, and regional classification within the software, a Sustainability Polygon (as depicted in Figure 1) was generated. This polygon, illustrating ten sustainability indicators, presents the results of the sustainability assessment for the study sample. This evaluation reflects the current reality, and these findings may not be typical for many farms operating in Baghdad Governorate.

The overall sustainability index was low due to the low scores of all indicators calculated within the polygon. The economic status can be considered acceptable, achieving approximately 57 points, as the sample demonstrated good economic performance indicators. However, a critically severe issue was identified with the labor indicator, which scored a low 36. This weakness stems from poor working conditions, long working hours, low wages, and the presence of child and female labor, with some

aspects representing disguised unemployment. A significant number of the farms are small, with few cattle, relying heavily on family labor.

The water use indicator within the polygon achieved 56 points. While cattle farms generally don't require extensive water, the primary challenges identified were the year-round availability and the quality of the available water. The biodiversity indicator also scored 56 points. Although no specific measures or actions were taken to conserve biodiversity, agricultural projects inherently possess a certain degree of spontaneous



biodiversity. Furthermore, the animal indicator achieved 50 points, the soil indicator 54 points, while the farm management indicator scored 48 points.

Figure 1: Sustainability Polygon and Sustainability Score. Source: Developed by the researchers using RISE software.

Soil Use

Soil Management

Fertile soil is a finite and easily degradable resource, fundamental to life and production. This indicator reflects the soil's condition on the farm and how it is influenced by agricultural practices. The results of this topic answer the following questions for the farmer: How is their soil fertility assessed? And what is the impact of their agricultural practices on soil fertility?

Within this indicator, soil management is addressed, with the sustainability objective being the active application of knowledge and technology to facilitate productive and site-adapted soil use and conservation. An assessment is conducted to determine whether soil analyses, nutrient and organic matter balances, and changes in soil carbon content are calculated and considered, and if any agricultural land has been lost in the past ten years. A score of 100 points is awarded if all relevant analyses have been performed and no agricultural land has been lost. The score for this indicator was 25 points, which is very low. This indicates that not all analyses were performed, and carbon levels are high. Furthermore, due to climate change and inadequate soil management, agricultural areas have been lost in recent years.

Crop Productivity

The sustainability objective we aim to measure through this indicator is that, through appropriate yields per unit area, the farm contributes quantitatively and qualitatively to meeting the demand for agricultural products and ensures its economic competitiveness. The yield per unit area for all crops cultivated on the farm is compared against regional benchmarks for very high, medium, and very low productivity. Product quality is also assessed based on regional or farm-specific standards. The three benchmark yields correspond to 100 RISE points (very high yield), 67 RISE points (average regional yield), and 34 RISE points (low yield), with 0 RISE points awarded for no yield, with a +/- 20-point correction for product quality. Linear interpolation is used to bridge the gaps between the three defined points. Crop productivity scored 75 points, indicating medium productivity within the study sample.

Soil Organic Matter

The sustainability objective through this indicator is that arable soil on the farm is characterized by good organic matter supply, ensuring that the topsoil organic matter content remains at least stable. The organic matter content of arable soil is assessed directly, or a simple soil organic matter balance is calculated and evaluated based on rotation and agricultural practices. For simplification, the RISE model assumes a high and stable soil organic matter content for permanent pastures, permanent crops, and forests (Kuntze et al., 1994). There are two options for assessing the situation in arable land (mineral soils). If reliable analysis data are available, the organic matter content in the topsoil is assessed based on elevation and soil type. Reference data were obtained through a comprehensive analysis of Bavarian farms (Capriel, 2010), although they are not valid for peaty and black soils. If reliable data are not available, a simple soil organic matter balance is calculated and assessed, differentiating between organic and conventional farms. Soil organic matter balance coefficients are derived from the "site-adapted STAND method" (Kolbe, 2008). The goal is a stable soil organic matter content capable of ensuring an adequate nutrient supply while preventing nutrient inefficiency and high greenhouse gas emissions (Kolbe, 2012). The evaluation functions for both procedures used in RISE are only valid for the temperate climate zone. For areas outside this zone, RISE uses coefficients that have not yet been scientifically validated. This indicator scored 100 points, as the soil had good organic matter content capable of supplying nutrients to plants.

Soil Reaction

The sustainability objective here is that soil reaction falls within the optimal range for crop growth, and soil use does not lead to salinization or acidification outside this range. Soil pH is assessed in terms of crop requirements, and the risk of salinization or acidification is evaluated (Figure 11). Soil acidity and salinity are assessed using a single indicator in the RISE system, as both are related to soil pH. 100 points are awarded if the farm's soil pH ranges between 5.5 and 7.0. Points are deducted when the pH is too high or too low. Additional points are deducted when acidic fertilizers are used without proper soil treatment. 25 points are deducted if the amount of physiologically acidic fertilizers (e.g., urea, ammonium sulfate) exceeds 100 kg/ha annually. In dry climates, good soil

drainage is essential, and soil pH should not exceed 7.0. This criterion received 0 points because we were unable to measure soil acidity and crop requirements for acidic fertilizers.

Soil Erosion

The sustainability objective here is that the amount of soil lost due to water and wind erosion does not exceed tolerance levels, even in the most vulnerable areas. Details regarding the frequency and severity of all erosion events that occurred on the farm over the past five years are required. Additionally, climate, slopes, soil type, vegetation cover, and agricultural practices are used to calculate the risk of water and wind erosion in the most vulnerable areas. 100 points are awarded if no soil erosion was observed and the erosion risk does not exceed soil loss tolerance levels, even in the most vulnerable areas. This indicator scored 75 points, which is a good score and indicates no significant erosion, as most of the land in the study sample is cultivated and has vegetative cover.

Soil Compaction

The sustainability objective we aim to measure through this indicator is that crop growth and soil life are not negatively affected by excessive compaction of the topsoil layer. The risk of excessive soil compaction is assessed based on risk factors (wheel load, soil moisture, soil type, tillage) and protective factors (compaction reduction, improved soil stability). 100 points are awarded if no excessive compaction was observed, the soil is not susceptible to compaction or tillage, and the maximum wheel load is 2.5 tons or less. This indicator scored 50 points, which suggests that the soil in the study sample is exposed to excessive compaction and tillage, and in some instances, tillage was not optimal.

Animal Husbandry

Animal husbandry is an integral part of many agricultural production systems. Livestock must be raised in a manner that ensures their welfare and does not harm the environment. Animal welfare practices encompass the "Five Freedoms": freedom from hunger or thirst; freedom from discomfort; freedom from pain, injury, or disease; freedom to express normal behavior; and freedom from fear and distress (FAWC, 1979).

Simultaneously, high performance and resource use efficiency should be pursued. This topic addresses the following:

- Whether livestock performance is at a high level.
- Whether the animal husbandry system allows for species-appropriate behavior.
- Whether the physiological needs of the animals have been met.
- Whether the animals are in good health.

Herd Management

The sustainability objective of herd management is that livestock numbers on the farm are managed in a long-term, site-adapted manner to improve animal health, welfare, and sustainability. An assessment is conducted to determine whether information related to livestock is collected and utilized in a targeted manner for breeding and care to improve animal welfare. 100 points are awarded if there is systematic monitoring and documentation of animal husbandry (health and performance), and balanced criteria for selection and breeding. This indicator scored 50 points, confirming that cattle rearing is still largely traditional and family-based, with insufficient consideration of scientific methods in management and breeding to improve animal performance and health.

Livestock Productivity

The sustainability objective through this indicator is to achieve appropriate livestock performance on the farm. The annual performance of all livestock categories on the farm is compared against regional benchmarks for very high, medium, and very low performance. Product quality is also assessed based on regional or farm-specific standards. The three reference performance values are 100 RISE points (very high yield), 50 RISE points (average regional yield), and 0 RISE points (very low yield), with a +/- 20-point correction for product quality. Linear interpolation is used to bridge the gaps between the three defined points. This indicator scored only 18 points, indicating low productivity compared to regional or area productivity. This is attributed to reliance on

low-yielding local breeds, the absence of a systematic veterinary program, and the non-optimal use of feed in terms of quantity and quality.

Opportunity for Species-Appropriate Behavior

The RISE system, through this indicator, aims to achieve the sustainability objective of providing an animal husbandry system that ensures the freedom for animals to engage in their natural social behaviors, movement, rest and sleep, feeding, outdoor access, reproduction, and exploration. An assessment is conducted to determine whether animals enjoy sufficient time outside the enclosure and contact with conspecifics, and whether their environment allows them to behave as naturally as possible. 100 points are awarded if, based on current knowledge, the conditions in which animals are kept allow for species-appropriate behavior for all behavioral categories listed in RISE. The sample achieved 65 points, which is a good indicator, suggesting ample space in the enclosures, allowing animals to move and go outside comfortably. Furthermore, a good portion of their time is spent in pastures, facilitating contact and exposure to natural light.

Living Conditions

The sustainability objective here is to meet the physiological needs of the animals, where they live in a suitable environment. An assessment is conducted to determine whether temperature, lighting, air quality, noise level, and feeding arrangements meet the needs of the respective species. 100 points are awarded if all animals live under species-appropriate conditions. There was an increase in temperatures and also relative air quality pollution, though with improved lighting, which resulted in an indicator score of 55, indicating a relatively moderate degree of suitable environment for animal rearing.

Animal Health

The sustainability objective is for animals to live free from pain and disease, and for the number of unintended losses to be as minimal as possible. An assessment is conducted on the number of unintended losses, veterinary treatments, animal interventions, and the external condition of the animals. 100 points are awarded if no veterinary treatments are needed, no deaths due to disease, injury, or accidents, and no

deformed animals. A score of 63 points for this indicator means that veterinary treatments are needed, especially with the recent spread of diseases.

Materials Use & Environmental Protection

Sustainable agricultural production relies on natural nutrient cycles, maintaining a good nutrient balance even at high productivity levels while minimizing environmental pollution and material consumption. This section indicates: whether tight cycles and sustainable sourcing are considered when acquiring materials (fertilizers, feed, etc.); and whether environmental harm is avoided during the storage, use, and disposal of materials.

Material Flows

Our sustainability objective for material flows is to encourage the sustainable production of consumables, machinery, infrastructure, feed, and fertilizers through responsible sourcing. Targeted material selection and optimal resource utilization contribute to waste reduction. An assessment is conducted to determine: (a) whether priority is given to using nutrient sources (especially feed and fertilizers) that are either produced on the farm itself or at least sourced locally (within a region-specific radius); (b) whether the acquisition of materials and equipment considers sustainability criteria, especially circular economy principles; and (c) finally, whether unproductive losses are prevented. This indicator integrates information on the following components:

Feed self-sufficiency (calculated): N self-sufficiency, P self-sufficiency.

Fertilizer self-sufficiency (calculated): N self-sufficiency, P self-sufficiency.

Regionality of feed supply.

Regionality of fertilizer supply.

Losses from crop production ("food loss").

Degree of implementation of recycling potential.

100 points are awarded if all materials are sourced locally and sustainably, and unproductive losses are minimized. However, this indicator scored 29 points, clearly

indicating low performance. This suggests that feed, especially concentrated feed, is imported or purchased from outside the farm. Similarly, fertilizers are purchased from markets at high prices, and there is no self-sufficiency in feed, fertilizers, or food. Furthermore, there is waste in resource use, and sustainability and circular economy principles are not observed.

Fertilization

The sustainability objective we aim to measure through this indicator is to facilitate balanced crop nutrient supply and good productivity while preventing environmental harm and soil nutrient deficiencies. Available farm nutrients are optimally utilized, and external nutrient sources are only supplemented when necessary. Nitrogen and phosphorus balances are calculated at the farm level (supply and demand balance; reference values for the scoring function can be adjusted to regional data). Nutrient surpluses are evaluated more rigorously than deficits in surplus areas. The tolerance limit for surpluses is only raised in cases of poor phosphorus supply, but not for poor nitrogen supply. The extent to which fertilizer use is rationalized according to best practices is also assessed. This indicator integrates information on the following components:

Fertilization management.

Farm-level nitrogen balance.

Farm-level phosphorus balance.

100 points are awarded if fertilizers are used only when necessary, based on relevant analysis results. The farm has a stable nitrogen and phosphorus balance, meaning the difference between supply and demand does not exceed 10%. The precise details of the evaluation function can be regionally defined for both nitrogen and phosphorus. As a general rule, more points are deducted for surpluses compared to deficits of similar magnitude. Figure 14 illustrates some examples of evaluation functions. This indicator scored 21 points, indicating poor and unsustainable performance. This suggests that organic fertilizers from crop residues are not utilized, and nitrogenous and a considerable amount of phosphorus fertilizers are used at unrecommended dosages

and quantities, causing environmental harm, and there is no balance between supply and demand.

Plant Protection

The sustainability objective is that plant protection on the farm relies on integrated plant protection principles. Environmentally harmful hazardous substances are used only when absolutely necessary, and their environmental impact is minimized through careful selection and application. An assessment is conducted on (a) the extent to which plant protection problems are managed according to integrated plant protection principles, (b) the toxicity and persistence of any plant protection products used, and (c) whether measures are in place to reduce any unintended side effects from the use of genetically modified organisms (GMOs). This indicator integrates information on the following components:

Management of plant protection challenges according to integrated plant protection principles.

Due diligence in GMO cultivation.

100 points are awarded if plant protection practices are fully compliant with integrated principles, or if no plant protection products or GMOs are used. This indicator scored zero, indicating the absence of integrated plant protection management. It also suggests that site-adapted production systems, variety selection based on pest and disease resistance, reliable species identification before chemical treatments, application of damage thresholds, use of biological and mechanical means instead of chemical plant protection, and measures to maintain the effectiveness of the plant protection program (e.g., herbicide rotation) were not considered. Furthermore, farmers did not comply with relevant legislation, measures to prevent unwanted spread or gene flow, maintenance of specific GMO traits (e.g., herbicide tolerance, pest resistance), and the development of GMO product use since GMO adoption.

Air Pollution

RISE aims to achieve the sustainability objective that the storage, use, and disposal of materials do not lead to gaseous emissions that threaten or harm human or animal

health or the environment (air, soil, water, and natural ecosystems). This indicator addresses gaseous emissions that may harm human health or ecosystems. It integrates information on:

Ammonia: Risk of ammonia emissions from animal production.

Exhaust gases, smoke, and odor.

The future risk of such incidents is also assessed. The indicator scores 100 points in the absence of pollution incidents and risks. The indicator scored 21 points, indicating unsustainable use and low performance. This suggests a significant risk of ammonia emissions from animal production, as well as ammonia emissions from organic fertilizers, and smoke and odor emissions in the area, leading to soil and water pollution. Additionally, proper storage facilities for feed and fertilizers are lacking.

Soil and Water Pollution

The sustainability objective we aim to measure through this indicator is that the storage, use, and disposal of materials do not lead to liquid or solid emissions that threaten or harm human or animal health or the environment (air, soil, water, and natural ecosystems). This indicator addresses liquid and solid emissions that may harm human health or ecosystems. It integrates information on:

Nutrients (nitrogen and phosphorus).

Pollutants in fertilizers: Heavy metals, radioactive isotopes, organic substances.

Plant protection products.

Pollutants in waste, residues, and wastewater.

This indicator scores 100 points in the absence of pollution incidents and risks. It scored 56 points, which is a relatively low indicator due to the storage and disposal of problematic materials, risks from domestic and agricultural wastewater, the proportion of appropriately treated wastewater, pollution from livestock entering water bodies, and other risks related to soil and water pollution. This is also due to the improper disposal of toxic materials (plant protection products, veterinary medicines, dyes and paints, etc.),

as well as other materials that may be harmful to humans, animals, or the environment. Furthermore, the absence of buffer strips (a 6-meter-wide vegetative buffer strip, permanent vegetation along field margins, prevention of siltation, maintenance of high water retention capacity = prevention of runoff), drift prevention, and the lack of buffer strips for manure storage, silt, and temporary storage of organic fertilizers on bare soil.

Water Use

Clean fresh water is essential for human life and the production of crops and livestock. The farmer's production system affects the quantity and quality of water available to other users. This indicator addresses:

- The quality and quantity of the farm's water supply.
- The intensity and efficiency of water use in production.
- The sustainability of irrigation practices on the farm.

Water Management

The sustainability objective we aim to measure through this indicator is the active application of knowledge and technology to ensure efficient, site-adapted, and resource-conserving water use. This indicator is calculated only if "blue" water (sourced from aquifers or surface water bodies) is used on the farm (as opposed to only "green" water, i.e., rainwater naturally absorbed by plants). It scores 100 points if water consumption is monitored, and potential water-saving measures are identified and fully implemented. This indicator scored 56 points, which is a good score, meaning average performance. There is no major water problem, and water is available for many days a year. However, the main reason for the lower score is the reliance on blue water and inefficient water use.

Water Supply

The sustainability objective is that the quantity and quality of the farm's water supply are secure in the short and long term. The current situation, trends, and potential conflicts regarding water supply quantity and quality are assessed (Figure 17). 100 points are awarded if there are no problems on the farm. This indicator scored 27 points,

which is weak and indicates unsustainable water use. This may be attributed to farm problems such as the need to deepen wells, water-related conflicts, deterioration in water quality, reduced water availability, and declining groundwater levels. This is coupled with a low level of regional water stress as defined by the WBCSD Global Water Tool.

Water Use Intensity

Our objective with this indicator is that the quantity of water used in agricultural production is adapted to local conditions through crop selection and planting times. The farm does not rely on externally supplied water and minimizes its irrigation needs. The water demand for the farm's crops and livestock is calculated based on standard regional coefficients and compared to water supply determined by climatic conditions throughout the year. Water needs are estimated considering the timing and duration of crop cultivation. 100 points are awarded if the farm's total water needs are less than the annual rainfall on its land. The sample achieved a full score of 100 points, indicating sustainable water use intensity, as the cultivated areas are small and not cultivated year-round.

Irrigation

The sustainability objective for this indicator is that efficient irrigation methods enable high material and human returns. An assessment is conducted to determine (a) whether irrigation is targeted and efficient, (b) whether irrigation is financially viable, and (c) whether there are any irrigation-related problems. The indicator scores 100 points if irrigation is implemented in a targeted and efficient manner, is financially sensible, and is problem-free. The indicator scored 41 points, clearly indicating that irrigation in the study sample achieves low financial returns and is not efficient. This is due to the reliance on traditional irrigation methods, the deterioration of rivers and reduced water quantities, and the erosion of irrigation canals, leading to waste and inefficient water use.

Biodiversity

The diversity of living organisms is closely linked to the health of ecosystems. In fact, agricultural production and human life can only be achieved through the regulation of water, nutrient, and gas balances; pollination; soil formation; and other functions performed by ecosystems. This indicator addresses:

- What is being done to promote the diversity of species, varieties, and breeds on the farm.
- The extent to which natural ecosystems and their connectivity within the agricultural landscape are maintained.
- The quality of plant protection management.
- Whether substances toxic to humans and nature were used to protect crops and livestock.

Biodiversity Management

The objective here is that the farm has a biodiversity management system that includes a strategic and systematic approach to planning, decision-making, implementation, and monitoring of activities aimed at species protection and ecosystem conservation. The indicator scores 100 points for providing comprehensive biodiversity advice. The indicator scored 2 points, indicating unsustainable biodiversity management. This suggests that the farm does not receive comprehensive biodiversity advice or is not aware of the current situation. Farmers have not taken necessary measures to protect species or agricultural measures to promote biodiversity in the agricultural area.

Ecological Infrastructures

The sustainability objective we aim to measure through this indicator is that the farm includes many areas with high biodiversity potential that provide habitat for rare and specialized plants and animals. 100 points are awarded if 17% of the farm has high biodiversity potential. This figure is based on the UN Convention on Biological Diversity (Nagoya, Aichi), which states that 17% of terrestrial areas should be managed for nature. This threshold can be adjusted at the regional level. This indicator achieved a full score

of 100 points, indicating the presence of a high proportion of agricultural land with high ecological value (level, linear, and punctiform structures). This is because the sample consists of large agricultural areas with a significant proportion of pastures, among others, which allowed it to achieve this percentage.

Distribution of Ecological Infrastructures

The ecological landscape is well-connected, allowing mobile animal species to move from one ecological starting point to another. There is no "erosion" of ecological structures. 100 points are awarded if 100% of arable land has ecologically valuable features within or near it (less than 50 meters), and if the development of these features is moving in a positive direction (+/- 20 points). The optimal value for the ecological quality of landscapes can be adjusted at the regional level. This indicator scored 98 points, indicating the presence of arable land and nearby ecological facilities. This is also dependent on the preceding indicator.

Intensity of Agricultural Production

Production intensity is low enough to provide habitats for a variety of plants and animals. 100 points are awarded if there is no nitrogen fertilization (0 kg N/ha), no use of pesticide substances, and low stocking density (one large animal unit per hectare). These values can be adjusted at the regional level. Any sprays used should have low toxicity to non-target organisms (including beneficial insects and aquatic organisms) and low persistence (half-life less than one month). The indicator scored 50 points, which is half the maximum score, indicating intensive use of fertilizers, especially nitrogen, and the use of agricultural pesticides. It also suggests inadequate measures to promote biodiversity in the agricultural area.

Diversity of Agricultural Production

To achieve the objective which states: "Through the diversity of agricultural production and the use of genetically diverse crops and livestock on the farm, the farm contributes to the survival and development of plant and animal genetic resources. This helps ensure the availability of a wide variety of primary genetic material for future generations for breeding purposes. By cultivating different types of crops, the farm

contributes to creating a more diverse agricultural environment." This indicator, which scored 39 points, was calculated by assessing various aspects of production diversity: the number of different land use types, the number of arable and permanent crops cultivated, and the number of livestock breeds on the farm (with additional points awarded for old or endangered varieties and breeds); for permanent grasslands, the frequency of use and yields are assessed; and beekeeping is positively rated.

This indicator is assessed as follows: 100 points are awarded if there are 5 different land use types (this figure may be regionally adjusted), 6 different livestock breeds, 3 rare and/or old varieties and/or breeds, and bees kept on the farm. A high proportion of diverse permanent grasslands (assessment based on frequency of use and yield) and 10 different arable and permanent crops (for more than 10 hectares of arable and permanent crops, a maximum of 10 crops; for less than 10 hectares of arable and permanent crops, one crop per hectare).

Working Conditions

A committed and productive workforce is a prerequisite for the success of any farm. These two characteristics are strongly influenced by working conditions on the farm. This indicator assesses the objective working conditions of farm employees and self-employed workers. It addresses the following aspects:

- Occupational health and safety / physical working conditions.
- Work organization.
- Respect for fundamental rights.
- Wages.
- Fairness.

Personnel Management

The sustainability objective for this indicator is that good personnel management ensures the farm has sufficient staff in the short, medium, and long term, who are satisfied, motivated, and adequately trained. Transparent and fair employment terms and conditions also reduce the likelihood of disputes. An assessment is conducted to

determine whether the farm has a professional personnel management system and whether working conditions comply with decent work standards stipulated in relevant human rights conventions and agreements. This indicator scored only 6 points, which is very low and indicates unsustainable low performance. This is because employee requirements are unknown, arrangements for replacing workers leaving the farm due to age are absent, there is no professional training program, employment contracts are not written, there are no payrolls, no work permits for all employees, and no measures have been taken to motivate the workforce (e.g., incentive systems and praise) / protection against unfair dismissal / adequate income protection in case of accidents, illness, or maternity, etc., and child labor is present.

Working Hours

The sustainability objective here is that everyone working on the farm has sufficient free time to recover physically and mentally, so they can remain healthy and productive in the long term. Daily, weekly, and annual working hours, and annual leave were recorded and assessed according to regional standards. 100 points are awarded for 5 days a week, 40 hours a week, 6 weeks of paid annual leave, and paid overtime. These values are regionally adjustable. The indicator scored 60 points, indicating a good and acceptable level given the production conditions, and that the work is not inherently arduous, with the understanding that family labor is not directly paid.

Safety at Work

The sustainability objective we aim to measure through this indicator is: "Appropriate measures are taken to ensure that work-related accidents and illnesses on the farm are minimized. Children are not harmed by any work they perform on the farm." An assessment was conducted on the frequency of work-related accidents and illnesses on the farm, the measures taken to prevent them, and whether there is a risk of illegal child labor. The indicator in the study sample scored 40 points, indicating low performance, meaning a lack of safety at work due to child and female labor without safety measures, leading to work-related accidents or illnesses. Additionally, direct handling of some highly toxic pesticides occurs.

Wage and Income Level

The sustainability objective aims for individuals working on the farm to earn an hourly wage that allows them to live comfortably above the poverty line when working normal hours. The indicator scored only 27 points. This means that workers earn wages that place them below the poverty line, as workers need to earn at least 34 points to live at the poverty line. 100 points are awarded if the hourly wage is twice the poverty line wage for an average family. For self-employed workers (unpaid family labor working on the farm), the same calculation was based on the figure derived by dividing private consumption plus all non-cash benefits enjoyed by the family by the total number of working hours of all self-employed workers. Relevant threshold values (poverty line, 100-point factor, family size, normal working hours) can be regionally adjusted. Additional points are awarded or deducted (+/- 50) based on the farm's financial results.

Economic Viability

A farm is, first and foremost, a business venture that seeks to achieve economic objectives while considering relevant environmental and social constraints. The goal is to ensure the project's profitability in the short and long term, and to maintain or even improve productivity, ensuring its stable and self-directed growth, thereby securing the farmer's family livelihood and the income of its workers. This criterion addresses the following aspects of the farm's economic sustainability: liquidity and stability, profitability, indebtedness, and livelihood security.

Liquidity

The sustainability objective here is: "The farm's liquid assets are sufficient to meet its financial obligations at all times." An assessment was conducted on the ratio of cash reserves (liquid assets plus available credit lines) to average weekly expenditure (annual expenses divided by 52 weeks), i.e., the number of weeks the farm can sustain itself from its cash reserves. The farm's reserves are considered sufficient if, at any point in its production cycles, it can pay wages and salaries, accounts payable to suppliers, loan installments, and interest payments from its own reserves. 100 points are awarded if it can cover 40 weeks from cash reserves. However, for the sample, the indicator scored only 6 points, meaning the sample can cover only 2.4 weeks. This is attributed to

weak performance and low liquid assets, and sometimes farmers are forced to purchase inputs on credit, incurring higher costs.

Profitability

The sustainability objective is that the farm achieves financial profit in both the short and long term. In other words, its profits enable it to meet its financial obligations, invest, and achieve a return equivalent to the capital invested in the project. The operating cash flow to sales ratio was assessed. The return on equity, i.e., the ratio of profits (cash flow minus depreciation) to invested capital, was also assessed. The judgment was based on the following rule: if the cash flow to sales ratio is 20%, 100 points are awarded; if it is 10%, 67 points are awarded. As for the return on equity, if its ratio is 5%, 100 points are awarded / 0% = 0 points. For the sample, the cash flow ratio was 20%, and thus the indicator scored 100 points, meaning the sample generates profits and has the ability to meet its financial obligations. This is consistent with what was stated in the first section of this chapter.

Stability

The sustainability objective we can ascertain through this indicator is that the farm enjoys financial stability, meaning its ability to regularly achieve financial break-even over several years with a normal level of family consumption, and that the future of farm production is secure in the long term. It scores 100 points if the farm's infrastructure is in good condition, the farm has many customers in all its main activity areas, its primary source of income represents less than 20% of total business revenue (no risk), access to all land is guaranteed in the long term, and it has a high equity ratio. The sample scored 67 points on this indicator, meaning the sample has diverse expertise, maintains modern infrastructure, and thus does not rely entirely on market price trends or individual customers. Access to land ensures planning capability and long-term production continuity, while a high capital ratio allows farmers to make their own decisions on how the business develops.

Indebtedness

The sustainability objective we aim to understand through this indicator is that the farm's level of indebtedness is not problematic and is proportionate to its financial resources. There is room to incur more debt when needed, for example, to overcome a period of funding shortfall. The financing ratio was calculated as a ratio between net debt and operating cash flow. This allows calculating the number of years required to fully repay the farm's debts using its current cash flows. The judgment was based on the following rule:

- Debt-to-Equity Ratio: 100 points if the farm would need 5 years to repay its debts using its operating cash flows / 0 points for 20 years.
- Debt Service Coverage Ratio: 100 points for a debt service coverage ratio of 0% / 67 points for 50% / 0 points if 100% of cash flow is used for debt service.

The sample scored 98% on this indicator, meaning it needs 5 years to cover its debts using its operating cash flows. In reality, debt was not a significant figure, and it was zero in some categories of the sample, which is consistent with what was stated in the RC indicator in the first section of this chapter.

Livelihood Security

The sustainability objective we aim to understand through this indicator is that the farm's income is sufficient to secure the economic livelihood of the family (unpaid family members). An assessment was conducted on the ratio of private expenditure to the adjusted minimum subsistence level. The minimum subsistence level is adjusted proportionally to the size of the farmer's family, and any in-kind payments received by the farm are deducted. The private expenditure of unpaid family members (farmer's family) should clearly exceed the minimum subsistence level. The indicator was judged based on the following rule:

Between 34 and 66 points maximum are awarded for household expenditure ranging between 100% and 200% of the poverty line (yellow, critical). If the household income is twice or up to three times the poverty line, the farm is awarded between 67 and 100 points maximum (green, sustainable). The sample achieved a low livelihood

security level, less than critical, as it scored only 18 points, indicating that the farm's income is insufficient and does not secure a decent economic life.

Farm Management

It may be entirely worthwhile to manage a farm using traditional methods, even in the long term. However, changes will be necessary if poorly designed management coincides with clear unresolved challenges. In this case, it is essential to adjust the farm's strategy by implementing:

- Measures that integrate sustainability into management systems, operations, and culture.
- Sustainable farm management.
- Achievement of goals and strategies that align with stakeholders' personal values and consider the natural, human, animal, environmental, financial, and societal constraints.
- Access to necessary knowledge for informed decision-making.
- Regular assessment of internal and external risks so that proactive measures can be taken and resources used productively, safely, and profitably.
- Promotion of sustainable relationships, ensuring that interactions with people and stakeholders inside and outside the farm are characterized by respect and fairness.

Business Goals, Strategy, Implementation

The sustainability objective we aim to measure through this indicator is whether those responsible for farm management consciously set goals, develop strategies to achieve them, and implement the necessary actions. In this context, "conscious" means alignment with individuals' personal values and the farm's surrounding conditions. The chosen strategy should have a positive impact on economic, social, and environmental sustainability. The sample scored 63 points for this indicator, which indicates a critical situation. This relatively means that the farmer does not have well-considered goals and

an appropriate strategy for the farm, and has not implemented them regularly. Furthermore, social and environmental aspects were not considered, and their work goals were not consistent with sustainability goals.

Availability of Information

Here, we aim to achieve the following sustainability objective: When necessary, those responsible for farm management have access to sufficient information and reliable planning tools so they can manage the farm systematically and professionally. An assessment was conducted to determine whether the farm has access to sufficient information and reliable planning tools necessary for systematic farm management, and whether these tools are actually used if necessary. The indicator scored 33 points, indicating unsustainable and low performance. This means that the farmer does not have access to all necessary information and reliable planning tools, or does not use them as needed to facilitate sustainable farm management.

Risk Management

Through this indicator, we try to achieve the sustainability objective that states: Those responsible for farm management are aware of the risks and impacts that may threaten the farm's livelihood and do their utmost to mitigate them. This indicator assesses how those responsible for farm management deal with risks that threaten their livelihoods. An assessment was conducted on the freedom of action available to farm management internally, especially regarding risk prevention, as well as minimizing the negative impacts of any adverse events. The application of quality assurance measures is essential to ensure healthy and marketable production. The sample's performance was unsatisfactory, unsustainable, and low, as it scored only 13 points, indicating the farm's inability to confront and manage risks. This is especially relevant given the high and inherent risk and uncertainty in agricultural production.

Resilient Relationships

Sustainability objective: The farm's internal and external relationships are managed in a way that provides a solid foundation for its long-term success. The farm cooperates with colleagues and neighbors whenever appropriate. Disputes are resolved

by consensus, not by coercion. The indicator scored 83 points, indicating sustainable and acceptable performance. This confirms the existence of stable relationships successfully built within and outside the farm, forming a solid foundation for its success. The farm engages in wise and productive cooperation with other farms and individuals. Disputes within or related to the farm are resolved by consensus rather than coercion. This aligns with the social environment of rural areas and their adherence to social values and principles within an ethical framework.

Table 2: Indicators, Standards, and Points Achieved

2	Animal husbandry	50
2.1	Herd management	50
2.2	Livestock productivity	18
2.3	Opportunity for species-appropriate behavior	65
2.4	Living conditions	55
2.5	Animal health	63

1	Soil use	54
1.1	Soil management	25
1.2	Crop productivity	75
1.3	Soil organic matter	100
1.4	Soil reaction	0
1.5	Soil erosion	75
1.6	Soil compaction	50

4	Water use	56
4.1	Water management	54
4.2	Water supply	27
4.3	Water use intensity	100
4.4	Irrigation	44

3	Materials use & environmental protection	25
3.1	Material flows	29
3.2	Fertilization	21
3.3	Plant protection	0
3.4	Air pollution	24
3.5	Soil and water pollution	56

6	Working conditions	36
6.1	Personnel management	8
6.2	Working hours	60
6.3	Safety at work	49
6.4	Wage and income level	27

5	Biodiversity	56
5.1	Biodiversity management	2
5.2	Ecological infrastructures	100
5.3	Distribution of ecological infrastructures	88
5.4	Intensity of agricultural production	50
5.5	Diversity of agricultural production	39

8	Farm management	48
8.1	Business goals, strategy, implementation	63
8.2	Availability of information	33
8.3	Risk management	12
8.4	Resilient relationships	83

7	Economic viability	57
7.1	Liquidity	6
7.2	Profitability	100
7.3	Stability	63
7.4	Indebtedness	98
7.5	Livelihood security	18

Source: The researchers' work, based on RISE3.

Conclusion

Sustainability at the farm level is crucial; it's the bedrock for achieving sustainability across the entire agricultural sector. Balancing economic, social, and environmental goals is paramount for farmers to ensure their practices and decisions are sustainable. It's important for sustainability indicators to be more than just target numbers. They should be adaptable over time and across different scales to reflect changing conditions. Ultimately, ensuring the sustainability of the agricultural community depends on effectively measuring and adapting to change as needed.

It's essential to determine whether sustainability commitments, from farm to national levels, translate into tangible results. Local communities act as the link between these levels. Without robust and accessible evaluation mechanisms, accountability might be lost, or tracking efforts could become impossible. A lack of accountability doesn't necessarily imply ill intent; it might simply stem from a shortage of the necessary tools for verification.

RISE can be a valuable tool for assessing farm sustainability. It provides a solid foundation for further verifying farm-level sustainability by calculating economic, social, environmental, and energy indicators. These include metrics for water, soil, biodiversity, emission potential, plant protection, waste and residues, cash flow, farm income, investments, local economy, and the social status of each farm.

The sustainability standing of the study sample was critical in terms of the seven polygon indicators and low in terms of sustainability degree. This was influenced by farm management points, which shifted the situation from critical to low. The farmers were not sustainable in their practices and did not balance economic, social, and environmental goals.

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تقييم الاستدامة على مستوى المزرعة باستخدام منهجية RISE: دراسة حالة محافظة بغداد

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الخلاصة:

هدف البحث إلى تقييم الاستدامة على مستوى المزرعة؛ لأن القرارات المتخذة على مستوى المزرعة، مثل التخصص وتخصيص الموارد وإدارة عمليات الإنتاج، تُعدّ حاسمة وأمرًا ضروريًا لتحقيق الاستدامة. يتطلب تعزيز مجتمعات قوية توازنًا بين الاقتصاد والبيئة والاجتماع. تم استبيان 72 مزرعة في محافظة بغداد للعام 2023 فضلًا عن بيانات أخرى تم الحصول عليها من الجهات المختصة. استُخدم تحليل RISE وهي أداة تُستخدم للتقييم الشامل لاستدامة الإنتاج الزراعي على مستوى المزرعة. تم حساب ثمانية مؤشرات، في كل مؤشر أكثر من أربعة معايير للوضع الاقتصادي والبيئي والاجتماعي: استهلاك الطاقة، واستهلاك المياه، ورعاية التربة، والتنوع البيولوجي، وإمكانية الانبعاث، وحماية النبات، وإنتاج النفايات والمخلفات، والتدفق النقدي، ودخل المزرعة، والاستثمارات، والمساهمة في الاقتصاد المحلي، والوضع الاجتماعي لأسر المزارع وموظفي المزرعة، وإدارة المزارع، مؤشر استخدام المياه حقق 56 نقطة وهو مؤشر حرج للاستدامة متأثرًا بإمدادات المياه التي حصلت على 27 نقطة، وهي تشير إلى وضع صعب. أما استخدام الهواء وحماية البيئة، فكان الأداء ضعيفًا إذ حقق 25 نقطة بسبب ضعف إمدادات المواد والتسميد، بينما مؤشرات ظروف العمل كانت غير مستدامة من خلال إدارة العمال ومستوى الأجر والدخل الذي حقق 27 نقطة، وكان حرجًا بمؤشرات ساعات العمل وسلامة العمل، أما مؤشر الجدوى الاقتصادية، فحقق 57 نقطة وهو حرج من حيث الاستدامة، وكان ضعيفًا من حيث السيولة (6 نقاط فقط) وأمن سبل العيش (18 نقطة)، بينما كان مستدامًا من خلال مؤشر الربحية، معيار إدارة المزارع كان حرجًا بـ48 درجة متأثرًا بإدارة المخاطر التي كانت غير مستدامة، المؤشرات الأخرى ضمن مضلع الاستدامة كانت حرجة أيضًا إذ تربية الحيوان حققت فقط 50 نقطة واستخدام التربة 54 نقطة، بشكل عام يمكن القول إن الاستدامة على مستوى مزارع محافظة بغداد كانت غير مستدامة، ولم تستطع الموازنة بين المؤشرات الاقتصادية والبيئية والاجتماعية. وإن الزراعة المستدامة مهمة شاقة ومعقدة للغاية، وتتطلب حلولًا فردية خاصة بالمزرعة. لذلك ينبغي أن يساهم تحليل استدامة المزرعة في تنمية القدرات.

الكلمات المفتاحية: مضلع الاستدامة، إمدادات المياه، حماية البيئة، RISE، إدارة المزارع.

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Assessment of the Gulf Cooperation Council (GCC) Countries' Direct Agricultural Investment in North and East Africa

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Abstract:

This scoping review examines the agricultural investment strategies of Gulf Cooperation Council (GCC) countries in North and East Africa, focusing on their implications for food security and economic development. The review is guided by four research questions that address the motivations, outcomes, challenges, and gaps in the literature associated with these investments. Following PRISMA-ScR guidelines, a systematic search of Scopus, Web of Science, and JSTOR, supplemented by grey literature, identified 34 sources for full review. The GCC's pursuit of agricultural investments is primarily driven by the need to secure stable food supplies and diversify the economies of countries heavily reliant on oil revenues. Three dominant investment models are identified: government-to-government agreements, long-term land leases, and state-backed financing through sovereign wealth funds. The review finds that while these investments have contributed positively to agricultural exports and food supply diversification, they also pose significant risks, including land displacement, infrastructure inequities, and geopolitical vulnerabilities. Five key gaps in the literature are identified: comprehensive risk analysis, innovative financing mechanisms, the role of technology in sustainable agriculture, market forecasting, and policy analysis. The

review concludes with evidence-based recommendations for investors and policymakers to conduct risk assessments, explore blended finance models, and leverage technology for sustainable outcomes.

Keywords: GCC Investments, African Agriculture, Food Security, Economic Growth, Sustainability

Introduction:

The nations that comprise the Gulf Cooperation Council (GCC), Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates (UAE), are characterized by their desert climates, limited water resources, and restricted arable land (FAO, 2017b; GCC Stat, 2020; Woertz, 2015). The countries in this region are further characterized by their wealth, primarily derived from fossil fuels and natural gas, which fosters rapid economic growth (Zaidan et al., 2019). However, these countries faced a significant challenge in ensuring food security as defined by the World Food Summit in 1996 indicating that "food security, at the individual, household, national, regional and global levels is achieved when all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life" mainly due to arid climates and scarce water resources (Ben Hassen & El Bilali, 2019; Saif et al., 2014). The GCC's food industry is highly reliant on imports, making it vulnerable to disruptions in those imports (Devesh et al., 2023). That can secure long-term food supplies and reduce dependency on volatile global markets. As a result, these nations have increasingly turned their attention towards agricultural investments in more fertile regions, particularly in North and East Africa. Countries like Sudan and Ethiopia were early targets due to large tracts of fertile land and lower costs (Woertz, 2020). This strategic move aims to secure a stable food supply while also contributing to economic development in the host countries (Woertz et al., 2008).

In general, the GCC countries are among the wealthiest nations due to their abundant oil resources. However, they have been unable to invest sufficiently in domestic agriculture to achieve food security, primarily due to their harsh climate. So far, four main models have been pursued by the Arab world in general, and by the GCC countries in particular, to ensure food security in the region. The first model involved investing in agriculture in Europe and the United States, primarily due to the political stability of those regions. The second approach focused on investing in domestic agriculture, as seen in countries such as the United Arab Emirates and Saudi Arabia, which have allocated substantial capital and deployed advanced technologies. The third model centers on the Arab Authority for Agricultural Investment and Development

(AAAID), which aims to establish a common fund to finance agricultural investment and development across the Arab world. The fourth strategy involves country-led initiatives to invest in geographically accessible African nations, such as Sudan, Ethiopia, and Kenya.

Diverse social, economic, and environmental effects might result from foreign agricultural investments. When properly managed, these investments can serve as a tool for development, creating job opportunities, enhancing rural infrastructure,

connecting smallholder farmers to international markets, introducing productivity-boosting technologies, and facilitating access to financing for farmers (Grote, 2018). The rationale behind the GCC's agricultural investments in Africa was multifaceted. Agricultural investment in Africa and other regions, initiated by GCC countries, was planned in response to the "food self-sufficiency" initiative, which relied on unsustainable groundwater use. These resources proved unsustainable during the 1975-1976 world food crisis (Woertz, 2020). Primarily, it serves as a hedge against food supply risks and global market price volatility. Additionally, it offers GCC countries an opportunity to diversify their economies, which are heavily reliant on oil revenues. The investments also align with the broader goals of enhancing bilateral relations and fostering economic cooperation with African nations (Alnafissa et al., 2022).

However, these investments are not without their complexities. They raise questions about the sustainability of such practices, the impact on local communities, and the geopolitical implications. Moreover, the investments must navigate the intricate landscape of African agricultural policies, market dynamics, and infrastructure challenges (Africa Development Bank, 2021). Studies affirmed that displacement of local communities and accusations of "land grabbing" led to reputational risks for GCC investment in African countries (Kohnert, 2023).

Despite the growing scale of GCC agricultural investments in Africa, the literature remains fragmented. Studies tend to focus on individual countries (particularly Sudan and Ethiopia), specific investment models, or narrow dimensions such as food security or land tenure, with few attempts to synthesize the full landscape of motivations, outcomes, and challenges across North and East Africa as a whole. This gap in consolidated, regionally comprehensive analysis constitutes the core problem this review addresses. The following objectives guide the study: (1) to document the historical evolution and current state of GCC agricultural investments in North and East Africa; (2) to analyze the motivations, investment models, and strategies employed by GCC countries; (3) to evaluate the documented economic, social, and environmental outcomes of these investments; (4) to identify critical gaps in the existing literature; and

(5) to provide evidence-based recommendations for investors and policymakers to enhance the sustainability and equity of these investments.

The review is structured to provide a systematic analysis of the literature, beginning with an overview of the current state of GCC agricultural investments and then discussing the methodologies employed in the studies. It then presents the key findings, outlines the gaps in the literature, and concludes with recommendations for investors and policymakers. The study's contributions and significance are highlighted, along with potential avenues for further research to enhance the body of knowledge on this subject.

Methodology:

This study employs a scoping review methodology, following the PRISMA-ScR (Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews) guidelines (Tricco et al., 2018). A scoping review is appropriate here because the primary aim is to map the existing literature, identify key concepts and research gaps, and synthesize evidence across a broad and heterogeneous body of work on GCC agricultural investments in Africa, rather than to answer a single narrow clinical or empirical question. This approach ensures transparency, replicability, and scholarly rigor.

The following research questions guide this review: (1) What are the primary motivations driving GCC countries to invest in agricultural land and production in North and East Africa? (2) What economic, social, and environmental outcomes have been documented in the literature? (3) What challenges and risks are associated with these investments? (4) What gaps remain in the existing literature that warrant further investigation? These questions frame the scope of the review and anchor the subsequent synthesis, gap analysis, and recommendations.

Literature Search and Selection:

A systematic search was conducted across three major academic databases, Scopus, Web of Science, and JSTOR, supplemented by grey literature sources including FAO reports, World Bank publications, IFPRI policy briefs, and reports from regional investment authorities. The search was conducted between January and July 2024, covering publications from 2000 to 2024, with seminal works from the 1990s included where directly relevant to the historical context. The following keyword combinations were used: (“GCC” OR “Gulf Cooperation Council”) AND (“agricultural investment” OR

"agri-investment" OR "farmland acquisition" OR "land grab") AND ("Africa" OR "East Africa" OR "North Africa" OR "Sudan" OR "Ethiopia" OR "Morocco" OR "Egypt"). Additional terms included "food security," "foreign direct investment," "sovereign wealth fund," and "land lease." Sources were included if they: (a) directly addressed GCC or Arab Gulf state agricultural investment in Africa, (b) examined food security policies of GCC countries with an external investment dimension, or (c) analyzed socioeconomic or environmental impacts of large-scale land acquisitions in the study region. Sources were excluded if they focused solely on domestic Gulf agriculture without an external investment dimension, or addressed African agriculture without reference to Gulf or Arab investment. The initial search returned over 200 records; after screening titles and abstracts for relevance and removing duplicates, 34 sources were retained for full-text review and synthesis.

Data Extraction and Synthesis:

For each included source, the following data were extracted and recorded in a standardized form: author(s), year of publication, country/region of focus, methodology employed, key findings, and relevance to the four guiding research questions. Sources were then grouped thematically into five categories: (1) motivations and drivers of GCC agricultural investment, (2) historical evolution and investment models, (3) economic and food security outcomes, (4) social and environmental impacts and risks, and (5) policy frameworks and future trajectories. This thematic synthesis enabled cross-source comparison and the identification of converging and diverging perspectives in the literature.

Critical Appraisal

Each included source was critically appraised for methodological quality, reliability, and relevance. Peer-reviewed articles and book chapters were assessed using standard academic quality indicators (clarity of methodology, validity of conclusions, and rigor of evidence). Grey literature sources, including industry reports from Fitch Solutions, Alpen Capital, and the African Development Bank, were assessed for institutional credibility, data transparency, and currency. Sources that relied heavily on anecdotal evidence without verifiable data were noted as lower-confidence inputs and treated as contextual rather than evidentiary. This tiered appraisal approach ensures that the review's conclusions are grounded in the strongest available evidence.

Analysis and Interpretation

The synthesized data were analyzed to identify recurring patterns, areas of agreement and disagreement, and understudied dimensions. The analysis proceeds deductively from the four research questions and inductively from themes that emerged from the literature. Where quantitative data on investment volumes, land areas, and trade flows were reported in multiple sources, these were cross-referenced to assess consistency. Discrepancies between sources are noted and discussed. The analysis culminates in a structured identification of five key gaps in the literature (presented in Table 2), each linked to a specific research question and a proposed future research direction.

Literature Review:

The following literature review table (Table 1) encompasses a diverse range of scholarly works that explore the multifaceted aspects of agriculture in the Gulf Cooperation Council (GCC) region and its broader interactions with the African continent. The table presents a synthesis of key findings from various authors who have explored topics ranging from the impact of foreign direct investment on agricultural exports to strategic measures for enhancing food security and agricultural productivity. The methodologies employed in these studies vary, encompassing empirical analyses, industry reports, policy reviews, and market forecasts, reflecting the comprehensive nature of research in this domain. The publications' time frame spans from 2008 to the projected data of 2024, offering both historical insights and a future outlook. This curated collection of literature serves as a critical resource for understanding the dynamic interplay among economic policies, technological advancements, and agricultural practices in shaping the GCC's agricultural landscape and its global linkages.

Table 1. Agricultural Dynamics in the GCC and Africa: An Empirical and Policy-Oriented Review

Author(s)	Title	Key Findings	Methodology	Year
Marzocchi & Arribas Cámara (2025)	Land Grabbing and Development: The Case of Ethiopia	This study assesses the impact of land grabbing on Ethiopia's development targeting the economic, environmental, and quality-of-life dimensions. The negative impacts of Saudi Star Agriculture Development PLC's development, including forced relocations of rural populations, land loss, and water shortages, have been reported. Additionally, environmental problems such as deforestation, severe flooding, decreased soil quality, and soil compaction were severe. However, land grabbing demonstrated positive aspects regarding employment and technology transfer.	The authors utilized data and narratives from published articles and unpublished reports of governmental and nongovernmental organizations, as well as personal observations.	2025
Hallam (2011)	International investment in developing country agriculture—issues and challenges	High local farmer displacement; limited spillover effects in technology transfer and local food security; adverse environmental impacts such as chemical contamination, land degradation, and depletion	It summarizes the existing known facts from different sources (literature, investors, and other stakeholders).	2011

Author(s)	Title	Key Findings	Methodology	Year
		of water resources; and limited labor rights and poor working conditions.		
CIRS (2014)	GCC States' Land Investments Abroad: The Case of Ethiopia. CIRS Summary Report.	The findings concluded that acquiring agricultural land in Ethiopia and Cambodia is a poor and risky strategy for securing food supplies for the GCC states.	The research was done by using data from fieldwork in Ethiopia.	2014
Alnafissa et al. (2022)	Impact of Gulf Cooperation Countries' Foreign Direct Investment on Sudan's Agricultural Exports	Analyzed the positive impact of the GCC's FDI on Sudan's agricultural exports, highlighting the role of exchange rates.	Empirical analysis using Sustainability metrics	2022
Africa Development Bank (2021)	Raising Africa's agricultural productivity	Discussed strategies for increasing agricultural productivity in Africa to ensure food security.	Policy review	2021
BMI- Fitch Solutions company (2023)	GCC Food Security: The UAE Seeks to Mitigate Food Supply Risks through Land Acquisitions, Trade Deals, and Domestic Agtech.	Explored the UAE's approach to enhancing food security through international land acquisitions and technology.	Market analysis	2023
Mapanje et al. (2023)	Financing Sustainable Agriculture in Sub-Saharan Africa: A Review of Policies	Reviewed policies for financing sustainable agriculture, with a focus on sub-Saharan Africa.	Policy analysis	2023
Oyelami et al. (2022)	ICT and agricultural sector performance: empirical evidence from sub-Saharan Africa	Examined the impact of ICT on agricultural performance in sub-Saharan Africa.	Empirical evidence review	2022
Odusola (2021)	Policies and Programmes for an	Investigated policies and programs aimed at	Policy analysis	2021

Author(s)	Title	Key Findings	Methodology	Year
	Agricultural Powerhouse in Africa	transforming Africa into an agricultural powerhouse.		
Statista (2024)	Agriculture Market Forecast in the GCC	Provided forecasts for the agriculture market in the GCC region.	Market forecast	2024
Woertz et al. (2008)	Potential for GCC Agro investments in Africa and Central Asia	Assessed the potential for GCC agricultural investments in Africa and Central Asia.	Descriptive analysis	2008
Lindsay (2012)	Compulsory Acquisition of Land and Compensation in Infrastructure Projects	Analyzed the implications of land acquisition for infrastructure projects on agriculture.	Policy analysis	2012

History of GCC Countries' Agricultural Investments:

The Gulf Cooperation Council (GCC) countries have long recognized the strategic importance of securing food supplies, given inherent constraints such as limited arable land and water scarcity (Woertz et al., 2008). This has led to a concerted effort to invest in agricultural sectors abroad, particularly in regions with which they share historical and sociopolitical ties. Countries such as Sudan, Ethiopia, Kenya, Uganda, and Tanzania were early targets due to their large tracts of fertile land and lower costs (Alnafissa et al., 2022; CIRS, 2014; Tanyeri-Abur & Hag Elamin, 2011).

Following the 1972-1975 world food crisis, some GCC countries, including Saudi Arabia and the United Arab Emirates, began investing heavily in domestic agricultural production to ensure food self-sufficiency, often utilizing unsustainable aquifers. However, this proved impossible during the 2007/2008 food crisis, when the aquifers were almost running out (Woertz, 2020). Post the 2008 global food crisis, there was a marked strategic shift in the investment approach of GCC countries. The crisis highlighted the vulnerabilities inherent in food supply chains and the risks associated with excessive reliance on global markets for essential food commodities. In response, GCC countries intensified their efforts to secure food by making direct investments and

acquiring agricultural land, primarily in North and East African nations (Aldhaheri, 2023; Benazza, 2024; Woertz et al., 2008).

These investments have been diverse, encompassing a range of crops and leveraging various technologies to optimize agricultural output. The primary motivation behind these investments has been to bolster food security in the GCC region, which is geographically closest. However, the investments have also been driven by economic considerations, aiming to capitalize on the agricultural potential of recipient countries while fostering closer economic ties (Alnafissa et al., 2022).

Sudan, in particular, has been a significant recipient of GCC agricultural investments. The country's agricultural sector, pivotal to its economy, has historically accounted for a substantial share of Sudan's foreign exchange earnings through the export of field crops, livestock, and forest products. Investments from GCC countries have been found to boost Sudan's agricultural exports, with the exchange rate playing a critical role in investment decisions (Alnafissa et al., 2022). Other countries, such as Ethiopia, Morocco, and Tanzania, among others, were also receiving foreign direct investment in agricultural areas from GCC countries (Benazza, 2024).

These investments have had varying impacts on regional agricultural development and food security. According to some studies, GCC investments have increased agricultural exports from countries such as Ethiopia and Sudan. However, concerns remain about the broader socioeconomic implications, particularly regarding land grabbing and community displacement (Alnafissa et al., 2022; CIRS, 2014). Furthermore, the living conditions of local inhabitants are not always improved when foreigners acquire land and agricultural resources. Local food producers, such as small-scale farmers and herders, often lose access to their land, leaving them vulnerable to hunger and food insecurity (Aab¯ & Kring, 2012). In certain countries, such as Sierra Leone and Mozambique, foreign investors have disregarded the rights of landowners and failed to fulfil their obligations to construct infrastructure for the local community (Aab¯ & Kring, 2012). Furthermore, the local communities' nomadic group is frequently disregarded. Therefore, the majority of disputes and public protests caused by foreign agricultural investments in African nations are similar to those that occurred in Sudan (McGinnis & Fredrick, 2019). Furthermore, the impact of foreign agricultural investment on natural resource depletion, such as fresh water and soil, shall not be ignored (Rakotoarisoa, 2011).

Although the GCC states rank higher in the food security index than nations known for their food production, such as Brazil and India, the relevance and sustainability of this ranking remain questionable. Hence, the food security issue remained a viable agenda item in these states. Following the COVID-19 pandemic, various states initiated diverse strategies to address the problem, utilizing both domestic and foreign investment. Saudi Arabia, Qatar, and the United Arab Emirates continued to invest in food, focusing on both domestic and international markets (Economist Impact, 2022). For instance, the UAE government launched the National Food Security Strategy in 2018, aiming to increase production of strategic food products by 100,000 tonnes by 2051. This strategy encompasses both domestic investment in vertical farming, which primarily focuses on fruit and vegetable production, and contract farming and the acquisition of arable land from East African countries such as Sudan and Ethiopia, among other countries (BMI- Fitch Solutions company, 2023; Nowacka, 2022; U.AE, 2024). Similarly, the Kingdom of Saudi Arabia is taking action by investing in domestic agriculture, particularly in dairy production and other agricultural products (El-Dukheri, 2024).

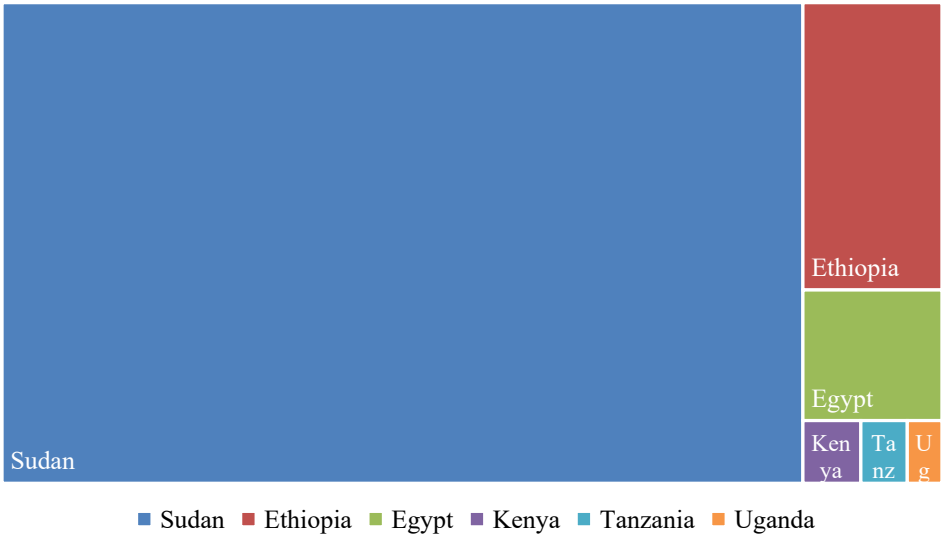


Figure 1: Estimated GCC Agricultural Investment by Host Country (Cumulative Commitments, 2000–2024)

Research Gaps in GCC-Africa Agricultural Development

Table 2 presents a critical examination of the existing gaps in the literature regarding the development of the agricultural sector within the GCC and its investment footprint in Africa. This analysis underscores the areas where further research could significantly enhance our understanding and operational strategies. The table identifies five key areas where the current body of literature falls short: comprehensive risk analysis, financing mechanisms, the role of technology, market forecasts, and policy analysis. Each gap is described, along with the potential impact of addressing it on the agricultural sector. By highlighting these areas, Table 2 serves as a roadmap for future research endeavours, aiming to fill the identified voids with robust empirical evidence and analytical rigor. Addressing these gaps holds the promise not only of advancing academic discourse but also of providing actionable insights for investors, policymakers, and practitioners seeking to foster sustainable agricultural development and food security in the GCC and Africa.

Table 2. Gap in Literature

Gap in Literature	Description	Potential Impact of Addressing the Gap
Comprehensive Risk Analysis	Limited studies provide a comprehensive risk analysis of GCC agricultural investments in Africa, including geopolitical and transport security risks1.	A thorough risk analysis could help investors and policymakers make informed decisions and mitigate potential investment risks.
Financing Mechanisms	There is a need for more research into innovative financing mechanisms, particularly given the multibillion-dollar financing gap in African agribusiness.	Understanding financing mechanisms could unlock new investment opportunities and drive sustainable agricultural growth.
Role of Technology	The impact of FinTech and other technologies on sustainable agriculture financing in sub-Saharan Africa remains poorly documented.	Insights into technology's role could lead to more efficient agricultural practices and improved food security.
Market Forecasts	Projections and forecasts for the agriculture market in the GCC are scarce, with limited data available for future planning.	Accurate market forecasts are crucial for strategic planning and ensuring food security in the GCC region.

Gap in Literature	Description	Potential Impact of Addressing the Gap
Policy Analysis	There is a lack of detailed analysis of policies and programs aimed at transforming Africa into an agricultural powerhouse.	Policy analysis could guide the development of effective strategies for agricultural investment and growth.

Types of investment models by GCC countries in Eastern African countries

There are three types of major investment models implemented by GCC countries, which are discussed as follows:

Government-to-government deals involve strategic partnerships that include long-term leases and infrastructure development. It is a strategic investment partnership in which a GCC government directly signs agreements with another sovereign government, often involving long-term land leases, joint infrastructure projects, and resource access agreements. The primary objective is to mitigate market risks and secure political backing for sensitive investments, particularly in agriculture and energy. Many GCC countries have increasingly pursued government-to-government investment models in the agriculture sector.

Sudan (Saudi Arabia–Sudan Agricultural Land Lease in 2009), the United Arab Emirates–Sudan (Al Ain Farms, 2012), and Kenya, which hosts the Qatar–Kenya Food Security Deal (2010), are the most notable East African nations that have attracted investments. Furthermore, there are government-to-government investments in Ethiopia from Saudi Arabia and the United Arab Emirates, such as those from Al Dahra Agriculture of the United Arab Emirates and Saudi Star Agricultural Development PLC of Saudi Arabia (Lavers, 2012; Marzocchi & Arribas Cámara, 2025). These models are particularly prevalent in resource management, food security, and strategic land acquisition (El-Dukheri, 2024).

Long-term leases, typically ranging from 20 to 99 years, are a common tactic employed by GCC nations to acquire land in Eastern Africa for food production to meet their domestic needs. Even though these deals are intended to benefit both parties financially, they are often contentious due to concerns about sustainability, fairness, and local impacts. Saudi Star Agricultural Development (Ethiopia), which is supported by Saudi investors and has long-term leases for rice cultivation, and Emirates Investment Group (in Sudan and Ethiopia) are two examples of such arrangements (The Oakland Institute, 2011).

Infrastructure Joint development model

This refers to the construction of roads, irrigation systems, storage facilities, and transportation networks in the host nation as part of GCC foreign agricultural investments, particularly under government-to-government (G2G) agreements. In addition to meeting the investor's needs for agricultural output, these facilities frequently support regional growth. Usually, the investor, the GCC government, or state-backed businesses share or finance the expense, occasionally in return for production rights or land leases. Saudi Star in Ethiopia, Al Dahra Agriculture of the United Arab Emirates in Egypt, and the port and agricultural agreement between Qatar and Kenya, proposed in 2010 to develop Lamu port in exchange for 40,000 hectares of farmland, but not finalized due to local opposition, are examples of such investments (Aldhaheri, 2023; Hartley, 2009).

State-backed financing model

This is a model in which GCC governments channel investments into agriculture abroad through sovereign wealth funds (SWFs), government-controlled investment agencies, or state-owned enterprises, to achieve strategic objectives such as food security, geopolitical influence, and economic diversification. Across the documented cases, government-to-government agreements and long-term land leases together account for the majority of investment activity, with SWF-backed equity, off-take/contract farming, and PPP/joint-venture arrangements making up the remainder (Figure 2). Table 3 summarizes investors from GCC countries, hosting countries, major focus crop types, and the types of models followed.

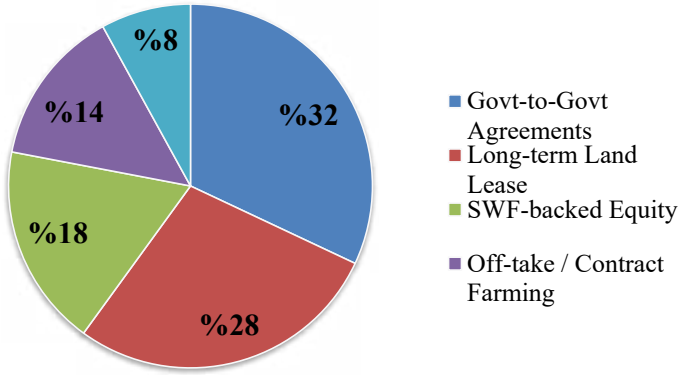


Figure 2. Distribution of GCC Agricultural Investment Models in North and East Africa (% of documented investments). Source: Authors' synthesis based on reviewed sources.

Table 3. GCC countries' investment model with their host countries in East Africa

GCC Country	Investor	Host Country	Product	Model	Reference
Saudi Arabia	SALIC	Sudan, Ethiopia	Rice, Wheat	SWF-backed investments	(The Oakland Institute, 2011)
UAE	Al Dahra	Sudan, Egypt	Forage, Wheat	State-owned enterprise	(Aldhaheri, 2023)
Qatar	Hassad Food	Sudan	Grain, Livestock	SWF-backed projects	(Hartley, 2009)

In addition to the above-mentioned models, there are also other types of investment models followed by GCC countries in East African countries, such as the mutual strategic interests (e.g., food security for the GCC, economic development for the host country), private-sector-led investments (such as agribusiness firms and sovereign wealth funds of Qatar Investment Authority, Saudi Agricultural and Livestock Investment Company - SALIC), and public-private partnerships (PPPs), which are a blend of state support with private sector efficiency. SALIC of Saudi Arabia was established in 2011 by the government to invest in agriculture worldwide. However, its journey proved most fruitful in East African countries like Sudan and Ethiopia, where it controlled rice production, and the Kingdom has doubled its investment in Sudan. In doing so, Saudi companies developed the ability to manage the supply chain and shield the nation from exogenous shocks (El-Dukheri, 2024).

Status of GCC countries' agricultural FDI in East African countries

There is no precise and up-to-date information on the amount of agricultural FDI flowing into East African nations, despite past investments and current agreements. The UAE's ADQ portfolio companies, including Al Dahra, have documented investments across farming operations in Sudan, Ethiopia, Egypt, and Serbia, though consolidated country-specific figures for Ethiopia alone are not publicly available (Calabrese, 2024). In a similar vein, GCC nations have contributed at least $53 billion to Sudanese agriculture in the last decade. Saudi Arabia has invested $35.7 billion, primarily to support 250 agricultural projects. With additional instalments to follow, Saudi Crown Prince Mohammed Bin Salman pledged to provide $3 billion to the Sudan Investment

Fund projects (Middle East Monitor, 2023). With billions of dollars in government-sponsored investments, such as those from SALIC, Saudi Arabia has expanded its scope by purchasing or leasing large tracts of land not only in East Africa but also globally for agricultural production. Diversifying the nation's food supply is the primary goal to ensure food security. While the program's negative impact is a rise in food prices, it has been acknowledged for its good impact in increasing food security and reducing reliance on domestic production (El-Dukheri, 2024).

Status of GCC Countries' Agricultural FDI in North African Countries

North Africa represents a strategically distinct but equally important arena for GCC agricultural investment, yet it remains significantly underrepresented in the existing literature relative to its actual investment footprint. The region's proximity to the Arabian Peninsula, well-developed port infrastructure, and large expanses of irrigable land, particularly in Egypt, Morocco, and Sudan's northern Nile corridor, make it a natural complement to East African investment strategies. Unlike the more frontier-market character of Ethiopian and Kenyan investments, North African engagements tend to involve more established institutional frameworks, stronger bilateral diplomatic ties, and greater integration into GCC food supply chains.

Egypt is the most prominent North African recipient of GCC agricultural investment. Unlike in Sudan and Ethiopia, much of this investment is concentrated in two long-running desert land-reclamation schemes: Toshka, in Egypt's Western Desert, and Sharq El-Oweinat. On the Toshka scheme, the UAE's Al Dahra Agriculture holds approximately 120,000 acres, while Saudi Arabia's Al-Rajhi Investments and Kingdom Holding Company (the latter subsequently reduced) hold substantial additional acreage; on Sharq El-Oweinat, the UAE's Jenaan and Al Dahra, alongside Saudi Arabia's Jannat, hold further large tracts (Henderson, 2021). These holdings are used primarily to cultivate alfalfa and, to a lesser extent, wheat, for export back to Gulf livestock and food supply chains. More recently, Al Dahra and the Abu Dhabi Exports Office (ADEX) signed a separate $500 million, five-year wheat trade-finance agreement with the Egyptian government in 2023 to supply Egypt with imported milling wheat, a transaction distinct from the earlier land-based investments, illustrating a parallel and growing emphasis on trade finance alongside land acquisition (Suwaidi, 2024). Morocco's relationship with GCC countries in agriculture is, by contrast, documented primarily as a trade relationship rather than direct investment: Saudi Arabia, the UAE, and Qatar are established importers of Moroccan citrus, tomatoes, and olive oil, but the literature reviewed for this study did not surface confirmed instances of GCC equity investment in Moroccan

farmland or agri-processing infrastructure comparable to the Egyptian or Sudanese cases. Tunisia presents a smaller-scale but verifiable example of GCC private equity entering North African agriculture: Gulf Capital, an Abu Dhabi-based private equity firm, invested in CHO Group, Tunisia's largest olive oil exporter, to support the expansion of its olive groves and the integration of exports. Libya, despite holding substantial groundwater reserves and underutilised arable land, has attracted little documented GCC agricultural investment; the literature attributes this primarily to the prolonged political instability following 2011, which has deterred the kind of large-scale, long-horizon capital commitments seen in Egypt and Sudan.

A key distinguishing feature of North African investments compared to their East African counterparts is the longer time horizon of the land-based holdings, several of which date to the early 2000s and predate the wave of Sudanese and Ethiopian deals documented in this review. Egypt's case in particular shows GCC investors operating on two parallel tracks: direct land ownership for export-oriented fodder and grain production, and separate government-to-government trade finance agreements for wheat imports, a combination not clearly documented elsewhere in the region. Table 4 below summarizes the documented GCC agricultural investments in North Africa by country, investor, product focus, and investment model; entries are limited to cases for which a specific, attributable source could be identified during the review.

Table 4. GCC Agricultural Investment in North Africa: Selected Examples

Host Country	GCC Country	Investor / Entity	Product / Focus	Investment Model	Reference
Egypt (Toshka)	UAE / Saudi Arabia	Al Dahra; Al-Rajhi; Kingdom Holding	Alfalfa, Wheat	Direct land ownership (≈120,000+ acres)	(Henderson, 2021)
Egypt (national)	UAE	Al Dahra / ADEX	Wheat (imported milling wheat)	Govt-backed trade finance ($500M, 5-yr)	(Suwaidi, 2024)
Egypt (Sharq El-Oweinat)	UAE / Saudi Arabia	Jenaan; Al Dahra; Jannat	Fodder, Wheat	Direct land ownership (groundwater-irrigated)	(Henderson, 2021)
Tunisia	UAE	Gulf Capital (private equity)	Olive oil (CHO Group)	Private equity stake (~$22M)	(Mubasher Info, 2023)

Host Country	GCC Country	Investor / Entity	Product / Focus	Investment Model	Reference
Morocco	Saudi Arabia / UAE / Qatar	N/A—importers, not investors	Citrus, Tomatoes, Olive oil	Trade relationship only; no confirmed GCC equity investment identified	(HAC Team, 2026)
Libya	—	No confirmed investor identified	N/A (potential cereals, per general literature)	No documented GCC deals; political instability cited as barrier	Authors' synthesis

Future Trends of Investments:

The trajectory of agricultural investments by the Gulf Cooperation Council (GCC) countries is poised to undergo significant evolution in the coming years. The overarching goal remains the same: securing food supplies for the GCC countries. However, the strategies to achieve this objective are becoming increasingly diverse. There is a discernible shift towards investments that go beyond primary agriculture to encompass trading houses and logistical infrastructure (BMI- Fitch Solutions company, 2023). In general, GCC agricultural investment abroad is diversifying, becoming more strategic, sustainable, and tech driven. Moreover, future focus is likely to be on climate-resilient agriculture, digital platforms, and biosecurity, ensuring both food security and return on investment.

Internal demographic and economic factors are also shaping the GCC's investment landscape. The region's population continues to grow, and with it, the demand for food. Concurrently, domestic agricultural productivity is facing challenges due to natural constraints, such as water scarcity and limited arable land (Alpen Capital, 2023). These factors are expected to contribute to an increase in agricultural investments abroad as GCC countries seek to ensure their food security (Statista, 2024).

Moreover, recent shocks to global agricultural trade flows, such as the COVID-19 pandemic, the Russia-Ukraine war, and India's rice export restrictions, have highlighted the GCC's external vulnerabilities and reinforced the importance of food security on the policy agenda (BMI- Fitch Solutions company, 2023). In response, the GCC countries are

exploring ways to mitigate these risks through land acquisitions, trade deals, and the adoption of domestic agricultural technologies (BMI- Fitch Solutions company, 2023).

The future of GCC agricultural investments is also likely to be influenced by advancements in food security. Leveraging technology for precision agriculture and optimizing supply chains will play a pivotal role in shaping the industry's future (Alpen Capital, 2023). There is growing interest in plant-based and alternative protein products that cater to health-conscious consumers, reflecting a broader trend towards sustainability and health (Alpen Capital, 2023). In a lump-sum approach, GCC countries are adopting a forward-looking approach to agricultural investment and food security, with an emphasis on advanced value-chain management. This approach focuses on strengthening control over the entire agri-food supply chain, from production to distribution, to enhance efficiency, reduce risks, and secure a consistent supply. Second, food diplomacy and multilateral cooperation emphasize active engagement and the fostering of multilateral partnerships to safeguard global trade frameworks and ensure uninterrupted food flows amid geopolitical uncertainties. Thirdly, addressing malnutrition and food-related health issues involves tackling both undernutrition and overnutrition (such as obesity) through comprehensive food policies, public health initiatives, and responsible food production strategies. Lastly, ensuring food accessibility for vulnerable populations: implementing inclusive policies and investment strategies to guarantee affordable, nutritious food access for vulnerable and low-income groups within and outside the GCC.

Guidelines for Positive Contributions

Agricultural investments, particularly in the context of the Gulf Cooperation Council (GCC) countries' direct investment in North and East Africa, must be designed to ensure positive contributions to food security and agricultural development. The focus on smallholder agriculture is pivotal, as it plays a central role in food security and nutrition. Smallholder farmers, who often form the backbone of rural economies, require support through enabling policies, effective governance structures, and access to markets, as well as training, research, technology, and farm support services to thrive (Osabuohien, 2020).

Enabling Policies and Governance: Creating an enabling environment for agricultural investments involves formulating policies that support sustainable farming practices, climate-smart agriculture, and equitable market access. These policies

should aim to mitigate market risks and address market power imbalances, thereby fostering a more inclusive agricultural sector (Lindsay, 2012).

Access to Markets and Training: Access to markets is crucial for smallholder farmers to sell their produce at fair prices. Investments should facilitate this access by improving infrastructure, reducing transaction costs, and providing farmers with the necessary business skills. Training programs are essential for enhancing farmers' ability to meet market standards and adopt new technologies (Africa Development Bank, 2021).

Research and Technology: Investments in research and technology can help address challenges related to land management, climate change, resource depletion, and biodiversity. The introduction of drones, satellite photography, IoT-based sensors, biotechnology, artificial intelligence, big data, and blockchain can revolutionize the agricultural landscape, making it more resilient and productive (Oyelami et al., 2022).

Farm Support Services: Farm support services, including advisory services, capacity building for adaptation, and regional food market integration, play a crucial role in enhancing food security. These services should be tailored to the needs of smallholder farmers, ensuring that they contribute to both food security and ecosystem services (Wiggins & Keats, 2014).

Designing Investments for Maximum Benefits: Investments should be carefully designed to maximise benefits for food security and nutrition while minimising associated risks. This involves planning, monitoring, and evaluating investment incentives for responsible investment in agriculture and food systems. The design process should consider the trade-offs and synergies between ecosystem services and agricultural productivity (FAO, 2014, 2017a).

Conclusion and Recommendations:

The literature review indicates that GCC countries' direct agricultural investments in North and East Africa have the potential to contribute to food security and economic growth significantly. However, challenges such as geopolitical risks, financing gaps, and the need for sustainable practices must be addressed. In addition to these, there are other challenges, such as land acquisition controversies, where the displacement of local communities and accusations of "land grabbing" have led to reputational risks. Furthermore, operational difficulties that arise from poor infrastructure, political instability, and limited local expertise hinder productivity in

some target countries. Investors in the GCC must take a calculated, risk-averse, and cooperative strategy to guarantee long-term, win-win results, such as:

Conduct Comprehensive Risk Assessment: To examine the operational, financial, environmental, and sociopolitical risks associated with African agriculture, GCC investors should conduct a comprehensive risk assessment. This entails being aware of market volatility, climatic concerns, political stability, and land tenure systems. Effective risk reduction techniques will improve long-term viability and investment security.

Innovative Financing Mechanisms: GCC nations should explore cutting-edge financial options, such as impact investing, blended finance, concessional loans, and public-private partnerships, to close the funding gap in African agribusiness. These systems can attract a range of funding sources and foster sustainable agriculture.

Leveraging Technology for Sustainability and Productivity: Numerous opportunities exist to enhance sustainability and productivity through advanced agricultural technologies, including digital platforms, supply chain innovations, precision farming, and climate-smart practices. Initiatives to increase capacity and adopt technology that empowers regional farmers and agribusinesses should be given top priority by GCC investors.

Market Intelligence and Forecasting: Making well-informed investment decisions requires the development of reliable market analysis tools and precise forecasting systems. To comprehend demand patterns, price fluctuations, and regional trade dynamics, GCC investors are increasingly investing in market research, data analytics, and predictive modeling.

Advocacy and Policy Interaction: To create investment frameworks and agricultural policies that are supportive, active interaction with African officials and regional organizations is crucial. To promote a favorable business climate, GCC investors should collaborate to formulate policies, advocate for clear laws, and participate in multi-stakeholder discussions.

Contributions and Significance of the Study

This study makes several distinct contributions to the existing body of knowledge. First, it provides the first regionally comprehensive scoping review that explicitly covers

both North and East Africa together, a geographic pairing that has rarely been treated as a unified analytical unit in prior literature. Most existing studies focus on a single country (typically Sudan or Ethiopia), leaving the comparative and regional dynamics underexplored. Second, this review synthesizes three distinct types of evidence: peer-reviewed empirical studies, institutional policy reports, and investment industry analyses, offering a more complete picture than reviews that rely solely on academic literature. Third, by applying a structured five-category framework (motivations, investment models, economic outcomes, social and environmental impacts, and policy trajectories), this review provides an organizing schema that future researchers can build upon. Fourth, the identification of five specific literature gaps, comprehensive risk analysis, financing mechanisms, the role of technology, market forecasting, and policy analysis, provides a concrete roadmap for future empirical and policy-oriented research. The significance of this study lies in its capacity to serve as a reference point for investors designing entry strategies, policymakers crafting bilateral agricultural agreements, and researchers scoping new studies in this rapidly evolving field.

Avenues for Further Research

The following topics could be investigated in future studies to fill in the gaps in the literature and improve the body of knowledge for agricultural investment and policy:

Comprehensive Risk analyses:
Conduct in-depth risk analyses that account for geopolitical instability, climate variability, environmental degradation, and market volatility. These studies would provide a thorough grasp of the various risks affecting agricultural investments, particularly in regions vulnerable to natural and geopolitical changes.

Case Studies for Creative Financing Models in Action: Analyze cutting-edge, effective financing techniques used in African agriculture, including digital microlending platforms, blended finance, and impact investing. Documenting their idea, implementation, and measurable outcomes would offer concrete guidelines for replication or adjustment in similar circumstances.

The Role of Emerging Technologies: An analysis of how cutting-edge technologies can enhance the efficacy, accountability, and scalability of agricultural finance and investment. Precision agriculture technologies, artificial intelligence for predictive analytics, and blockchain for supply chain transparency are a few examples.

Long-term Market Forecasts: Develop robust forecasts for the Gulf Cooperation Council (GCC) agricultural industry that account for anticipated impacts from demographic shifts, policy changes, and climate change. Policymakers, investors, and development organizations should use these projections as a reference when creating future-proof plans.

Comprehensive Policy Analyses: Conduct thorough assessments of current agricultural policies to identify best practices for replication and gauge the success of ongoing projects. Policy frameworks would be improved by such assessments, ensuring they remain flexible in the face of new opportunities and challenges. Future studies could yield practical insights and evidence-based recommendations by addressing these research areas, empowering stakeholders, from private investors to policymakers, to make more resilient, impactful, and informed decisions in the agricultural sector.

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تقييم الاستثمار الزراعي المباشر لدول مجلس التعاون الخليجي في شمال وشرق أفريقيا

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الملخص:

تستعرض هذه المراجعة الاستطلاعية (Scoping Review) استراتيجيات الاستثمار الزراعي لدول مجلس التعاون الخليجي في شمال وشرق أفريقيا، مع التركيز على انعكاساتها على الأمن الغذائي والتنمية الاقتصادية. وتسترشد المراجعة بأربعة أسئلة بحثية تتناول الدوافع والنتائج والتحديات والفجوات البحثية المرتبطة بهذه الاستثمارات. وباتباع إرشادات PRISMA-ScR، أسفر بحث منهجي في قواعد بيانات Scopus وWeb of Science وJSTOR، مدعوماً بالأدبيات الرمادية، عن تحديد 34 مصدراً خضعت للمراجعة الكاملة. وتُعزى استثمارات دول مجلس التعاون الخليجي الزراعية بشكل أساسي إلى الحاجة إلى تأمين إمدادات غذائية مستقرة وتنويع الاقتصادات التي تعتمد بشكل كبير على عائدات النفط. وتحدد المراجعة ثلاثة نماذج استثمارية رئيسية: الاتفاقيات الحكومية الثنائية، وعقود الإيجار طويلة الأجل للأراضي، والتمويل المدعوم من الدولة عبر صناديق الثروة السيادية. وتخلص المراجعة إلى أنه في حين ساهمت هذه الاستثمارات إيجاباً في الصادرات الزراعية وتنويع الإمدادات الغذائية، فإنها تنطوي أيضاً على مخاطر جوهرية، منها تهجير السكان، وعدم المساواة في البنية التحتية، والهشاشة الجيوسياسية. وتحدد المراجعة خمس فجوات رئيسية في الأدبيات، هي: التحليل الشامل للمخاطر، وآليات التمويل المبتكرة، ودور التكنولوجيا في الزراعة المستدامة، والتنبؤ بالأسواق، وتحليل السياسات. وتختتم المراجعة بتوصيات مستندة إلى الأدلة موجهة للمستثمرين وصانعي السياسات، تدعو إلى إجراء تقييمات للمخاطر، واستكشاف نماذج تمويل مختلطة، وتوظيف التكنولوجيا لتحقيق نتائج مستدامة.

الكلمات المفتاحية: استثمارات دول مجلس التعاون الخليجي، شمال وشرق أفريقيا، الأمن الغذائي، النمو الاقتصادي، الاستدامة.

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Building Sustainable Arab Food Systems through Eco-friendly Innovations, Green Technologies, Local Products Valorization, and Food Tourism

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Abstract:

Food security remains a critical challenge in the Arab world, where population growth, climate change, import dependency, conflicts, and limited natural resources exert unprecedented pressure on food systems. In this context, novel approaches should be implemented to transform existing systems, guarantee sustainability, catalyze economic growth, and meet consumer needs. In this study, a scoping review methodology is employed to map relevant literature on recent advances in green technologies and innovative practices. Data are categorized based on eco-friendly innovations, local or *terroir* products valorization, and green policies. This review investigates the role of local products in the Arab region and how the application of green technologies can strengthen sustainable food security. Particular attention is given to circular economy approaches, technological advances in food processing, and community-driven initiatives that reduce food waste and enhance nutritional availability. Findings show that local products and by-products constitute a natural reservoir of valuable bio-resources. However, many of these resources remain underutilized due to insufficient marketing, limited compliance with quality standards, limited processing capabilities, and the digital divide. To resolve these issues, it is essential to pave the way for functional green innovations and establishment of Arab policies that bolster creativity, environmental preservation, and economic growth. By drawing attention to

food tourism, organizations are encouraged to support *terroir* products valorization and deploy sustainable practices. Green technologies, including the Internet of Things (IoT), Artificial Intelligence (AI), and data analytics, play a pivotal role in mitigating carbon emissions and minimizing environmental impact. The combined integration of eco-friendly innovations, local product valorization, and food tourism offers a promising pathway to empower communities, strengthen regional economies, and build resilient food systems across the Arab world. Furthermore, multidisciplinary alliances, stakeholder involvement, and policy coherence are vital for promoting equitable and significant development and investment in Arab food systems.

Keywords: Arab region, food system, local product, eco-friendly innovation, valorization, food tourism.

Introduction:

Global population growth is driving a significant rise in food demand (FAO, 2018). With the world's population expected to surpass 9.8 billion by 2050, the global food system is under increasing pressure (FAO, 2017a), which could result in an increase of approximately 0.5 °C in global temperature only due to a high demand for food (Ivanovich *et al.,* 2023). Consequently, the growing demand for food is constrained by resource scarcity, climate change, food waste, conflicts, and environmental degradation, making it essential to develop resilient, responsible, and sustainable food systems (Bell *et al., 2018*). In this regard, several national and international policies have been established to achieve food security and sustainability, like geographical origin and *terroir* products labels for local products whose quality is linked to their origin (Seyfang, 2006). Consequently, strengthening sustainable and diversified food systems is fundamental for safeguarding food security, particularly in regions which are rich in local and traditional products. Accordingly, food security is often defined in terms of food availability, utilization, and access (FAO, 1996). For food access, it is ensured when all individuals within a household have adequate income to obtain appropriate products (Rivera and Qamar, 2003). In the Arab world, local products valorization and by-products upcycling offer a promising pathway to enhancing the sustainability of food systems, empowering small-scale actors such as cooperatives, reconciling tradition with modernity, satisfying consumer needs, ensuring economic growth, and aligning community livelihoods with the principles of the circular economy and eco-friendly innovations.

Indeed, the Arab region encompasses a wide range of local products that reflect its agro-ecological diversity and cultural heritage. Building on this diversity of local products, it is important to note that the Arab countries are a group of 22 countries that fall under the umbrella of the Arab League. These countries extend over an approximate area of 13.13 million square kilometres, with an aggregate population of around 356.8 million. Geographically, these countries extend from the northern and eastern parts of Africa to the Middle East in Asia (Wilson, 2017). They exhibit a remarkable diversity of local products. These products — such as traditional dairy derivatives, olive oil, dates, aromatic and medicinal plants, and other products — are not only emblematic of geographical identities but also serve as vectors for sustainable development. These *terroir* products are distinguished by intrinsic natural attributes that underscore their close linkage to the territory. Their production is further characterized by the reputation and expertise mobilized in the process, drawing upon historical, cultural, and innovative references. Moreover, the family-based dimension remains predominant in their elaboration (Harrak, 2018). Despite their recognized value, Arab local products and their eco-friendly valorization have received relatively limited attention in the scientific literature and research, particularly when compared to the extensive diversity present within each country. Few studies have explored the link between local Arab products and their considerable potential in fostering sustainability, boosting green innovations, and scaling by-products upcycling. Therefore, this review highlights the importance of advancing discourse on Arab food systems by examining the interconnectedness between eco-friendly innovations and local products valorization, while exploring circular economy approaches, technological advances in food processing, and community-driven initiatives that reduce food waste, stimulate economic growth, and upgrade product quality. It further identifies key challenges — namely the digital divide, low awareness of marketing strategies, and branding — while also seizing potential opportunities, including food tourism. The research questions that this review seeks to address are:

What obstacles and opportunities arise when integrating sustainable technologies into Arab local product valorization?

How does digitalization contribute to the valorization of local products while integrating eco-friendly innovations and cultural heritage in Arab food systems?

In what ways can food tourism enhance the competitiveness of Arab local products while promoting sustainability?

(4) How do green practices, local product valorization, and food tourism collectively contribute to Arab food security?

Methods:

A scoping review approach was employed to map relevant literature on recent advances in green technologies and innovative practices. This methodology was chosen to provide a comprehensive overview of research, identify key opportunities, and point out gaps in the field. The literature search was conducted using the following databases: Scopus, Web of Science, ScienceDirect, PubMed, Google Scholar.

The search covered publications from 2010 to 2025 to collect recent developments in sustainable food systems, eco-friendly innovations, green technologies, local product valorization, and food tourism. The review included scientific reports, books, research articles, and online resources. Keywords and Boolean operators were used to extract the intersection of key themes.

The collected information was classified according to the criteria outlined in Figure 1. These criteria represent the key dimensions used to organize and analyze the data in the scoping review. They include:

- Economic impact: Assessing how local products and circular economy practices contribute to economic growth, job creation, and market development.
- Environmental sustainability: Evaluating the use of green technologies, waste reduction, resource efficiency, and overall ecological benefits.
- Product valorization: Considering the processes that enhance the value of local products, such as innovation, processing, quality improvement, labeling, and the implementation and application of quality standards.
- Social and cultural relevance: Accounting for local traditions, community engagement, and promotion of regional identity.
- Technological integration: Examining the role of digital tools and technologies in promoting, tracking, and improving local products.

These criteria were designed to retrieve high-quality, peer-reviewed publications and literature that directly highlight the role of green practices and eco-friendly innovations in ensuring sustainability and economic growth. Studies focusing on the potential of local products, food tourism, and by-products valorization were also considered. Preference was given to studies employing clear methodological frameworks, including empirical research, case studies, systematic and scoping reviews, for ensuring pertinence of

findings. In parallel, exclusion criteria were established to refine the scope of the review, whereby publications that focused solely on innovations — without reference to green practices, sustainability impacts, or direct relevance to Arab food systems — were not considered. Studies were excluded if they lacked full-text availability, consisted of editorials or opinion papers, were duplicate records, or addressed food systems issues without considering environmental, social, economic, or sustainability dimensions.

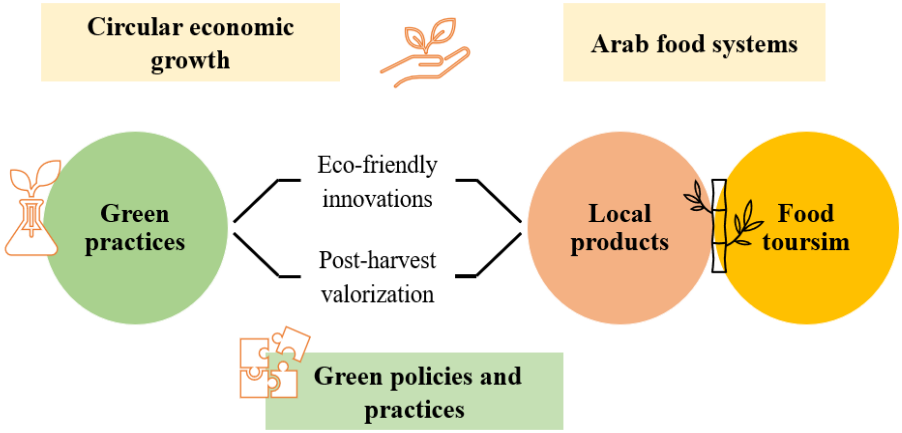


Figure 1. Criteria of data selection for the review study.

By applying these criteria, the review sought to highlight the interconnections between eco-friendly innovations, food tourism, and local products valorization, emphasizing their collective contribution to the sustainability of Arab food systems and the advancement of circular economic growth.

Results and Discussion:

Green Innovation: A Pathway to Sustainable Food Valorization

The findings suggest that innovation serves not only as a mechanism to satisfy consumer needs but also as a fundamental pillar in strengthening circular economy systems and promoting the development and attractiveness of tourism regions. Innovations are generally defined as new or improved products, processes and services, or policy and institutional arrangements that intend to produce value (Nagji and Tuff, 2012). They can be of a technological nature (new machine, new product, new process, new seed variety, digital tool, or device, etc.) or a non-technological nature (capacity

development approach, policy, business model, changing gender norms, etc.) (Geldes Felzensztein and Palacios-Fenech, 2017). It is often the combined availability and use of technological and non-technological innovations that allow for change or transformation to happen, which is referred to as an innovation package (Sartas *et al.,* 2020) or innovation bundle (Barrett *et al.,* 2022). Many innovations undergo a maturation process, evolving from an initial idea into a fully developed product or service. Maturation often happens as a result of basic research, design, rigorous testing, and adaptation in both controlled and uncontrolled environments. Once there is sufficient confidence that an innovation is proven to work, there is usually an aspiration to make it available to more clients or in other geographies. This is also referred to as innovation scaling – an important precondition for achieving impact (Woltering *et al.,* 2019; Schut *et al.,* 2020).

Over the past few years, a global innovation paradigm has evolved to respond to food demand and consumer needs while simultaneously preserving the environment and promoting economic growth. This approach is commonly referred to as green or eco-friendly innovation. This innovation is an element that leads to green innovative products (e.g., products made from recycled or plant-based materials) (Widodo and Wahid, 2020), which is an organizational strategy that emphasizes the development and production of new products that consider aspects of technologies and sustainability. While green products refer to the production process designed to reduce resources and recycle them at the end of their life cycle, green innovative products take a broader environmental perspective throughout every step of the production, making the process more sustainable worldwide (Dagher and Itani, 2012; Widodo and Wahid, 2020). The results clearly demonstrate that green technologies are critical to promoting environmental resilience and sustainability. They offer original answers to interconnected issues of climate change, environmental degradation, and resource scarcity. By utilizing green technologies, societies can lessen their impact on the environment and become more resilient to shocks from it (van Zanten and van Tulder, 2021).

Studies have pointed out that the application of green technologies is crucial for managing, reducing, and upcycling food waste in a sustainable manner. Green technology also goes under the names *environmental technology* and *clean technology* (Madaleno *et al.,* 2022). It is reasonable to define "green technology" as the creation and implementation of tools, machinery, and systems meant to preserve the environment and natural resources while minimizing and reducing the negative impacts of human activity. Another way to define "green technology" is technology that meets present

needs without compromising the ability of future generations to meet their own (Islam, 2023).

Food Waste: Impacts and Opportunities for Sustainable Development

Globally, food waste accounts for about 8–10% of greenhouse gas emissions (Mbow *et al.*, 2019), necessitating its reduction (FAO, 2017b). In this situation, developments driven by global technological advancements and a competitive environment can enhance innovations in products, processes, and services in the food industry (Albertsen *et al.,* 2020; Talwar *et al.,* 2020). One type of innovation is upcycling, which is transforming food lost during the production process into new products, thereby reducing food waste (Aschemann-Witzel *et al.,* 2022).

From this perspective, the adoption of green technology becomes particularly relevant for addressing food loss and waste. Indeed, food waste has become a major concern and a top priority at both the global and Arab levels. Food waste occurs at various steps within the food supply chain, including production, processing, distribution, and consumption (Raak *et al.,* 2017). Such losses not only waste resources like water, energy, and labor but also contribute significantly to greenhouse gas emissions, worsening climate change. Countries like Egypt, Pakistan, Sri Lanka, and Iraq have the highest food waste levels, indicating inefficiencies in their consumption and waste management systems. The transition to sustainable Arab food systems depends heavily on effective innovative approaches, green practices such as waste management policies that encourage the transformation of by-products and agro-industrial residues. In contrast to the traditional "linear economic model" of "take, make, and dispose," the circular economy emphasizes resource efficiency, waste minimization, and the continuous use of materials and products (Pal *et al.,* 2024).

The valorization of agricultural waste is critical to environmental sustainability, and multiple strategies can be followed for obtaining value-added products from food waste, such as animal feed, composting/vermicomposting, anaerobic digestion, and thermal treatments to produce charcoal, oils, and gases. Alternatively, novel valorization techniques include the extraction of bioactive compounds, the production of enzymes, exopolysaccharides, the synthesis of bioplastics, biopolymers, and the production of biofuels with significant potential in critical economic sectors such as food, pharmaceuticals, chemicals, fuels, and medicine (Esparza *et al.,* 2020).

Plant-derived waste and by-products, such as peel, leaves, seeds, bran, kernel, pomace, and oil cake, can be obtained from a wide variety of fruit, vegetables, cereals, oil crops, roots and tubers, and other legumes during the primary production and the

subsequent processing and distribution stages (Jin *et al.,* 2018; Difonzo *et al.,* 2021; Pathania and Kaur, 2022). Growing research shows that such waste and by-products can be valorized by the extraction of valuable nutrients and compounds, such as proteins, vitamins, fatty acids, amino acids, dietary fibers, flavonoids, and phenolic compounds, among others (Ali *et al.,* 2021; Joshi *et al.,* 2022; Nirmal *et al.,* 2023; Hadidi *et al.,* 2024).

Local Products: Driving Sustainable Consumption Trends

Food is one of the three main consumption areas that contribute the most to the environmental impacts in the household context (European Environment Agency, 2023), and several studies have highlighted the need to change to more sustainable food consumption patterns (Reisch, 2013; Willett *et al.,* 2019). Thus, when developing new products from a sustainable perspective, it is important to know which ingredient, technique, or process is the most convenient to apply from an environmental point of view. Considering this, the valorization and promotion of local products constitute a key element in enhancing the sustainability and resilience of Arab food systems. Findings highlighted that the consumption of local or *terroir* products emerges as a pivotal factor in promoting global sustainability, strengthening regional economies, and preserving cultural identities (Bannor and Abele, 2021; Emile *et al.,* 2021; Vargas *et al.,* 2021). This trend toward geographical origin has also generated positive environmental impacts by reducing fuel use and minimizing the environmental impact linked to global food transport (La Trobe, 2002; Seyfang, 2006; Karner *et al.,* 2010; Işik *et al.,* 2024). This paradigm shift becomes even more relevant when we consider that exports have been identified as a crucial factor in environmental pollution patterns (Işik, 2010). Both energy and natural resources used in the various stages of the production of internationally traded goods can cause environmental pollution (Işik, 2013; Işik and Turk, 2018; Chaturvedi *et al.,* 2024). Moreover, unsustainable consumption and production patterns, particularly prevalent in industrialised economies, represent one of the main drivers of continued environmental degradation on a global scale (Sijtsema *et al.,* 2020). Consumers, through their food choice decisions, have a central role in the transition toward a more sustainable food system. Thus, for an effective change, it is essential to understand the demands and expectations of consumers when promoting local products or developing new products or services that seek to contribute to more sustainable consumption patterns (Martinez *et al.,* 2010; Guinė *et al.,* 2020).

Consumer demand for sustainable, nutrient-rich, and clean-label products is rapidly increasing, which is driving the need for innovative eco-friendly formulations. Within this framework, the Arab world region has the potential to invest smartly in the promotion and valorization of its diverse local products as a strategy to ensure food

security. This approach enhances availability and access to diverse, nutritious foods by reducing reliance on imported or industrially processed products, thus improving dietary quality. Additionally, valorization fosters economic empowerment of local producers and cooperatives, ensuring stable livelihoods that reinforce local supply chains and reduce vulnerability to market shocks. Based on the selected studies, a key barrier impeding the promotion and expansion of local products is the limited use of appropriate marketing strategies and digital tools to enhance product quality and increase market visibility. The review revealed that consumers who consider both quality and environmental impact are inclined to invest more in locally produced food. Several studies have explored consumer preferences for locally produced food. Motives for "buying local" include perceived quality and freshness of local food and support for the local economy. Consumers who are willing to pay higher prices for locally produced foods place importance on product quality, nutritional value, sensory attributes (aroma, flavor, texture, etc.), production methods, their effects on the environment, and support for local farmers and cooperatives (Caro *et al.,* 2018).

Digital Transformation as a Catalyst for Local Product Promotion and Food Security

To satisfy consumer needs, guarantee sustainable Arab food systems, and respond effectively to these challenges, the Arab countries can leverage digital transformation to bridge existing gaps. Findings demonstrated that digitalization offers opportunities through e-commerce platforms, social media marketing, and digital storytelling, which can expand market reach and strengthen consumer awareness of the cultural, historical, and ecological significance of local products. For instance, blockchain technology helps to solve problems of traceability, food safety, and quality, thereby benefitting the "Farm to Fork" strategy in the context of globalisation and multiple intermediaries (Zeng *et al.,* 2017; Kamilaris *et al.,* 2019). The use of social networks and digital platforms to share information expedites contact between actors. In this regard, e-commerce constitutes an important digital service that contributes to cost reduction, market access, and demand stimulation, principally for small farmers and cooperatives (Zeng *et al.,* 2017).

Green products, places, and promotions significantly influence green purchase intentions. In several intriguing ways, environmental attitude modifies this connection. Customers' education level and income affect their desire to make green purchases (Kaur *et al.,* 2022). Consumers' environmental consciousness and awareness levels may vary, influencing their sensitivity and reactivity to green marketing methods. Personal benefits, such as health and safety, may be more motivating for certain consumers than environmental benefits (Sharma, 2021). However, consumers' views and expectations of

green products and marketing promises may differ, influencing their trust and satisfaction. Some customers may need clarifications about the legitimacy and reliability of green labels, certifications, and promotions (Sharma, 2021; Kaur *et al.,* 2022). Digital transformation is a prerequisite and enabler for improving local products, as well as the management of operations, making them more efficient. It also offers the potential to boost food tourism, which represents an asset for Arab countries.

Context-specific training, tailored support programs, eco-friendly initiatives such as agrotourism, and practical affordable methods play an indispensable role in bridging the gaps related to digitalization, boosting the awareness concerning green practices, and enhancing the cooperatives' performance and market integration. Accordingly, strong collaboration among stakeholders, including public institutions, researchers, consultants, and cooperatives, in parallel with establishing digital support hubs is fundamental to guarantee access to effective support, knowledge-sharing, and scalable solutions (Alami *et al.,* 2025).

Food Tourism: A Channel to Strengthen Economic Growth and Enhance the Visibility of Local Products

Studies suggested that growing demand for authentic culinary experiences has fuelled the growth of this sector within the tourism industry. This trend does not only attract tourists but also stimulates local economies in various ways (Badu-Baiden *et al.,* 2022; Putri and Wijoyo, 2023). It emphasizes that one crucial aspect of food tourism is its ability to showcase local or *terroir* products through events, fairs, festivals, and culinary tours. It serves as a platform to present eco-friendly local products produced by local farmers and cooperatives (Badu-Baiden *et al.,* 2022). Such experiences provide tourists with immersive opportunities to engage with the local culture and traditions (Yüksel, 2017). When combined with green practices, it contributes to the economic growth of local communities. It must be noted that Italy stands out as a prime example of a country renowned for its culinary offerings and food tourism experiences (Banerjee, 2015; Yüksel, 2017). This European country attracts food enthusiasts from around the world with its diverse and flavorful cuisine, including iconic dishes like pasta, pizza, and gelato (Yüksel, 2017). If Arab countries prioritize their authentic local products, strategically invest in gastronomy as well as natural landscapes, and integrate these efforts into policies promoting food security and sustainability, they can accelerate the transformation of food systems and maximize their potential. By focusing on food tourism, they can promote local products and implement strategies to enhance market visibility and regional economic development. Food tourism is increasingly recognized as a key contributor to both travel experiences and economic development worldwide.

Illustrating the Interplay between Food Tourism and Sustainable Promotion of Arab Local Products

An exemplary case of how the intersection of valorization of local products, green practices, and food tourism contributes to regional economic growth is argan oil. Whereas argan oil has been traditionally used for nutritional purposes in Central-West Morocco, nowadays, it is particularly prized by the cosmetic industry because of its broad spectrum of functional properties including skin hydration, hair revitalizing, antioxidant, anti-aging, and antiradical (Guillaume and Charrouf, 2011). Argan oil is the first Moroccan *terroir* product to benefit from the Protected Geographical Indication (PGI), a label obtained in accordance with the Moroccan law No. 26-05 of Distinctive Signs of Origin and Quality (SDOQ). When ingested, argan oil is endowed with pharmacological properties such as blood-cholesterol stabilization, hypertension, and diabetes prevention; moreover, it possesses antibacterial activity (El Monfalouti *et al.,* 2010). Preparing argan oil involves the elimination of the external parts of the fruit (pulp and nutshell), to free cold-pressed argan kernels. Through eco-friendly innovations, these by-products can be used and generate income for the cooperatives. Biorefining of argan biomass can help reduce waste and create jobs in rural areas, a key factor given that the unemployment rate is currently 19.7% in the Sous Massa region, where the argan tree mainly grows (Charrouf and Guillaume, 2018; MEO, 2024). It can also increase the added value of argan by-products, particularly for women's cooperatives. Oil, proteins, fibers, and other useful components could be extracted from the argan oil by-products and recycled or utilized in various industries, including food, cosmetics, and pharmaceuticals. In this context, digitalization and food tourism act as strategic allies in promoting local products and strengthening food systems, without overlooking the crucial role of product labeling and quality certifications. Currently, Morocco has 84 local products labeled under SDOQ1. These products have been labeled under three distinctive signs: Protected Geographical Indications, Protected Appellations of Origin, and Agricultural Labels. These labeled products mainly include local *terroir* products such as olive and argan oils, fresh and dried fruits (including dates and almonds), aromatic and medicinal plants (e.g., rosemary, rose, and saffron), as well as animal-origin products (e.g., honey and cheese) (MAMFRDWF, 2019). The establishment of such labels and protective legislation is essential for the recognition and valorization of Arab local products. They not only preserve traditional know-how but also promote sustainable and equitable economic development for local communities. Moreover,

[1] Personal communication. Labeling Division, Ministry of Agriculture, Maritime Fisheries, Rural Development, and Water and Forests, March 12th, 2026.

these initiatives strengthen the competitiveness of products in national and international markets, ensuring consumers the authenticity and quality of the products they purchase. The example of argan oil illustrates the importance of legal protection for *terroir* products in supporting their development and long-term sustainability. This model can be extended to other Arab local products, taking into consideration their diversity.

The studies included in the scoping review indicate a substantial growth in scientific publications, highlighting the interrelated roles of economic growth, green technologies, and the valorization of local products within the framework of the circular economy. As illustrated in Figure 2, the interconnectedness between eco-friendly innovations, green technologies, local product valorization, and food tourism contributes to the development of sustainable Arab food systems. This figure also demonstrates the pivotal role of the circular economy, which aims to establish closed-loop systems where materials and products remain in continuous circulation within the economy. When integrated into the value chain of local products and their valorization, it contributes to extending product lifespan. Eco-friendly products are intentionally designed to be durable, reusable, and repairable, thereby reducing the need for new resource extraction. At the end of their lifecycle, components are recovered and reintegrated into the production process, preventing them from becoming waste. Green technologies and digitalization further enhance the system's circularity while simultaneously creating new business and employment opportunities in sectors such as remanufacturing, repair, resource recovery, and upcycling. In addition, this model decreases reliance on virgin resources, minimizes waste and pollution, and plays a vital role in mitigating climate change. By maintaining materials in circulation, it reduces dependence on volatile global supply chains and alleviates pressures linked to the scarcity of finite resources.

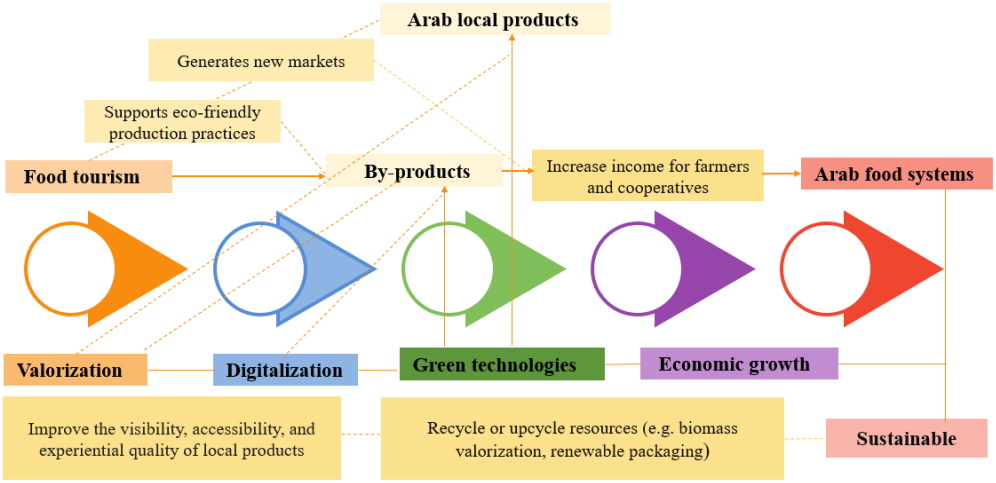


Figure 2. Interconnected Pathways Toward Sustainable Arab Food Systems.

Conclusions:

This review has made a key contribution by illustrating the challenges and opportunities at the intersection of eco-friendly innovations, green technologies, local product valorization, and food tourism. Building on these insights, it has further explored the essential components required for the sustainability and transformation of Arab food systems, linking them directly to the opportunities identified above and applying them specifically to the local food sector. To advance sustainability of Arab food systems and mitigate environmental impact related to food, a potential solution lies in the valorization of local products and their by-products, supporting eco-friendly innovations and empowering cooperatives to adopt digitalization and green technologies. These two tools play a capital role in improving the quality of local products and strengthen their visibility in the market. The goal is to build resilient sustainable Arab systems that satisfy consumer needs, protect the environment, honour territorial heritage, and develop local economies. To fasten this switch, food tourism emerges as a catalyst. It leverages traditional know-how, opens opportunities for locals — including cooperatives — to access new markets, and encourages them to step out of their comfort zones and innovate sustainably. This review concludes that by adopting a system thinking perspective, digitalization benefits the entire organization by improving workflows, reducing costs, and enhancing customer experiences. This approach considers long-

term sustainability, scalability, and collaboration with partners and stakeholders to create a networked digital ecosystem. It also allows organizations to remain agile and adaptable, responding quickly to market changes and technological advancements.

Recommendations:

This review lays the baseline for the future debate by recommending a system or ecosystem approach towards merging eco-friendly innovations with local products valorization while using food tourism and green technologies as strategic allies and resilient tools to ensure sustainable success of Arab food systems. These concepts provide Arab countries with opportunities to promote their local products and enhance their competitiveness. It is important to strengthen the link between terroirs and cooperatives by increasing awareness of the value and potential of local products and by integrating them into tourism services through the development of compelling storytelling narratives. In addition, leveraging digitalization can support the documentation, promotion, and traceability of local products, while also facilitating market access, enhancing visibility, and enabling more efficient communication between producers and consumers within sustainable food and tourism systems.

These opportunities can position local products as catalysts for green innovation, sustainability, and socio-economic growth within Arab food systems. Indeed, bolstering the adoption of labels linked to the geographical origins and quality certifications is essential to protect local products and improve their quality, enhance their credibility, and facilitate their access to diverse markets. In this regard, implementation and training on relevant standards are crucial. Moreover, collaborations among researchers, cooperatives, local chefs, food artisans, and restaurateurs constitute a cornerstone for advancing food tourism, fostering the valorization of local products, and promoting innovative sustainable formulations. Additionally, strategic alliances between public and private structures establish a concrete connection between knowledge, resources, and practical implementation of eco-friendly solutions, enriching the overall promotion of local products. Furthermore, the transition toward sustainable resilient Arab food systems requires a seamless integration of creativity, innovation, cultural elements, and collective intelligence supported through cooperation among Arab countries.

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بناء أنظمة غذائية عربية مستدامة من خلال الابتكارات الصديقة للبيئة، والتقنيات الخضراء، وتثمين المنتجات المحلية، والسياحة الغذائية

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الملخص:

يُشكّل تغيّر المناخ، والاعتماد على الاستيراد، والنزاعات، ومحدودية الموارد الطبيعية المتاحة ضغوطًا غير مسبوقة على النظم الغذائية. في هذا السياق، ينبغي تطبيق مناهج جديدة لتحويل النظم القائمة، وضمان استدامتها، وتحفيز النمو الاقتصادي، وتلبية احتياجات المستهلكين. تعتمد هذه الدراسة على منهجية البحث الموسع للمراجع العلمية للتركيز على أهم الدراسات المنجزة سابقًا والمتعلقة بالتطورات الحديثة في التقنيات الخضراء والممارسات المبتكرة. تُصنّف البيانات بناءً على الابتكارات الصديقة للبيئة، وتثمين المنتجات المجالية، والسياسات الخضراء. تهدف هذه المراجعة إلى استكشاف وتحليل إسهام المنتجات المحلية في دعم المنظومة الغذائية والتنموية في المنطقة العربية وكيف يُمكن لتطبيق التقنيات الخضراء تعزيز الأمن الغذائي المستدام. يُولى اهتمام خاص لنهج الاقتصاد الدائري، والتقدم التكنولوجي في تصنيع الأغذية، والمبادرات المجتمعية التي تُقلّل من هدر الطعام وتعزّز من الاستفادة من قيمته الغذائية. تُبيّن النتائج أن المنتجات المحلية ومشتقاتها الثانوية تمثل رصيدًا طبيعيًا استراتيجيًا من الموارد الحيوية ذات القيمة العالية. مع ذلك، لا يزال الكثير من هذه الموارد غير مُستغلّ بشكل كافٍ بسبب ضعف التسويق، وعدم توفر معايير الجودة أو عدم مطابقة معايير الجودة للمستوى المطلوب، ومحدودية قدرات التصنيع، وكذا الفجوة الرقمية. لحل هذه المشكلات، من الضروري تمهيد الطريق أمام الابتكارات الخضراء الفعّالة ووضع سياسات عربية تدعم الابتكار والحفاظ على البيئة والنمو الاقتصادي. ومن خلال تسليط الضوء على

السياحة الغذائية، تُشجَّع المنظمات على دعم تثمين المنتجات المحلية وتطبيق الممارسات المستدامة. تُظهر أن التقنيات الخضراء، بما في ذلك إنترنت الأشياء والذكاء الاصطناعي وأنظمة تحليل البيانات، تلعب دورًا محوريًا في الحد من انبعاثات الكربون وتقليل الأثر البيئي. ويُوفر التكامل بين هذه الابتكارات وتثمين المنتجات المحلية والسياحة الغذائية مسارًا واعدًا لدعم التمكين المجتمعي وتعزيز الاقتصادات الإقليمية وبناء أنظمة غذائية مرنة في جميع أنحاء العالم العربي. علاوة على ذلك، يُعتبر العملُ المشترك بين مختلف التخصصات وإشراكُ الفاعلين ركيزة أساسية للدفع بالتنمية والاستثمار العادل والفعّال في النظم الغذائية العربية.

الكلمات المفتاحية: المنطقة العربية، النظام الغذائي، المنتجات المجالية، الابتكار الأخضر، التثمين، السياحة الغذائية.

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Rosmarinic Acid as a Promising Biopesticide Against Rhynchophorus Ferrugineus in Date Palm

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Abstract:

The red palm weevil (*R. ferrugineus*) is one of the most destructive pests of date palm (*P. dactylifera* L.), causing substantial economic losses and threatening the sustainability of date palm production worldwide. The extensive use of synthetic insecticides has accelerated the evolution of insecticide resistance while raising serious concerns regarding environmental contamination, non-target effects, and food safety. Consequently, the development of effective botanical alternatives has become a priority for sustainable pest management. This study evaluated the insecticidal potential of Rosmarinic acid, a naturally occurring plant phenolic compound, against *R. ferrugineus* under laboratory and field conditions. Laboratory bioassays assessed acute toxicity and sublethal physiological effects using an artificial diet incorporation method. Toxicity was determined by estimating LC_{50} values, whereas nutritional indices, including the efficacy of conversion of ingested food (ECI) and digested food (ECD), were used to evaluate physiological disruption. In addition, the molecular mechanism of action was investigated by analyzing the expression of key detoxification genes, including cytochrome P450, glutathione S-transferase (GST), and general esterases. Field trials conducted during 2022–2023 in Baltim, Kafr El-Sheikh, Egypt, evaluated trunk injection of Rosmarinic acid at 3, 4, and 5 mL L^{-1}, with Deltamethrin (0.25 mL L^{-1}) serving as the reference insecticide. Treatment performance was assessed through destructive sampling, Palmear® acoustic detection, and residue analysis of palm tissues and fruits. Rosmarinic acid exhibited clear dose-dependent toxicity, with LC_{50} values of 2.041, 2.230, and 2.575 mL L^{-1} against fourth-instar larvae, eighth-instar larvae, and adults, respectively. It also significantly reduced nutritional efficiency and suppressed detoxification-related gene expression, indicating a multi-target mode of action. The highest field recovery rate (93.33%) was achieved with

Rosmarinic acid at 5 mL L^{-1}, exceeding both Rosmarinic acid at 4 mL L^{-1} and Deltamethrin (86.67%). Furthermore, no Rosmarinic acid residues were detected in palm tissues or fruits, whereas Deltamethrin residues remained detectable. These findings highlight Rosmarinic acid as an effective, environmentally compatible, residue-free botanical insecticide suitable for integration into sustainable management programs against the red palm weevil.

Keywords: Rosmarinic acid, Red palm weevil, *Rhynchophorus ferrugineus*, Date palm, Sustainable pest management.

Introduction:

Date palm (*Phoenix dactylifera* L.) is one of the most important fruit crops cultivated in arid and semi-arid regions worldwide. Global date production reached approximately 9.66 million metric tons, harvested from around 1.29 million hectares worldwide, with an average productivity of 6.84 tons ha^{-1} (FAO, 2023). Egypt is the leading global producer of dates, contributing approximately 1.71 million metric tons annually from nearly 14.63 million productive palms cultivated over 78.21 thousand hectares, with an average productivity of 116.38 kg $palm^{-1}$ (MALR, 2021). The economic importance of date palm production makes the protection of this crop from destructive pests a major priority.

The red palm weevil (*Rhynchophorus ferrugineus* Olivier) represents one of the most damaging insect pests affecting date palm production worldwide. The cryptic feeding behavior of larvae inside the trunk often results in delayed detection, extensive tissue destruction, and, in severe cases, palm death (Al-Dosary et al., 2016). Pest-related losses contribute substantially to reductions in date palm productivity, with *R. ferrugineus* considered among the primary biological constraints affecting date palm cultivation (El-Juhany, 2010). In Egypt, economic losses associated with red palm weevil infestations have been estimated at approximately 4 billion Egyptian pounds between 1992 and 2000 (Abbas, 2019), highlighting the urgent need for effective and sustainable management approaches.

Management of *R. ferrugineus* has traditionally depended on repeated applications of synthetic insecticides. However, intensive reliance on chemical control has raised concerns related to environmental contamination, effects on beneficial

organisms, pesticide residues, and the development of insecticide resistance (Al-Ayedh et al., 2016). Reports of reduced susceptibility to commonly used insecticides, including pyrethroids, further emphasize the limitations of conventional control strategies and the need for alternative approaches compatible with integrated pest management (IPM) programs.

Plant-derived bioactive compounds have received increasing attention as potential alternatives to synthetic insecticides because of their diverse biological activities and generally favorable environmental characteristics. Essential oils, botanical extracts, and plant secondary metabolites have demonstrated insecticidal, antifeedant, and growth-regulating effects against several agricultural pests (Piri et al., 2020; Darrag et al., 2022). Among these compounds, phenolic metabolites have attracted considerable interest due to their antioxidant, antimicrobial, and insecticidal properties (Darrag et al., 2022; Guan et al., 2022).

Rosmarinic acid ($C_{18}H_{16}O_8$) is a naturally occurring phenolic ester widely distributed in numerous plant species, particularly members of the Lamiaceae family (Guan et al., 2022). Owing to its broad spectrum of biological activities, Rosmarinic acid has attracted increasing attention as a plant-derived bioactive compound with potential applications in sustainable pest management. Previous studies have demonstrated that purified Rosmarinic acid, as well as Rosmarinic acid-enriched plant fractions, can adversely affect insect survival, development, feeding behavior, and physiological performance. Insecticidal activity has been reported against several economically important insect pests, including the pea aphid (*Acyrthosiphon pisum*), lesser grain borer (*Rhyzopertha dominica*), citrus mealybug (*Planococcus citri*), and oriental fruit fly (*Bactrocera dorsalis*) (Khan et al., 2016; Mughees et al., 2021). Moreover, evidence from lepidopteran and hemipteran insects suggests that Rosmarinic acid may disrupt oxidative homeostasis and alter detoxification-related pathways, including cytochrome P450 monooxygenases and glutathione S-transferases, thereby contributing to its insecticidal activity (Khan et al., 2019; Kashyap and Reddy, 2025).

Despite these promising findings, current knowledge remains largely limited to laboratory-based evaluations involving a relatively narrow range of insect species.

Information regarding the efficacy of purified Rosmarinic acid against the red palm weevil (*R. ferrugineus*), one of the most destructive pests of date palm, remains scarce, particularly under field conditions. Furthermore, the relationships among insecticidal activity, physiological disruption, detoxification responses, field performance, and residue behavior in treated palms have not yet been comprehensively investigated. Recent advances in formulation technologies, including nanoemulsions and biodegradable delivery systems, have further highlighted the potential of Rosmarinic acid as a botanical insecticidal candidate while emphasizing the need for comprehensive biological evaluation before practical application (Naveed et al., 2023).

Therefore, the objective of the present study was to comprehensively evaluate the insecticidal potential of purified Rosmarinic acid against *R. ferrugineus* using an integrated laboratory-to-field approach. Specifically, the study aimed to (1) evaluate the insecticidal activity of Rosmarinic acid against different developmental stages of *R. ferrugineus* under laboratory conditions by determining lethal concentrations (LC_{50}); (2) assess the sublethal effects of Rosmarinic acid on larval feeding performance and nutritional utilization through determination of nutritional indices, including approximate digestibility (AD), efficiency of conversion of ingested food (ECI), and efficiency of conversion of digested food (ECD); (3) investigate potential molecular responses associated with Rosmarinic acid exposure by analyzing the expression patterns of major detoxification-related genes, including cytochrome P450 monooxygenases, glutathione S-transferases (GSTs), and esterases; (4) evaluate the field efficacy of Rosmarinic acid applied through trunk injection against naturally infested date palms and compare its performance with Deltamethrin using destructive assessment and Palmear® acoustic detection technology; (5) characterize the residue behavior of Rosmarinic acid and Deltamethrin in palm tissues and date fruits following trunk injection to provide preliminary information regarding residue persistence and food safety considerations.

Materials and Methods:

Rosmarinic acid isolation, purification, and quantification

Fresh aerial parts of Origanum vulgare L., Melissa officinalis L., Salvia officinalis L., Rosmarinus officinalis L., and Thymus vulgaris L. were collected during the 2022

growing season. Plant materials were authenticated, shade-dried at room temperature (25 ± 2 °C), and finely ground. The powdered samples were subjected to Soxhlet extraction using n-butanol as the extraction solvent for 6 h, following the procedure described by Sik et al. (2020). The obtained extracts were concentrated under reduced pressure using a rotary evaporator at 40 °C and stored at 4 °C until further analysis.

Rosmarinic acid was subsequently isolated from the obtained extracts using appropriate purification procedures. The isolated fractions were subjected to chromatographic and spectrometric analyses to confirm the identity of the target compound. High-performance liquid chromatography coupled with mass spectrometry (HPLC–MS) was used for qualitative and quantitative determination of Rosmarinic acid. Compound identification was based on comparison of retention time and mass spectral fragmentation patterns with those of an authentic Rosmarinic acid standard.

Chromatographic separation was achieved using a C18 reversed-phase column (250 mm × 4.6 mm, 5 µm) with a gradient mobile phase consisting of water containing 0.1% formic acid and acetonitrile at a flow rate of 1.0 mL min^{-1}. Detection was performed at 330 nm. Quantification was carried out using an external calibration curve generated from authentic Rosmarinic acid standards.

The Rosmarinic acid content was calculated based on the amount of compound recovered relative to the initial dry plant material used for extraction and expressed as mg g^{-1} dry weight (DW). This approach enabled accurate comparison of Rosmarinic acid yield among the evaluated plant species. For subsequent biological assays, the isolated Rosmarinic acid fraction was used as the tested active compound, rather than crude plant extracts, to minimize the potential influence of other co-extracted phytochemicals on biological responses.

Insects

The red palm weevils (*R. ferrugineus*) used in this study were obtained from laboratory colonies originally established from adults collected in date palm–infested fields between October and December 2022. The adults were maintained in mesh cages (57.5 × 29 × 58 cm) containing pineapples to facilitate mating and oviposition under controlled environmental conditions of 30 ± 1°C, 75 ± 5% relative humidity (RH), and a 16 h light:8 h dark photoperiod. Newly hatched larvae were initially reared on pineapples, while second-instar larvae were transferred individually to an artificial diet and kept in 400 mL perforated plastic cups under the same temperature, humidity, and photoperiod conditions (Hussain et al., 2016).

Laboratory Bioassays

Laboratory bioassays were conducted during 2022–2023 at the Plant Protection Research Laboratory, Agricultural Research Center (ARC), Dakahlia, Egypt. Laboratory colonies of *R. ferrugineus* were maintained under controlled environmental conditions (30 ± 1 °C, 75 ± 5% relative humidity, and a 16:8 h light:dark photoperiod). Fourth-instar larvae, eighth-instar larvae, and adults were used for toxicity evaluation.

Rosmarinic acid obtained from the isolated active fraction and confirmed by HPLC–MS analysis was used in all biological assays. Insects were exposed to artificial diets supplemented with Rosmarinic acid at concentrations of 3, 4, and 5 mL L^{-1}. Deltamethrin (Decis® 25 EC) at 0.25 mL L^{-1} was used as the reference insecticide, while untreated insects receiving the same artificial diet without Rosmarinic acid or insecticide served as the control.

For each developmental stage, 100 individuals were evaluated per treatment. The experiment consisted of five independent replicates, with 20 insects per replicate. Larvae and adults were continuously exposed to treated diets for 10 days. Mortality was recorded daily, and mortality percentages were corrected for control mortality using Abbott's formula (Abbott, 1925).

Corrected mortality data were subjected to probit analysis to estimate median lethal concentrations (LC_{50}) using POLO-PC software (LeOra Software LLC, Berkeley, CA, USA) according to Russell et al. (1977). Cumulative mortality data at different exposure periods were analyzed using repeated-measures ANOVA after angular transformation. Treatment means were separated using Fisher's least significant difference (LSD) test (SAS Institute, 2017).

Growth Inhibition and Nutritional Indices

The effects of Rosmarinic acid on larval feeding performance and nutritional utilization were evaluated using fourth- and eighth-instar larvae of *R. ferrugineus*. These developmental stages were selected because they allow accurate measurement of larval biomass gain, food consumption, and frass production.

Artificial diets were prepared by incorporating Rosmarinic acid at the previously determined LC_{50} concentrations for each larval instar. The untreated control diet contained no Rosmarinic acid. Twenty-five larvae of each instar were individually placed in aerated plastic containers containing treated or untreated diets. Five independent

biological replicates were established for each treatment, with five larvae considered as one replicate.

Larvae were maintained under controlled laboratory conditions (30 ± 1 °C, 75 ± 5% relative humidity, and a 16:8 h light:dark photoperiod). After three days of continuous feeding, larval weight gain, food consumption, and frass production were measured using an analytical balance.

Nutritional indices were calculated according to standard procedures:

- Approximate digestibility (AD):

AD (%) = [(food ingested – frass weight) / food ingested] × 100

- Efficiency of conversion of ingested food (ECI):

ECI (%) = [weight gained / food consumed] × 100

- Efficiency of conversion of digested food (ECD):

ECD (%) = weight gained / (food ingested – frass weight)

Data were analyzed using one-way ANOVA, and treatment means were compared using Fisher's LSD test (SAS Institute, 2017).

Detoxification-Related Gene Expression Analysis

The molecular response of *R. ferrugineus* larvae to Rosmarinic acid exposure was investigated by analyzing the expression patterns of major detoxification-related gene families, including cytochrome P450 monooxygenases, glutathione S-transferases (GSTs), and esterases.

Fourth- and eighth-instar larvae were fed artificial diets containing Rosmarinic acid at their respective LC_{50} concentrations. Control larvae received untreated diets. Five biological replicates were established for each treatment, with five larvae pooled per replicate.

After 72 h of exposure, larvae were dissected under sterile conditions in ice-cold physiological saline. Midgut tissues were collected, immediately frozen in liquid nitrogen, and stored at –80 °C until RNA extraction.

Total RNA was extracted using the RNeasy® Universal Mini Kit (Qiagen, Hilden, Germany). Complementary DNA synthesis was performed using the PrimeScript First Strand cDNA Synthesis Kit (TaKaRa Clontech, Paris, France). Quantitative real-time PCR was conducted using a CFX96 Touch™ Real-Time PCR System (Bio-Rad, UK) with SYBR® Premix Ex Taq™ II.

The expression levels were normalized using β-actin (GenBank accession no. KM438516) as an internal reference gene. Relative expression changes were calculated using the $2^{-}\Delta\Delta Ct$ method (Livak and Schmittgen, 2001). Statistical differences among treatments were determined using one-way ANOVA followed by Fisher's LSD test.

Field Evaluation:

Field experiments were conducted during the 2023 growing season in a commercial date palm orchard naturally infested with *R. ferrugineus* in Baltim, Kafr El-Sheikh Governorate, Egypt. Two economically important cultivars, 'Barhi' and 'Hayani', were selected for evaluation.

Experimental Design and Trunk Injection Application

The experiment was arranged as a completely randomized design (CRD). Treatments included Rosmarinic acid at 3, 4, and 5 mL L^{-1} and Deltamethrin (Decis® 25 EC) at 0.25 mL L^{-1}. Water-injected palms served as untreated controls.

Each treatment consisted of three replicates, with each replicate represented by one naturally infested palm. Palms were selected based on comparable infestation symptoms and similar infestation severity before treatment.

Trunk injection was performed using a Syngenta® injection device following a standardized procedure. Four downward-angled holes (30 cm depth and 1.2 cm diameter) were drilled uniformly around the trunk above the soil surface. Rosmarinic acid solution was injected at 15 mL per hole (60 mL $palm^{-1}$ total), whereas Deltamethrin solution was applied at 25 mL per hole (100 mL $palm^{-1}$ total). After injection, holes were sealed with moist clay to reduce leakage and facilitate systemic movement of the injected solutions.

Evaluation of Treatment Efficacy

The efficacy of the insecticide treatments was evaluated 60 days after trunk injection using three complementary assessment methods to improve the reliability of field evaluation.

1) Visual assessment of external symptoms: Each treated palm was visually inspected for the presence of characteristic symptoms of *Rhynchophorus ferrugineus* infestation, particularly the exudation of yellowish-brown viscous sap from trunk tissues. The absence of these symptoms was considered an initial indication of palm recovery.

2) Destructive assessment: Following visual inspection, the infested trunk tissues were carefully dissected to determine the survival status of *R. ferrugineus* individuals. Palms were scored according to the presence of living insects as follows:
    - 0 = No living *R. ferrugineus* individuals detected (recovered palm).
    - 1 = One or more living *R. ferrugineus* individuals detected (non-recovered palm).

3) Acoustic assessment: Trunk infestation was also evaluated using the Palmear® acoustic detection system, which integrates acoustic sensing technology with artificial intelligence to detect internal feeding activity of *R. ferrugineus*. Detection results were interpreted according to the manufacturer's recommendations and converted into numerical scores as follows:
    - 0 = Green signal (no detectable infestation).
    - 0.5 = Orange signal (uncertain detection).
    - 1 = Red signal (active infestation detected).

The final assessment of treatment efficacy was based primarily on the destructive examination, while visual symptom assessment and acoustic detection were used as complementary methods to support the diagnosis and improve the accuracy of field evaluation.

Collection of Plant Samples for Residue Analysis:

To evaluate residue persistence and systemic distribution, palm frond bases and fruits were collected after treatment. Frond bases were collected one month after trunk injection. Four fronds from different directions around each palm were sampled, and basal sections were combined to form one composite sample per palm.

Fruit samples were collected at two developmental stages: Bisr (early ripening) one month after treatment and Tamr (fully ripe stage) two months after treatment. Approximately 250 g of fruits were collected from each direction of the palm, pooled into a composite sample (approximately 1 kg per palm), and transported under refrigerated conditions for residue analysis.

Rosmarinic Acid and Deltamethrin Residue Determination

Residue analyses were performed at the Central Laboratory for Analysis of Pesticide Residues and Heavy Metals in Food (QCAP), Agricultural Research Center, Giza, Egypt. The laboratory is accredited according to ISO/IEC 17025:2017 by the Egyptian Accreditation Council (EGAC) and the American Association for Laboratory Accreditation (A2LA).

Sample extraction was performed using the validated QuEChERS procedure. Rosmarinic acid residues were quantified using LC–MS/MS, whereas Deltamethrin residues were analyzed using GC–MS according to validated analytical protocols.

The analytical method showed a limit of quantification (LOQ) of 0.01 mg kg^{-1}. Quality control procedures, including calibration, recovery tests, and analytical validation, were performed according to laboratory accreditation requirements.

Field data were analyzed using analysis of variance (ANOVA). Treatment effects were considered significant at $p \leq 0.05$. Mean comparisons were performed using Fisher's LSD test (SAS Institute, 2017).

Results and Discussion:

Purification and quantitative profiling of rosmarinic acid from Lamiaceae plant sources.

Rosmarinic acid was isolated and purified from the aerial parts of *Origanum vulgare* L., *Melissa officinalis* L., *Salvia officinalis* L., *Mentha piperita* L., *Thymus vulgaris* L., and *Rosmarinus officinalis* L. using Soxhlet extraction followed by purification procedures. The extracted compound was obtained separately from each plant source and was not applied as a crude botanical extract in subsequent bioassays. Instead, purified Rosmarinic acid was used as the active compound in all toxicity, physiological, biochemical, and molecular experiments.

The extraction process was performed using different solvents, and n-butanol exhibited the highest recovery efficiency, which is consistent with its suitable polarity for extracting phenolic compounds (Sik et al., 2020). The identity and purity of the isolated compound were confirmed by high-performance liquid chromatography coupled with mass spectrometry (HPLC–MS), based on the characteristic retention time and mass spectral profile of authentic Rosmarinic acid. The quantitative content of Rosmarinic acid was calculated based on the amount of compound recovered per gram of dry plant material (mg g^{-1} dry weight), allowing direct comparison among different plant sources.

Quantitative analysis revealed significant variation in Rosmarinic acid content among the examined species. *O. vulgare* showed the highest concentration (46.7 ± 2.0 mg g^{-1} dry weight), followed by *M. officinalis* (32.0 ± 0.1 mg g^{-1} dry weight), whereas lower concentrations were detected in *S. officinalis*, *M. piperita*, *T. vulgaris*, and *R. officinalis* (Table 1). These differences may reflect species-specific variation in genetic background, enzymatic regulation, and environmental factors affecting the phenylpropanoid biosynthetic pathway (Sik et al., 2020). The obtained results indicate that *O. vulgare* and *M. officinalis* represent efficient natural sources for Rosmarinic acid production and provide suitable starting materials for further development of botanical insecticidal formulations.

Table 1. Yield and quantitative profiling of purified rosmarinic acid isolated from different Lamiaceae plant species based on HPLC–MS analysis.

Plant species	*Rosmarinic acid content (mg g^{-1} DW ± SE)
Origanum vulgare L.	46.7 ± 2.0
Melissa officinalis L.	32.0 ± 0.1
Salvia officinalis L.	20.6 ± 0.1
Mentha piperita L.	18.2 ± 0.3
Thymus vulgaris L.	16.1 ± 1.1
Rosmarinus officinalis L.	10.3 ± 0.3

*Values are expressed as mean ± standard error (SE) of three independent extractions. DW = Dry Weight.

Laboratory Toxicity of Rosmarinic Acid Against Adults and Larvae of the Red Palm Weevil

The mortality responses of different developmental stages of *R. ferrugineus* exposed to purified Rosmarinic acid and Deltamethrin are presented in Figure 1 (a–d).

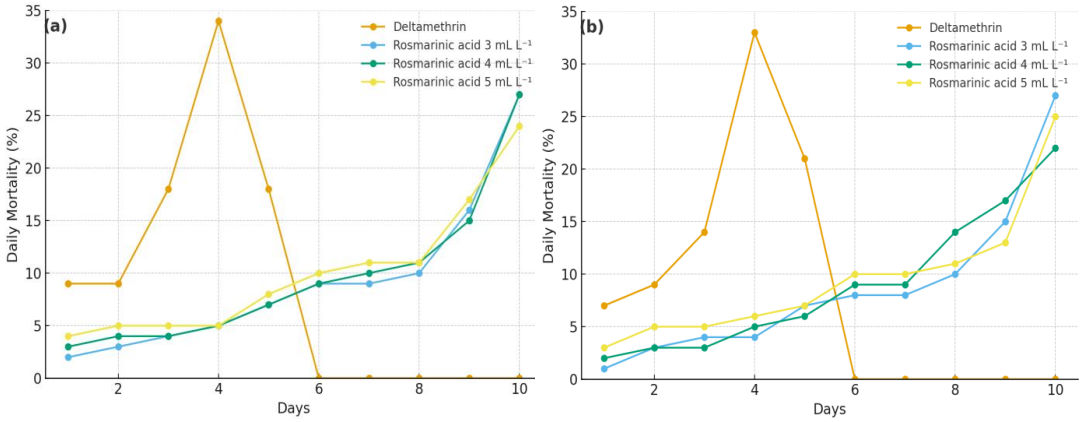
Both compounds induced detectable toxic effects under laboratory conditions, with mortality increasing progressively throughout the exposure period, indicating a time-dependent response to treatment.

The susceptibility of *R. ferrugineus* varied among developmental stages. Fourth-instar larvae exhibited the highest sensitivity to Rosmarinic acid, followed by eighth-instar larvae, whereas adults showed relatively lower susceptibility. In addition, Rosmarinic acid produced a concentration-dependent response, as increasing the concentration from 3 to 5 mL L^{-1} resulted in increased mortality across all tested stages.

The cumulative mortality results (Figure 1d) showed that Rosmarinic acid at 5 mL L^{-1} resulted in 100% mortality of fourth-instar larvae. For eighth-instar larvae, mortality reached 95% and 90% following exposure to Rosmarinic acid at 5 and 4 mL L^{-1}, respectively. In comparison, Deltamethrin at 0.25 mL L^{-1} caused mortality rates of 87%, 84%, and 77% in fourth-instar larvae, eighth-instar larvae, and adults, respectively. These results demonstrate that Rosmarinic acid exhibited significant insecticidal activity against different developmental stages of *R. ferrugineus*, with greater effectiveness observed at higher concentrations and against larval stages.

The differences in susceptibility among developmental stages may be related to developmental variation in physiological characteristics, feeding behavior, or other stage-specific factors that influence insect response to toxic compounds. Similar variations in susceptibility among insect stages have been reported for several botanical compounds and synthetic insecticides, where differences in insect development and metabolic capacity may affect toxicity outcomes.

Previous studies have also reported the insecticidal activity of Rosmarinic acid



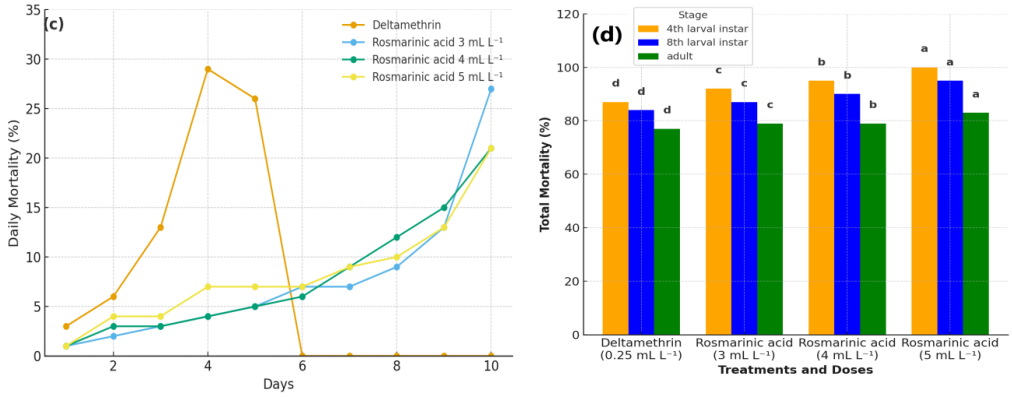


Figure 1. Mortality responses of *R. ferrugineus* to Deltamethrin (Decis® 25 EC) at 0.25 mL L^{-1} and Rosmarinic acid at three concentrations of 3, 4, and 5 mL L^{-1} under laboratory conditions: (a) fourth-instar larvae, (b) eighth-instar larvae, (c) adults, and (d) cumulative mortality of the three developmental stages.

The toxicity of purified Rosmarinic acid differed among the developmental stages of *R. ferrugineus*, although all tested stages exhibited susceptibility to the compound (Table 2). Fourth-instar larvae were the most sensitive stage, with an LC_{50} value of 2.041 mL L^{-1} (95% CI: 1.487–2.594 mL L^{-1}), followed by eighth-instar larvae (LC_{50} = 2.230 mL L^{-1}; 95% CI: 1.717–2.743 mL L^{-1}). Adults exhibited the lowest susceptibility, with an LC_{50} value of 2.575 mL L^{-1} (95% CI: 2.030–3.119 mL L^{-1}). The approximately 26.2% increase in LC_{50} from fourth-instar larvae to adults indicates a reduction in sensitivity with advancing developmental stage under the experimental conditions.

The probit slope values varied among developmental stages, with values of 1.16 ± 0.24, 0.81 ± 0.13, and 0.60 ± 0.10 for fourth-instar larvae, eighth-instar larvae, and adults, respectively. The higher slope value observed in younger larvae suggests a more consistent concentration–mortality response within this developmental stage, whereas the lower slope values in older larvae and adults indicate greater variability in individual responses to Rosmarinic acid exposure. These differences may reflect developmental

variation in physiological characteristics affecting insect susceptibility; however, further investigations are required to clarify the underlying mechanisms.

The goodness-of-fit analysis indicated that the probit model adequately described the concentration–mortality relationships for all tested stages. The calculated χ^2 values were 0.3250, 1.6652, and 3.3362 for fourth-instar larvae, eighth-instar larvae, and adults, respectively, with no significant deviations between observed and expected mortality values ($p > 0.05$). These results confirm the suitability of the fitted probit models and support the reliability of the estimated LC_{50} values.

Previous studies have reported insecticidal activity of Rosmarinic acid against other insect species. For example, Rosmarinic acid exhibited toxicity against the stored-product pest *Rhyzopertha dominica*, with an LC_{50} value of 42.4 µg mL^{-1} (Mughees et al., 2021). Additionally, Rosmarinic acid has shown biological activity comparable to some conventional insecticides in laboratory assays against different insect pests, including *Bactrocera dorsalis*, suggesting its potential as a botanical insecticide candidate. However, further studies addressing formulation development, non-target effects, and field-scale performance are required before practical implementation.

Table 2. Dose mortality and probit analysis of different developmental stages of *R. ferrugineus* treated with pure Rosmarinic acid.

Stage	LC_{50} (mL L^{-1})	95% CI (low – high)	Slope ± SE	χ^2
4th larval instar	2.041	1.487 – 2.594	1.16 ± 0.24	0.3250
8th larval instar	2.230	1.717 – 2.743	0.81 ± 0.13	1.6652
Adult	2.575	2.030 – 3.119	0.60 ± 0.10	3.3362

LD_{50} values were calculated after three days of feeding. LD_{50} values were not determined at 10 days because all treatments produced mortality exceeding 50% before the end of the experimental period.

Larval Growth- and Development-Retarding Effects of Rosmarinic Acid at LC_{50} Concentrations

The effects of Rosmarinic acid on larval nutritional performance and growth-related parameters of *R. ferrugineus* were evaluated using LC_{50} concentrations previously estimated for the fourth- and eighth-instar larvae (2.041 and 2.230 mL L^{-1},

respectively). After 72 h of continuous feeding on Rosmarinic acid-treated artificial diets, significant differences were observed in the nutritional indices, including efficiency of conversion of ingested food (ECI), efficiency of conversion of digested food (ECD), and approximate digestibility (AD) (Table 3).

Fourth-instar larvae exposed to Rosmarinic acid at their corresponding LC_{50} concentration (2.041 mL L^{-1}) exhibited a significant reduction in ECD compared with eighth-instar larvae treated with 2.230 mL L^{-1} ($p < 0.0001$). Similarly, ECI values were significantly reduced in fourth-instar larvae, indicating a lower efficiency in converting ingested food into larval biomass following Rosmarinic acid exposure. These results suggest that Rosmarinic acid affected food utilization efficiency, particularly in younger larvae, under the tested experimental conditions.

In contrast, AD values showed a different response pattern, with significant increases observed following Rosmarinic acid exposure in both larval stages ($p < 0.0001$). The fourth-instar larvae treated with 2.041 mL L^{-1} exhibited a 25.39% higher AD value compared with eighth-instar larvae treated with 2.230 mL L^{-1}. The increase in AD, accompanied by reductions in ECI and ECD, indicates that although larvae were able to digest a greater proportion of consumed food, the conversion of digested nutrients into body biomass was reduced.

The observed alterations in nutritional indices demonstrate that Rosmarinic acid exposure influenced larval feeding efficiency and nutrient utilization, with stronger effects recorded in fourth-instar larvae. Differences between larval stages may be related to developmental variation in feeding behavior, metabolic activity, or physiological requirements; however, further biochemical investigations are required to clarify the mechanisms underlying these responses.

Similar effects of Rosmarinic acid on insect growth and nutritional performance have been reported in other insect species. Khan et al. (2019) observed growth inhibition in *Acyrthosiphon pisum* following exposure to Rosmarinic acid, suggesting that this phenolic compound may interfere with physiological processes involved in insect development. Together with the present findings, these results support the potential role of Rosmarinic acid in disrupting insect growth and feeding performance and highlight its relevance for further evaluation as a botanical insecticidal compound.

Table 3. Nutritional indices (mean ± SE) of 4th and 8th larval instars of R. ferrugineus fed on artificial diets incorporated with Rosmarinic acid at LD_{50} (2.041 mL L^{-1} and 2.230 mL L^{-1}, respectively) compared with control diets.

Treatment	Larval instar	*AD	*ECI	*ECD
Control (untreated)	4th	65.02 ± 0.15b	19.03 ± 0.30a	35.04 ± 0.74a
	8th	63.45 ± 0.28b	17.91 ± 0.10b	32.19 ± 0.31b
Rosmarinic acid (2.041 mL L^{-1})	4th	74.01 ± 0.35a	5.75 ± 0.53d	7.76 ± 0.71d
Rosmarinic acid (2.230 mL L^{-1})	8th	59.02 ± 0.44c	16.01 ± 0.11c	27.13 ± 0.20c

AD = approximate digestibility; ECI = efficacy of conversion of ingested food; ECD = efficacy of conversion of digested food. Means ± SE values having the same letter(s) within the column are not significantly different (Fisher's LSD test, α = 0.05).

Physiological Impacts of Rosmarinic acid at LC_{50} on the Host Detoxification Defense Mechanism

Figure 2 illustrates the relative expression of three major detoxification gene families, namely Cytochrome P450, Glutathione S-transferase (GST), and Esterase, in the 4th- and 8th-instar larvae of *R. ferrugineus* following exposure to Rosmarinic acid at their respective LC_{50} concentrations (2.041 and 2.230 mL L^{-1}). Detoxification-related gene expression was generally higher in the 8th instar than in the 4th instar. The greatest transcriptional response was observed for GST, followed by Cytochrome P450, indicating that these enzymes constitute the primary metabolic response to Rosmarinic acid exposure. In contrast, Esterase expression remained relatively low and showed no significant variation between larval instars, suggesting a limited contribution to the detoxification process under the experimental conditions (Figure 2).

Cytochrome P450 monooxygenases, glutathione S-transferases (GSTs), and esterases represent the principal detoxification enzyme families in arthropods and play fundamental roles in the metabolism of xenobiotics and insecticide resistance. GSTs catalyze the conjugation of reduced glutathione with electrophilic compounds, producing more water-soluble metabolites that can be readily eliminated (Xu et al., 2015). Esterases hydrolyze ester-containing compounds into their corresponding acids and alcohols, thereby contributing to the detoxification of a wide range of xenobiotics (Bhatt et al., 2021). Cytochrome P450 enzymes catalyze oxidative reactions that facilitate the

metabolism and clearance of both endogenous metabolites and foreign chemicals (Scott et al., 1998). Increased expression of these detoxification genes is widely recognized as an adaptive response that enhances insect tolerance to toxic compounds.

Despite the induction of detoxification-related genes, Rosmarinic acid produced high mortality in both larval instars, indicating that the induced detoxification response was insufficient to counteract its toxic effects. These findings suggest that Rosmarinic acid disrupts essential metabolic defense pathways in *R. ferrugineus*, thereby contributing to its pronounced insecticidal activity.

The precise mode of action of Rosmarinic acid in insects has not yet been fully elucidated. However, plant-derived phenolic compounds are known to interfere with multiple physiological targets involved in insect survival. Previous studies have demonstrated that these compounds can inhibit detoxification enzymes, including GSTs and acetylcholinesterase, and modulate key neurophysiological targets such as γ-aminobutyric acid (GABA)-gated chloride channels and octopamine receptors, ultimately leading to neurotoxic effects (Yu and Abo-Elghar, 2000; Enan, 2005). Therefore, further investigations integrating biochemical, molecular, and neurophysiological approaches are required to elucidate the precise mechanism by which Rosmarinic acid exerts its insecticidal activity against *R. ferrugineus*.

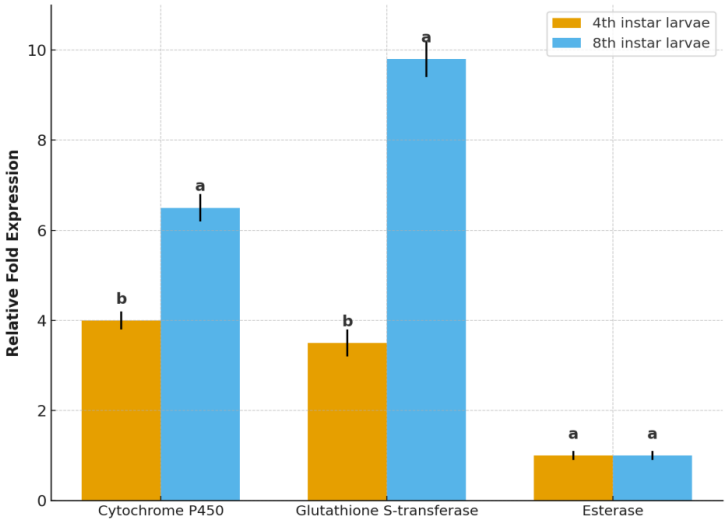


Figure 2. Expression pattern of detoxification genes of 4th- and 8th-instar red palm weevil larval midguts in response to Rosmarinic acid LD_{50} (2.041 mL L^{-1} and 2.230 mL L^{-1}). Bars (means ± SE) followed by different letters are significantly different (Fisher's LSD test, α = 0.05).

Trunk infestation experiment

Trunk injection treatments significantly improved the recovery of date palms naturally infested with *R. ferrugineus* 30 days after application (Table 4). All Rosmarinic acid treatments and the reference insecticide, Deltamethrin (Decis® 25 EC), resulted in significantly higher recovery rates than the water-injected control ($p \leq 0.0001$), in which no palm recovery was observed and all weevils remained alive. The highest recovery rate (93.33%) was achieved with Rosmarinic acid at 5 mL L^{-1}, where 14 out of 15 treated palms showed complete recovery. Rosmarinic acid at 4 mL L^{-1} and Deltamethrin at 0.25 mL L^{-1} each produced an identical recovery rate of 86.67% (13 of 15 palms), whereas the lowest Rosmarinic acid concentration (3 mL L^{-1}) resulted in 80.0% recovery (12 of 15 palms).

The efficacy of Rosmarinic acid increased with concentration, demonstrating a clear dose-dependent response under field conditions. The highest concentration (5 mL L^{-1}) produced the greatest recovery among all treatments and numerically exceeded

that obtained with Deltamethrin. However, this difference should be interpreted cautiously unless supported by a direct statistical comparison between treatments. Overall, these findings indicate that Rosmarinic acid is highly effective in suppressing red palm weevil infestations and has strong potential as a botanical component of integrated pest management programs.

The slightly higher recovery observed with Rosmarinic acid than with Deltamethrin may be associated with the increasing occurrence of pyrethroid resistance in some *R. ferrugineus* populations, including reduced susceptibility to deltamethrin, as previously reported (Wakil et al., 2018). Although resistance was not directly evaluated in the present study, this explanation is consistent with previous reports and further supports the need to develop alternative control strategies that reduce reliance on conventional synthetic insecticides.

In addition to its insecticidal activity, Rosmarinic acid possesses well-documented antioxidant and antimicrobial properties (Petersen and Simmonds, 2003). These biological activities may contribute to limiting secondary microbial infections and promoting tissue recovery following larval damage. Although these mechanisms were not investigated in the present study, they may partially explain the favorable field performance of Rosmarinic acid and warrant further investigation under commercial production conditions.

Table 4. Effect of Deltamethrin and Rosmarinic acid injected into date palm trunks on the number of trees recovering from red palm weevil infestation.

Treatment	Concentration (mL L^{-1})	Number of palm recovery	Palm recovery (%) after 30 days
Control (distilled water)	0	0	0.0^{d}
Deltamethrin (Decis® 25 EC)	0.25	13	86.67^{b}
Rosmarinic acid	3	12	80.0^{c}
	4	13	86.67^{b}
	5	14	93.33^{a}

*Values having the same letter(s) within the column are not significantly different (Fisher's LSD test, $\alpha = 0.05$).

Residue Analysis of Rosmarinic Acid and Deltamethrin in frond bases and date palm fruits

Residue analysis was conducted using palm frond bases collected one month after trunk injection and date fruits harvested at the Bisr (early ripening) and Tamr (fully ripe) stages two months after treatment. No detectable residues of Rosmarinic acid were found in any of the analyzed tissues collected from Rosmarinic acid-treated palms. Likewise, no pesticide residues were detected in samples obtained from the water-injected control. In contrast, residues of the reference insecticide Deltamethrin were detected in all analyzed tissues from treated palms, with mean concentrations of 0.55 mg kg^{-1} in palm frond bases, 0.27 mg kg^{-1} in Bisr fruits, and 0.15 mg kg^{-1} in Tamr fruits (Table 5).

These findings indicate clear differences in the persistence of the two compounds following trunk injection. Under the sampling conditions of the present study, Rosmarinic acid declined to concentrations below the analytical detection limit within one month in palm frond bases and within two months in date fruits, whereas measurable Deltamethrin residues remained detectable in both vegetative and reproductive tissues. This behavior is consistent with the reported fate of many plant-derived phenolic compounds, which are readily metabolized by endogenous plant enzymes and soil microorganisms into naturally occurring metabolites, resulting in relatively low environmental persistence (Isman, 2020; Lengai et al., 2020). Consequently, botanical pesticides generally exhibit shorter persistence and lower residue burdens than many conventional synthetic insecticides, including pyrethroids (Isman, 2020).

Although the absence of detectable Rosmarinic acid residues suggests a low potential for residue persistence under the conditions evaluated in the present study, these findings should be interpreted within the limits of the experimental design and the analytical detection method employed. Residue dissipation may vary according to formulation, application rate, environmental conditions, and plant physiological status. Therefore, additional studies investigating residue dissipation kinetics, metabolite identification, and multi-location field validation are required to comprehensively characterize the environmental fate and food safety of Rosmarinic acid under commercial production conditions. Nevertheless, the present results indicate that

Rosmarinic acid exhibits a favorable residue profile compared with the reference synthetic insecticide Deltamethrin, supporting its potential as a botanical insecticide for integration into sustainable integrated pest management (IPM) programs.

Table 5. Rosmarinic Acid and Deltamethrin residues in frond bases and fruits (Bisr and Tamr) of injected date palms.

Treatment	Concentration (mL L^{-1})	Residue concentration (mg kg^{-1})		
		Palm frond bases	Bisr (early ripening)	Tamr (fully ripe)
Control (distilled water)	0	NO	NO	NO
Deltamethrin (Decis® 25 EC)	0.25	0.55	0.27	0.15
Rosmarinic acid	3	NO	NO	NO
	4	NO	NO	NO
	5	NO	NO	NO

Conclusions:

Rosmarinic acid was effectively extracted from *O. vulgare* and *M. officinalis*, which exhibited the highest yields. Laboratory and field evaluations demonstrated strong insecticidal activity of Rosmarinic acid against *R. ferrugineus*, with the highest concentration providing efficacy comparable to or exceeding that of Deltamethrin. The fourth larval instar was the most susceptible developmental stage (LC_{50} = 2.041 mL L^{-1}). Rosmarinic acid significantly impaired larval growth and nutritional performance and modulated the expression of detoxification-related genes, particularly GST and Cytochrome P450, indicating disruption of the insect's metabolic defense mechanisms. Field application resulted in 93.33% recovery of infested date palms. Moreover, residue analysis revealed no detectable Rosmarinic acid residues in palm frond bases one month after trunk injection or in Bisr and Tamr fruits two months after treatment, whereas Deltamethrin residues remained detectable, confirming the superior environmental compatibility and food safety profile of Rosmarinic acid. Collectively, these findings demonstrate that Rosmarinic acid is a promising botanical insecticide and support its future commercial development as an eco-friendly component of integrated management programs against the red palm weevil.

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حمض الروزمارينيك كمبيد حيوي واعد ضد سوسة النخيل الحمراء في نخيل التمر

حمض الروزمارينيك كمبيد حيوي واعد لمكافحة سوسة النخيل الحمراء (*Rhynchophorus ferrugineus*) في نخيل التمر

إبراهيم الدسوقي عرفات

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الملخص:

تُعد سوسة النخيل الحمراء (*Rhynchophorus ferrugineus* Olivier) من أخطر الآفات التي تهدد زراعة نخيل التمر (*Phoenix dactylifera* L.) على مستوى العالم، لما تسببه من خسائر اقتصادية كبيرة وتأثيرات سلبية على استدامة الإنتاج. وقد أدى الاعتماد المكثف على المبيدات الكيميائية إلى ظهور سلالات مقاومة، إضافة إلى زيادة مخاطر التلوث البيئي وبقايا المبيدات في الأغذية، مما يستدعي البحث عن بدائل نباتية آمنة وفعالة ضمن برامج المكافحة المتكاملة للآفات. هدفت هذه الدراسة إلى تقييم الكفاءة الإبادية لحمض الروزمارينيك، وهو مركب فينولي طبيعي مشتق من النباتات، ضد سوسة النخيل الحمراء تحت الظروف المعملية والحقلية. أُجريت اختبارات السمية باستخدام الغذاء الصناعي المحتوي على تراكيز مختلفة من حمض الروزمارينيك، مع تقدير قيم LC_{50}، ودراسة التأثيرات الفسيولوجية من خلال مؤشرات كفاءة تحويل الغذاء المأكول (ECI) والمهضوم (ECD). كما تم تقييم آلية التأثير الجزيئية بقياس مستوى التعبير الجيني لإنزيمات إزالة السمية، وهي السيتوكروم P450، وجلوتاثيون إس-ترانسفيراز (GST)، والإستريزات العامة. ونُفذت التجارب الحقلية خلال عامي 2022–2023 في بلطيم بمحافظة كفر الشيخ باستخدام تقنية الحقن في جذع النخيل بتركيزات 3 و4 و5 مل/لتر، مع استخدام الدلتامثرين (0.25 مل/لتر) كمبيد مرجعي. وتم تقييم كفاءة المعاملات من خلال الفحص الإتلافي، وجهاز Palmear® للكشف الصوتي المبكر، وتحليل متبقيات المبيدات في قواعد السعف والثمار. أظهرت النتائج علاقة واضحة بين الجرعة والاستجابة، حيث بلغت قيم LC_{50} نحو 2.041 و2.230 و2.575 مل/لتر لليرقات في العمرين الرابع والثامن والحشرات الكاملة على التوالي. كما أدى حمض الروزمارينيك إلى خفض كفاءة الاستفادة من الغذاء وتثبيط واضح للتعبير الجيني لإنزيمات إزالة السمية، مما يشير إلى آلية تأثير متعددة الأهداف. وحقق التركيز 5 مل/لتر أعلى معدل تعافٍ للأشجار (93.33%) مقارنة بكلٍ من تركيز 4 مل/لتر والدلتامثرين (86.67%). ولم تُسجل أي متبقيات لحمض الروزمارينيك في قواعد السعف أو الثمار، بينما استمرت متبقيات الدلتامثرين في الظهور، مما يؤكد التوافق البيئي العالي وسلامة الغذاء المرتبطة باستخدام

حمض الروزمارينيك، ويدعم إمكاناته كمبيد نباتي مستدام ضمن برامج المكافحة المتكاملة لسوسة النخيل الحمراء.

الكلمات المفتاحية: حمض الروزمارينيك، سوسة النخيل الحمراء، *Rhynchophorus ferrugineus*، نخيل التمر، الإدارة المستدامة للآفات.