UNIVERSIDADE FEDERAL DE UBERLÂNDIA
INSTITUTO DE CIÊNCIAS AGRÁRIAS
PROGRAMA DE PÓS-GRADUAÇÃO EM AGRONOMIA

ANA LUISA ALVES RIBEIRO

GENOTYPIC AND ENVIRONMENTAL EFFECTS ON MORPHOAGRONOMIC PERFORMANCE IN TOMATO HYBRIDS DERIVED FROM DWARF MALE PARENTAL LINES

Uberlândia
2026

ANA LUISA ALVES RIBEIRO

GENOTYPIC AND ENVIRONMENTAL EFFECTS ON MORPHOAGRONOMIC PERFORMANCE IN TOMATO HYBRIDS DERIVED FROM DWARF MALE PARENTAL LINES

Tese apresentada à Universidade Federal de Uberlândia, como parte das exigências do Programa de Pós-graduação em Agronomia – Doutorado, área de concentração em Produção Vegetal, para a obtenção do título de "Doutora".

Orientador: Prof. Dr. Gabriel Mascarenhas Maciel

Coorientador: Profª. Drª. Ana Carolina Silva Siquieroli

Uberlândia

2026

ANA LUISA ALVES RIBEIRO

GENOTYPIC AND ENVIRONMENTAL EFFECTS ON MORPHOAGRONOMIC PERFORMANCE IN TOMATO HYBRIDS DERIVED FROM DWARF MALE PARENTAL LINES

Tese apresentada à Universidade Federal de Uberlândia, como parte das exigências do Programa de Pós-graduação em Agronomia – Doutorado, área de concentração em Produção Vegetal, para a obtenção do título de "Doutora".

Uberlândia, 26 de fevereiro de 2026

Banca Examinadora:

Prof. Dr. Gabriel Mascarenhas Maciel- UFU (Orientador)

Prof[a]. Dr[a]. Renata Castoldi – UFU

Prof. Dr. Amilton Ferreira da Silva - UFSJ

Dr. Danilo Araújo Gomes - EPAMIG

Dr[a] Joicy Vitória Miranda Peixoto - IFGOIANO

Dados Internacionais de Catalogação na Publicação (CIP)
Sistema de Bibliotecas da UFU, MG, Brasil.

R484g
2026

Ribeiro, Ana Luisa Alves, 1997-
Genotypic and environmental effects on morphoagronomic performance in tomato hybrids derived from dwarf male parental lines [recurso eletrônico] / Ana Luisa Alves Ribeiro. - 2026.

Orientador: Gabriel Mascarenhas Maciel.
Coorientadora: Ana Carolina Silva Siquieroli.
Tese (Doutorado) - Universidade Federal de Uberlândia, Programa de Pós-graduação em Agronomia.
Modo de acesso: Internet.
Disponível em: http://doi.org/10.14393/ufu.te.2026.10004
Inclui bibliografia.
Inclui ilustrações.

1. Agronomia. I. Maciel, Gabriel Mascarenhas, 1982-, (Orient.). II. Siquieroli, Ana Carolina Silva, 1982-, (Coorient.). III. Universidade Federal de Uberlândia. Programa de Pós-graduação em Agronomia. IV. Título.

CDU: 631

Nelson Marcos Ferreira
Bibliotecário(a)-Documentalista - CRB-6/3074

UNIVERSIDADE FEDERAL DE UBERLÂNDIA
Secretaria da Coordenação do Programa de Pós-Graduação em Agronomia
Rodovia BR 050, Km 78, Bloco 1CCG, Sala 206 - Bairro Glória, Uberlândia-MG, CEP 38400-902
Telefone: (34) 2512-6715/6716 - www.ppgagro.iciag.ufu.br - posagro@ufu.br

ATA DE DEFESA - PÓS-GRADUAÇÃO

<table>
<tr><td>Programa de Pós-Graduação em:</td><td colspan="5">Agronomia</td></tr>
<tr><td>Defesa de:</td><td colspan="5">Tese, 005/2026, PPGAGRO</td></tr>
<tr><td>Data:</td><td>Vinte e seis de fevereiro de dois mil e vinte e seis</td><td>Hora de início:</td><td>13:30</td><td>Hora de encerramento:</td><td>17:25</td></tr>
<tr><td>Matrícula do Discente:</td><td colspan="5">12213AGR001</td></tr>
<tr><td>Nome do Discente:</td><td colspan="5">Ana Luisa Alves Ribeiro</td></tr>
<tr><td>Título do Trabalho:</td><td colspan="5">GENOTYPIC AND ENVIRONMENTAL EFFECTS ON MORPHOAGRONOMIC PERFORMANCE IN TOMATO HYBRIDS DERIVED FROM DWARF MALE PARENTAL LINES</td></tr>
<tr><td>Área de concentração:</td><td colspan="5">Produção Vegetal</td></tr>
<tr><td>Linha de pesquisa:</td><td colspan="5">Melhoramento de Plantas</td></tr>
</table>

Reuniu-se por videoconferência, a Banca Examinadora, designada pelo Colegiado do Programa de Pós-graduação em Agronomia, assim composta: Professores Doutores: Renata Castoldi - UFU; Joicy Vitória Miranda Peixoto - IF-Goiano, Amilton Ferreira da Silva - UFSJ; Danilo Araújo Gomes - Empresa Brasileira de Pesquisa Agropecuária de Minas Gerais; Gabriel Mascarenhas Maciel - UFSJ orientador(a) do(a) candidato(a).

Iniciando os trabalhos o(a) presidente da mesa, Dr. Gabriel Mascarenhas Maciel, apresentou a Comissão Examinadora e o(a) candidato(a), agradeceu a presença do público, e concedeu ao(à) Discente a palavra para a exposição do seu trabalho. A duração da apresentação do(a) Discente e o tempo de arguição e resposta foram conforme as normas do Programa.

A seguir o(a) senhor(a) presidente concedeu a palavra, pela ordem sucessivamente, aos examinadores, que passaram a arguir o(a) candidato(a). Ultimada a arguição, que se desenvolveu dentro dos termos regimentais, a Banca, em sessão secreta, atribuiu o resultado final, considerando o(a) candidato(a):

Aprovada.

Essa tese possui mérito para ser indicada como destaque do Programa?   (X) SIM
NÃO (   )

Esta defesa faz parte dos requisitos necessários à obtenção do títub de Doutor.

O competente diploma será expedido após cumprimento dos demais requisitos, conforme as normas do Programa, a legislação pertinente e a regulamentação interna da UFU.

Nada mais havendo a tratar foram encerrados os trabalhos. Foi lavrada a presente ata que após lida e achada conforme foi assinada pela Banca Examinadora.

Documento assinado eletronicamente por **Renata Castoldi**, **Professor(a) do Magistério Superior**, em 26/02/2026, às 17:30, conforme horário oficial de Brasília, com fundamento no art. 6º, § 1º, do Decreto nº 8.539, de 8 de outubro de 2015.

Documento assinado eletronicamente por **Gabriel Mascarenhas Maciel**, **Usuário Externo**, em 26/02/2026, às 18:05, conforme horário oficial de Brasília, com fundamento no art. 6º, § 1º, do Decreto nº 8.539, de 8 de outubro de 2015.

Documento assinado eletronicamente por **Amilton Ferreira da Silva**, **Usuário Externo**, em 26/02/2026, às 20:54, conforme horário oficial de Brasília, com fundamento no art. 6º, § 1º, do Decreto nº 8.539, de 8 de outubro de 2015.

Documento assinado eletronicamente por **Danilo Araújo Gomes**, **Usuário Externo**, em 26/02/2026, às 22:23, conforme horário oficial de Brasília, com fundamento no art. 6º, § 1º, do Decreto nº 8.539, de 8 de outubro de 2015.

Documento assinado eletronicamente por **Joicy Vitória Miranda Peixoto**, **Usuário Externo**, em 27/02/2026, às 09:06, conforme horário oficial de Brasília, com fundamento no art. 6º, § 1º, do Decreto nº 8.539, de 8 de outubro de 2015.

A autenticidade deste documento pode ser conferida no site https://www.sei.ufu.br/sei/controlador_externo.php?acao=documento_conferir&id_orgao_acesso_externo=0, informando o código verificador **7087980** e o código CRC **3E3F20C5**.

Referência: Processo nº 23117.011312/2026-84 SEI nº 7087980

AGRADECIMENTOS

Agradeço a Deus, por me dar força, sabedoria e coragem para concluir esta etapa tão importante da minha vida.

Aos meus pais, por todo amor, apoio e incentivo durante toda a minha trajetória. Obrigada por sempre acreditarem em mim e por estarem ao meu lado em todos os momentos.

Ao meu noivo, pelo amor, companheirismo, paciência e apoio durante esta caminhada. Obrigada por compreender minhas ausências e por tornar os momentos difíceis mais leves.

Aos meus familiares e amigos, pelo carinho, incentivo e por todos os momentos compartilhados.

Ao meu orientador, professor Gabriel Mascarenhas Maciel, pela oportunidade, orientação, confiança e por todos os ensinamentos que contribuíram para minha formação.

À minha coorientadora, professora Ana Carolina Silva Siquieroli, pela atenção, disponibilidade e importantes contribuições para o desenvolvimento deste trabalho.

Aos integrantes do Grupo de Estudos em Melhoramento Genético de Hortaliças — GEN-HORT, pela amizade, ajuda, colaboração e pelos conhecimentos compartilhados ao longo desta pesquisa.

À Universidade Federal de Uberlândia (UFU), pela oportunidade de realizar minha formação e pela estrutura disponibilizada para o desenvolvimento deste trabalho.

À Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), pela concessão da bolsa de estudos, fundamental para a realização desta pesquisa.

O presente trabalho foi realizado com apoio da Coordenação de Aperfeiçoamento de Pessoal de Nível Superior Brasil (CAPES) Código de Financiamento 001.

Por fim, agradeço a todos que, de alguma forma, contribuíram para a conclusão desta etapa. Minha sincera gratidão.

RESUMO

RIBEIRO, Ana Luisa Alves. **Genotypic and environmental effects on morphoagronomic performance in tomato hybrids derived from dwarf male parental lines**. 2026, 59 f. Tese (Doutorado em Agronomia/Produção Vegetal) – Universidade Federal de Uberlândia, Minas Gerais, Brasil.

A busca por híbridos de tomateiro mais produtivos e resilientes frente às condições adversas de cultivo tem se intensificado diante do cenário climático atual. A obtenção de híbridos a partir de linhagens de tomateiro anão tem se consolidado como uma estratégia eficiente para o incremento da produtividade por meio de modificações na arquitetura da planta. Apesar dos avanços alcançados, ainda é incipiente o entendimento sobre o uso de linhagens anãs como parentais masculino para a obtenção de híbridos do tipo Santa Cruz. Assim, o objetivo deste trabalho é obter um banco de germoplasma de tomateiro anão do tipo Santa Cruz por meio de sucessivos retrocruzamentos, e desenvolver híbridos compactos, produtivos e resilientes provenientes do cruzamento entre linhagens normais *versus* linhagens anãs. O trabalho foi desenvolvido em duas etapas: caracterizar as populações de tomateiro anão obtidas após três retrocruzamentos, visando observar os incrementos obtidos em cada geração. Na segunda etapa, foram desenvolvidos os híbridos de tomateiro do tipo Santa Cruz provenientes do cruzamento entre linhagens de porte normal *versus* linhagens anãs e avaliados em campo e cultivo protegido quanto aos efeitos genotípicos e ambientais. Ambos os experimentos foram conduzidos em casa de vegetação na Estação Experimental de Hortaliças da Universidade Federal de Uberlândia (UFU), Monte Carmelo-MG. No primeiro experimento, as populações de tomateiro anão mostraram melhorias significativas para os caracteres agronômicos após três retrocruzamentos. As plantas anãs apresentaram elevados teores de acilaçúcares nas folhas e um aumento expressivo de aminoácidos, especialmente L-serina e glicina. No segundo experimento, os híbridos do tipo Santa Cruz apresentaram alterações estruturais marcantes, como redução no comprimento de internódios e maior número de pencas por metro linear, tanto no campo quanto em cultivo protegido. Além disso, os híbridos produziram frutos biofortificados e apresentaram elevadores teores de acilaçúcares,

Palavras-chave: *Solanum lycopersicum* L.; nanismo; retrocruzamentos.

ABSTRACT

RIBEIRO, Ana Luisa Alves. **Genotypic and environmental effects on morphoagronomic performance in tomato hybrids derived from dwarf male parental lines**. 2026, 59 f. Thesis (PhD in Agronomy/Plant Production) – Federal University from Uberlândia, Minas Gerais, Brasil.

The search for more productive and resilient tomato hybrids in the face of adverse growing conditions has intensified in the current climate scenario. The development of hybrids from dwarf tomato lines has become an efficient strategy to increase productivity through changes in plant architecture. Despite the advances achieved, the understanding of the use of dwarf lineages as male parents for obtaining Santa Cruz-type hybrids is still limited. Thus, the objective of this work is to obtain a germplasm bank of Santa Cruz-type dwarf tomato plants through successive backcrosses, and to develop compact, productive, and resilient hybrids from the crosses between normal lineages and dwarf lineages. The work was developed in two stages. The first stage consisted of characterizing dwarf tomato populations obtained after three backcrosses, aiming to observe the improvements achieved in each generation. In the second stage, Santa Cruz-type tomato hybrids derived from crosses between normal-sized lineages and dwarf lines were developed and evaluated under field and protected cultivation conditions regarding genotypic and environmental effects. Both experiments were conducted at the Vegetable Experimental Station of the Federal University of Uberlândia (UFU), Monte Carmelo, Minas Gerais, Brazil. In the first experiment, the dwarf tomato populations showed significant improvements in agronomic traits after three backcrosses. The dwarf plants showed high levels of acylsugars in the leaves and a significant increase in amino acids, especially L-serine and glycine. In the second experiment, the Santa Cruz-type hybrids showed marked structural changes, such as reduction internode length and a greater number of bunches per linear meter, both in the field and under protected cultivation. In addition, the hybrids produced biofortified fruits and found high levels of acylsugars.

Palavras-chave: *Solanum lycopersicum* L.; dwarf; backcrosses.

SUMÁRIO

1 INTRODUÇÃO GERAL

As condições climáticas atuais têm comprometido a produtividade do tomateiro (*Solanum lycopersicum* L.) em diversos países. O Brasil ocupa a oitava posição entre os maiores produtores mundiais (Blain *et al*., 2023; Pereira *et al*., 2018; Kürklü *et al*., 2025). No país, o cultivo ocorre predominantemente em campo e apresenta suscetibilidade aos estresses bióticos e abióticos (Flemer *et al*., 2022), o que aumenta a complexidade do cultivo e resulta em elevados riscos produtivos e custos associados ao manejo e aos recursos operacionais (Ilie *et al*., 2025). Além disso, as cultivares comerciais disponíveis atualmente apresentam limitações frente aos fatores desfavoráveis que afetam o desenvolvimento da cultura (Chaughary *et al*., 2019). Diante desse cenário, torna-se essencial desenvolver estratégias que aumentem a produtividade e a sustentabilidade nos sistemas de cultivo (Aladele *et al*., 2025).

O incremento da produtividade em tomateiro tem sido favorecido por meio de técnicas agronômicas como, manejo da adubação (Jing *et al*., 2025), ajustes no espaçamento (Amare *et al*., 2020) e controle da lâmina de irrigação (Ayankojo *et al*., 2021). Porém, são escassos os estudos que abordam o aumento da produtividade em tomateiro do tipo Santa Cruz, por meio de alterações na arquitetura da planta envolvendo genes de nanismo. Finzi *et al*. (2017) observaram incremento na produtividade em híbridos de minitomate provenientes do uso de um parental masculino anão. Apesar do porte normal, os híbridos apresentaram arquitetura modificada, com redução no comprimento dos internódios e maior número de pencas por metro linear.

O tomateiro anão UFU MC TOM1 (*S. lycopersicum* L.), utilizado nesse estudo como parental masculino, apresenta frutos do tipo minitomate e tem se destacado como um material promissor por reunir características de interesse. Dentre essas características, destacam-se a herança genética do nanismo (Maciel *et al*., 2015), biofortificação dos frutos (Oliveira *et al*., 2021), presença de acilaçúcares associada à resistência a pragas (Maciel *et al*., 2024), resistência a bactérias (Jacinto *et al*., 2024, Jacinto et al., 2025) e maior concentração de compostos secundários associados à resposta aos estresses bióticos e abióticos (Mattos *et al*., 2025).

As pesquisas realizadas com tomateiro anão UFU MC TOM1 abriram caminhos para a obtenção de linhagens de tomateiro anão com frutos adaptados para os diferentes segmentos do mercado. A partir do genitor doador UFU MC TOM1, foi desenvolvido um germoplasma de linhagens de tomateiro anão do tipo salada (Mattos *et al*., 2025; Finzi *et al*., 2022; Finzi *et al*.,

2020) e saladete (Oliveira *et al.*, 2024; Oliveira *et al.*, 2022; Oliveira *et al*., 2021) por meio de três retrocruzamentos. Posteriormente, as linhagens foram utilizadas como parentais masculinos para a obtenção de híbridos de porte normal dos tipos salada (Pereira *et al*., 2024a) e saladete (Pereira *et al.*, 2024b), com incremento na produtividade associado a modificações estruturais na arquitetura da planta.

A condução de sucessivos retrocruzamentos possibilita recuperar, progressivamente, o *background* genético dos genitores recorrentes, mantendo frutos de interesse comercial (Borém e Miranda, 2005). O número de gerações necessárias varia de acordo com os parentais utilizados e a característica de interesse. Gomes *et al.* (2022) e (2023), ao avaliarem as populações do tipo Santa Cruz provenientes do genitor doador UFU MC TOM1 relataram avanços no tamanho dos frutos após dois retrocruzamentos. Apesar dos avanços obtidos, ainda é necessário confirmar se o terceiro retrocruzamento promove ganhos adicionais, aumentando a frequência de alelos efetivos favoráveis ao tamanho e ao padrão comercial dos frutos. A obtenção de um germoplasma de tomateiro anão do tipo Santa Cruz por meio de sucessivos retrocruzamentos representa uma estratégia promissora para consolidar linhagens com desempenho agronômico superior e de maior resiliência.

Embora já existam evidências em outros segmentos, torna-se fundamental avaliar o desempenho das linhagens de tomateiro anão em cada geração de retrocruzamento, além de sua contribuição como parental masculino para a obtenção de híbridos do tipo Santa Cruz. Espera-se que as características presentes nas linhagens de tomateiro anão sejam expressas e transmitidas aos híbridos. Além disso, a avaliação da interação genótipo *x* ambiente contribui para o melhor entendimento da adaptabilidade e estabilidade dos híbridos frente às variações de cultivo, visando maximizar os ganhos genéticos e aprimorar a eficiência de seleção (Pereira *et al*., 2025). Nesse sentido, são necessários estudos que permitam compreender o comportamento dos híbridos, analisando, em conjunto, a arquitetura da planta, o desempenho agronômico e a resiliência frente às condições adversas de cultivo.

2 OBJETIVO GERAL

Objetivou-se com este trabalho obter um banco de germoplasma de tomateiro anão do tipo Santa Cruz por meio de sucessivos retrocruzamentos, e desenvolver híbridos compactos, produtivos e resilientes provenientes do cruzamento entre linhagens de porte normal *versus* linhagens anãs.

2.1 Objetivos específicos

Os objetivos específicos elencados são:

Avaliar a dissimilaridade genética, o potencial agronômico e os teores de acilaçúcares das linhagens de tomateiro anão do tipo Santa Cruz após cada retrocruzamento.

Avaliar o potencial do uso de linhagens de tomateiro anão como parentais masculinos para a obtenção de híbridos compactos, produtivos e resilientes.

Verificar a transmissão de metabólitos associados à tolerância aos estresses bióticos e abióticos das linhagens de tomateiro anão para os híbridos obtidos.

Propor uma tecnologia adaptada às condições de campo e cultivo protegido, capaz de maximizar a produtividade e promover práticas sustentáveis de cultivo.

REFERÊNCIAS

ALADELE, A. *et al*. Genomic approaches to enhance biotic stress tolerance in horticultural crops. *In:* RAI, A. C. *et al* (ed.). *Biotic Stress Tolerance in Horticultural Crops.* Cambridge: Woodhead Publishing, 2025. p.119-140. DOI:10.1016/B978-0-443-27324-7.00008-2 Acesso em: 20 jun. 2025.

.KUMAR, A.; SANTOYO, G.; AZEVEDO, L. C. B. de (org.). *Biotic Stress Tolerance in Horticultural Crops*. [*S.l.*]*:* Woodhead Publishing, 2025. p.119-140. DOI: http://dx.doi.org/10.1016/B978-0-443-27324-7.00008-2. Acesso em: 28 jan 2026.

AMARE, G.; GEBREMEDHIN, H. Efeito do espaçamento das plantas sobre o rendimento e os componentes de rendimento do tomate (Solanum lycopersicum L.) em Shewarobit, Etiópia Central. *Scientifica*, Cairo, v. 20, p. 8357237, 2020. DOI: http://dx.doi.org/10.1155/2020/8357237. Acesso em: 28 jan 2026.

AYANKOJO, I.; MORGAN, K. Optimizing tomato growth and productivity using nitrogen and irrigation application timing. *Agronomy*, v. 11, p. 1968, 2021. DOI: http://dx.doi.org/10.3390/agronomy11101968. Acesso em: 28 jan 2026.

BLAIN, G.; SOBIERAJSKI, G.; LOPES MARTINS, L. Elevações na frequência de ocorrência de secas meteorológicas no Estado de São Paulo sob condições de mudanças climáticas. *Derbyana*, São Paulo, v. 44, 2023. DOI: http://dx.doi.org/10.14295/derbv44.789. Acesso em: 28 jan 2026.

BORÉM, A.; MIRANDA, G. V. *Melhoramento de plantas*. 4. ed. Viçosa, MG: Editora UFV, 2005. 546 p.

CHAUDHARY, J. *et al*. Avanços nas abordagens ômicas para tolerância ao estresse abiótico em tomate. *Biology*, v. 8, p. 90, 2019. DOI: http://dx.doi.org/10.3390/biology8040090. Acesso em: 28 jan. 2026.

FINZI, R. R. *et al*. Agronomic performance of mini-tomato hybrids from dwarf lines. *Ciência e Agrotecnologia*, v. 41, p. 15-21, 2017. DOI: http://dx.doi.org/10.1590/1413-70542017411021416. Acesso em: 28 jan. 2026.

FINZI, R. R. *et al.* Agronomic potential of BC1F2 dwarf round tomato populations. *Ciência e Agrotecnologia*, v. 44, p. 1-8, 2020. DOI: http://dx.doi.org/10.1590/1413-7054202044028819. Acesso em: 28 jan. 2026.

FINZI, R. R. *et al.* Agronomic potential, pest resistance, and fruit quality in BC1F3 dwarf round tomato populations. *Comunicata Scientiae*, v. 13, p. 1-8, 2022. DOI: http://dx.doi.org/10.14295/cs.v13.3759. Acesso em: 28 jan. 2026.

FLEMER, B. *et al.* Biotic and abiotic stress factors induce microbiome shifts and enrichment of distinct beneficial bacteria in tomato roots. *Phytobiomes Journal*, St. Paul, v. 6, n. 4, p. 276-289, 2022. DOI: http://dx.doi.org/10.1094/PBIOMES-10-21-0067-R. Acesso em: 28 jan 2026.

GOMES, D. A. *et al*. Dwarf tomato plants allow for managing agronomic yield gains with fruit quality and pest resistance through backcrossing. *Agronomy*, Basel, v. 12, p. 3087, 2022. DOI: http://dx.doi.org/10.3390/agronomy12123087. Acesso em: 29 jan. 2026.

GOMES, D. A. *et al*. Agronomic potential of BC1F2 populations of Santa Cruz type dwarf tomato plant. Acta Scientiarum. *Agronomy*, v. 45, p. 1-9, 2023. DOI: http://dx.doi.org/10.1590/1678-4499.20210046. Acesso em: 29 jan. 2026.

ILIE, D. M. *et al.* Avaliando a vulnerabilidade econômica dos produtores de tomate romenos a eventos climáticos extremos. *Sustainability*, Basel, v. 17, n. 19, p. 8754, 2025. DOI: http://dx.doi.org/10.3390/su17198754. Acesso em: 29 jan. 2026.

JACINTO, A. C. P. *et al.* Reaction of tomato lineages and hybrids to *Xanthomonas euvesicatoria* pv. *perforans*. *Agronomy*, Basel, v. 14, p. 1211, 2024. DOI: http://dx.doi.org/10.3390/agronomy14061211. Acesso em: 29 jan. 2026.

JACINTO, A. C. P. *et al.* Inactivated bacterial suspension as an attenuator for the control of bacterial spot (*Xanthomonas euvesicatoria* pv. *perforans*) in dwarf tomato plants. *Tropical Plant Pathology*, v. 50, p. 40, 2025. DOI: http://dx.doi.org/10.1007/s40858-025-00727-y. Acesso em: 29 jan. 2026.

JING, L. *et al.* A proporção ótima N:P:K de fertilização melhora a produção e a qualidade do tomate sob irrigação em água salobra. *Plants*, Basel, v. 14, n. 16, p. 2496, 2025. DOI: http://dx.doi.org/10.3390/plants14162496. Acesso em: 29 jan. 2026.

KÜRKLÜ, A.; PEARSON, S.; FELEK, T. Climate change impacts on tomato production in high-tech soilless greenhouses in Türkiye. *BMC Plant Biology*, v. 25, p. 339, 2025. DOI: http://dx.doi.org/10.1186/s12870-025-06307-. Acesso em: 29 jan. 2026.

MACIEL, G. M.; SILVA, E. C.; FERNANDES, M. A. R. Ocorrência de nanismo em planta de tomateiro do tipo grape. *Revista Caatinga*, v.28, p. 259-264, 2015. DOI: http://dx.doi.org/10.1590/1983-21252015v28n429rc. Acesso em: 29 jan. 2026.

MACIEL, G. M. *et al*. New insights into the use of dwarf tomato plants for pest resistance. *Bragantia*, v. 83, p. 1-9, 2024. DOI: http://dx.doi.org/10.1590/1678-4499.20240066. Acesso em: 29 jan. 2026.

MATTOS, T. P. *et al*. Introgression of dwarfing genes into tomato fruit through backcrossing aiming at salad-type background. *Revista Caatinga*, v. 38, p. 1-10, 2025. DOI: http://dx.doi.org/10.1590/1983-21252025v3812718rc. Acesso em: 29 jan. 2026.

OLIVEIRA, C. S. *et al*. Artificial neural networks and genetic dissimilarity among saladette-type dwarf tomato plant populations. *Food Chemistry*, v. 3, p. 1-8, 2021. DOI: http://dx.doi.org/10.1016/j.fochms.2021.100056. Acesso em: 29 jan. 2026.

OLIVEIRA, C. *et al*. Selection of F2RC1 saladette-type dwarf tomato plant populations for fruit quality and whitefly resistance. *Revista Brasileira de Engenharia Agrícola e Ambiental*,

v. 26, p. 28-35, 2022. DOI: http://dx.doi.org/10.1590/1807-1929/agriambi.v26n1p28-35. Acesso em: 30 jan. 2026.

OLIVEIRA, C. S. *et al*. Saladette-type dwarf tomato introgression lines with agronomic potential, improved fruit quality, and biotic stress tolerance. *Ciência e Agrotecnologia*,v. 48, p. 1-9, 2024. DOI: http://dx.doi.org/10.1590/1413-7054202448002624. Acesso em: 26 jan. 2026.

PEREIRA, V. R. *et al.* Impacts of climate change on drought: changes to drier conditions at the beginning of the crop growing season in southern Brazil. *Bragantia*, Campinas, v. 77, n. 1, p. 201-211, 2018. DOI: http://dx.doi.org/10.1590/1678-4499.201700. Acesso em: 26 jan. 2026.

PEREIRA, L. M. *et al*. Introgression of the Self-Pruning Gene into Dwarf Tomatoes to Obtain Salad-Type Determinate Growth Lines. *Plants*, v. 13, p. 1522, 2024. DOI: http://dx.doi.org/10.3390/plants13111522. Acesso em: 26 jan. 2026.

PEREIRA, L. M. *et al.* Additional advantages for agronomic performance and fruit quality in tomato hybrids of the saladette type derived from a dwarf male parent. *Horticulturae*,v. 10, p. 1145, 2024. DOI: http://dx.doi.org/10.3390/horticulturae10111145. Acesso em: 26 jan. 2026.

PEREIRA, G. R. *et al.* Exploring genotype-by-environment interactions in tropical soybean multi-environment trials. *Euphytica*, v. 221, p. 1-17, 2025. DOI: http://dx.doi.org/10.1007/s10681-025-03576-7. Acesso em: 26 jan. 2026.

CHAPTER 1

GENETIC VARIATION, AGRONOMIC POTENTIAL, AND ACYLSUGAR CONTENT IN SANTA CRUZ DWARF TOMATO AFTER BACKCROSSING [1]

[1] Artigo publicado na Revista Crop Breeding and Applied Biotechnology
Ribeiro, A. L. A.; Maciel, G. M.; Siquieroli, A. C. S.; Pereira, L. M.; Silva, N. C. Q.; Oliveira, C. S. de.; Pinto, F. G. Genetic variation, agronomic potential, and acylsugar content in Santa Cruz dwarf tomato after backcrossings. Crop Breeding and Applied Biotechnology 2024 , e48722438. https://doi.org/10.1590/1984-70332024v24n3a33

3 GENETIC VARIATION, AGRONOMIC POTENTIAL, AND ACYLSUGAR CONTENT IN SANTA CRUZ DWARF TOMATO AFTER BACKCROSSINGS

ABSTRACT

Tomato cultivation is globally significant, demanding enhanced yields and biotic stress resilience for sustainability. Dwarf plant utilization in tomato genetic enhancement offers underexplored benefits. Yet, Santa Cruz dwarf tomato germplasm is unavailable. This work evaluated genetic dissimilarity, agronomic potential, and acylsugar content of Santa Cruz dwarf tomato plants across three successive backcrossings. Twelve advanced backcrossing populations (BC) and a commercial control (cv. Kada) were assessed, totaling 15 treatments. Agronomic traits and acylsugar content were measured, and analysis techniques were applied to assess genetic dissimilarity and backcrossing superiority. BC3 populations UFU-Sci#8, UFU-Sci#6, UFU-Sci#5, and UFU-Sci#1 excelled. Dwarf plants predominantly exhibited high leaflet acylsugar levels, suggesting potential for hybrid acquisition with pest resistance. Notably, UFU MC TOM1 (dwarf plant) displayed significant glycine and L-serine presence, associated to various biotic stresses. These findings unveil promising the creation of dwarf Santa Cruz tomato hybrids with a broad spectrum of resistance.

Keywords: *Solanum lycopersicum* L.; biotic stress; metabolomic; dwarf plants; genetic improvement.

3.1 INTRODUCTION

Increased interest in consuming a healthy diet has greatly increased the consumption of vegetables in Brazil and worldwide. Vegetable farming plays an important role in ensuring food security. New strategies are needed to meet the Sustainable Development Goals, particularly to enable the development of new sustainable agricultural technologies using available genetic resources (Maggio *et al*. 2018, Adalja and Lichtenberg, 2018).

The tomato plant (*Solanum lycopersicum* L.) is considered as one of the most important vegetables due of its high nutritional value and high levels of vitamins, minerals, and antioxidants (Flores *et al*. 2017). This plant is also socio-economic relevant in terms of job creation and marketing. In Brazil, the vegetable can be classified as mini tomato, round, beefsteak, saladette and Santa Cruz. Santa Cruz stands out for its high yield potential and post-harvest durability (Alvarenga, 2013).

The tomato production is considered a high-risk activity due of the susceptibility of tomatoes to pests and diseases attacks. Thus, a main challenge for breeders is identifying biofortified and highly productive individuals with broad resistance to pests and diseases (Peixoto *et al*. 2020). Crossbreeding of dwarf tomato plants and mini tomato strains has resulted in the production of compact and promising hybrids (Maciel *et al*. 2015, Finzi *et al*. 2017). To get Santa Cruz tomato hybrids from dwarf tomato populations, it is necessary to have a detailed understanding of these plants.

Backcrossing is used to obtain progenies with high agronomic performance. This technique enables the introgression of a specific characteristic, of the donor parent (Finzi *et al*. 2020, Oliveira *et al*. 2022). After the first backcrossing, dwarf tomato plants of the Santa Cruz type were identified and selected for the propagation of the next generations (Gomes *et al*. 2022, Gomes *et al*. 2023). We obtained hybrid dwarf populations from additional backcrossings and evaluated their agronomic performance and acylsugar levels in the leaves.

The aim of this study was to evaluate genetic dissimilarity, agronomic potential, and acylsugar content of Santa Cruz dwarf tomato plants obtained through three successives backcrossings.

3.2 MATERIAL AND METHODS

3.2.1 Experimental location and genotypes used

The experiment was performed from April 2021 to August 2022 at the Horticultural Experimental Station of the Federal University of Uberlândia (UFU), Monte Carmelo Campus, MG, Brazil (lat 18° 42' 43.19" S, long 47° 29' 55.8", alt 873 m asl). The plants were grown in an arched greenhouse (7 × 21 m) with a ceiling height of 4 m, anti-aphid net side curtains, and a transparent polyethylene cover protective against ultraviolet rays.

Twelve populations of Santa Cruz dwarf tomato plants were evaluated: two populations from the first backcrossing (BC1 = UFU-Sci#11 and UFU-Sci#12), two populations from the second backcrossing (BC2 = UFU-Sci#9 and UFU-Sci#10), eight populations from the third backcrossing (BC3 = UFU-Sci#1, UFU-Sci#2, UFU-Sci#3, UFU-Sci#4, UFU-Sci#5, UFU-Sci#6, UFU-Sci#7, and UFU-Sci#8), donor parent (UFU MC TOM 1), recurrent parent (UFU-TOM-Mother 2) and the commercial control Santa Cruz Kada, resulting 15 populations. The wild accession *Solanum pennellii* were used to examine acylsugar content, variable related to pests resistance (Maluf *et al*. 2010).

The Santa Cruz type dwarf tomato populations belong to the UFU tomato germplasm bank and were obtained after hybridizing a homozygous pre-commercial strain with Santa Cruz type fruit patterns (UFU-TOM-Mother-2) versus the UFU MC TOM1 dwarf variety (Maciel *et al*. 2015). This homozygous dwarf strain (UFU MC TOM1) was used as a donor parent as it expresses the dwarf-bearing phenotype of recessive, monogenic origin, and mini tomato-type fruit (Maciel *et al*. 2015).

The populations of BC1 were obtained by crossing the F1 generation (UFU-TOM-Mother-2 *versus* UFU MC TOM1) *versus* UFU-TOM-Mother-2, followed by self-pollination. BC2 was formed through hybridization of segregating plants selected in BC1 *versus* UFU-TOM-Mother-2 followed by self-fertilization. Subsequently, populations of BC3 were obtained by segregating plants selected in BC2 *versus* UFU-TOM-Mother-2. In the segregating populations of each backcrossing (BC1, BC2, and BC3), normal plants were eliminated, and only dwarf plants were selected, based on previous studies of dwarfism inheritance in tomato plants (Maciel *et al*. 2015, Oliveira *et al*. 2022).

The seeds were sown in polystyrene trays with a commercial coconut fiber substrate. At 40 days after sowing, the dwarf plants were selected and transplanted into 5-L plastic pots. The experiment was conducted in a randomized block design with four replications, totaling 60 plots. Each plot consisted of six plants distributed in double rows with 0.3×0.3 m spacing.

Cultivation was performed as recommended for tomato growing in protected cultivation (Filgueira, 2013). The harvest began 65 days after transplant and was performed weekly, totaling eight crops. For agronomic assessment, the fruits were harvested when they were fully ripe.

3.2.2 Characteristics evaluated

The following characteristics were analyzed in agronomic assessments: fruit shape (cm) (FS): ratio between the transverse and longitudinal diameter, measured using a caliper. Number of locules (fruit locules -1) (NL): number of locules after cutting the fruit horizontally. Flesh thickness (cm) (FT): measurement with a caliper of the length between the skin of the fruit and beginning of the loculus after cutting the fruit horizontally. Mean weight (g) (MW): ratio between the mass and number of fruits in each experimental plot. Number of internodes per linear meter (m) (ITM): ratio between the number of internodes and total plant height.

The acylsugar content (nmol cm2 leaf), was determined at 50 days after transplanting, using a sample of eight leaf disks (equivalent to 4.2 cm2) from in the upper third of each plant in the plot. The extraction and quantification were performed as described by Resende *et al*. (2002) and adapted by Maciel and Silva (2014).

3.2.3 Statistical analyses

Statistical assumptions were checked for normality (Lilliefors test), homogeneity (Oneill-Matheus test) and additivity (Tukey) analyses. The data were analyzed using F test ($p < 0.05$), and means were compared using Scott-Knott test ($p < 0.05$).

Genetic dissimilarity between populations of dwarf plants from the first, second, and third backcrossings was determined from the generalized Mahalanobis (D2) distance matrix. This matrix was represented by a heat map and dendrogram obtained using the maximum and minimum distances with R version 3.6.3 software (R Core Team 2020).

The selection index was calculated using the genotype-ideotype distance only for dwarf populations. To estimate selection gains, 33% of the populations were selected. The selection criterion was based on the magnitude of the genetic distance using an ideotype. The ideal ideotype was defined as the lowest mean ITM and highest means for the other characteristics. Dwarf plant populations were classified according to the Mahalanobis distance (D2) in relation to the ideotype. Those with the smallest distances were considered as more favorable.

The Kohonen's self-organizing map (SOM) was obtained using the unsupervised artificial neural network technique. Different training sessions were performed for each possible combination to select the best architecture. The combination that best represented genetic dissimilarity between the dwarf tomato populations had three rows and two columns (six neurons) with a neighbor radius pattern of 1, architecture referring to 2000 seasons, hexagonal topology, and based on Euclidean distance to form the groups. All analyses were performed using GENES software, integrated with R version 3.6.3 software (R Core Team 2024) and MATLAB (MATLAB 2012).

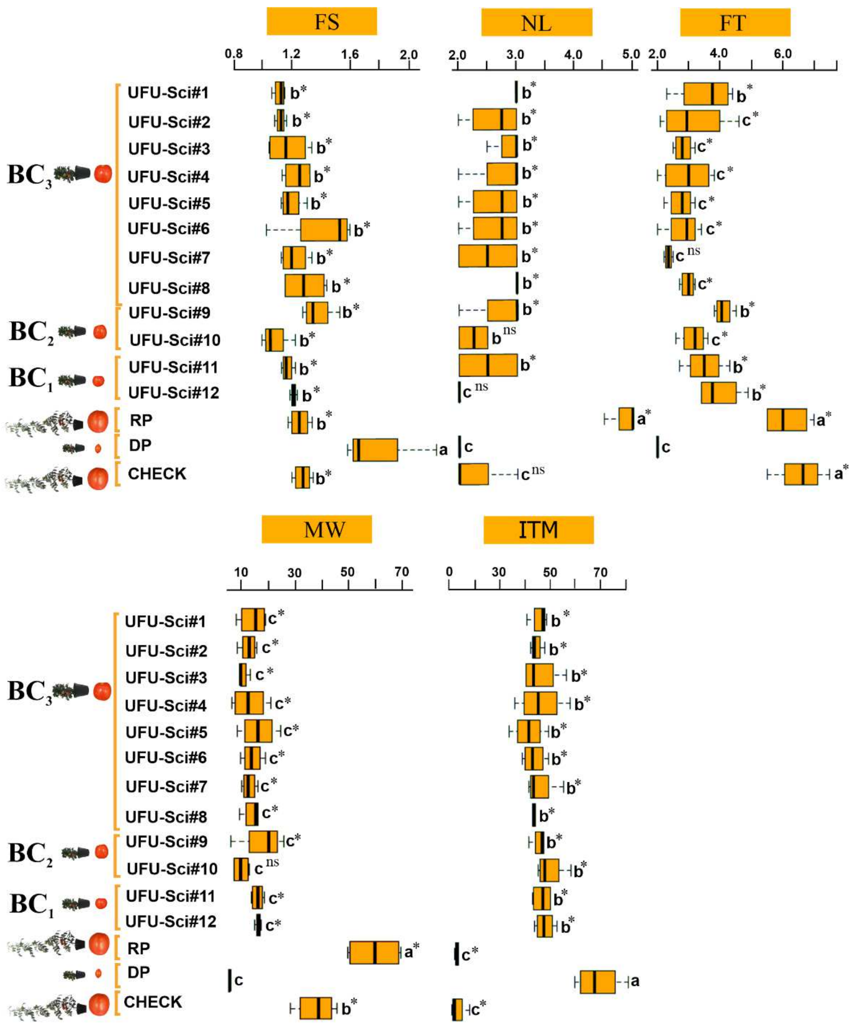
3.2.4 Chromatographic analysis and metabolomic profile

Leaflet samples (n = 6) were collected from the middle portion of the plant and crushed with liquid nitrogen using a mortar and pestle until a fine powder was obtained. The analysis of metabolite by gas chromatography-mass spectrometry (GC-MS) was performed using 100 mg freeze dried. Extraction, derivatization and GC-MS analysis were carried out as described by Lisec *et al*. (2006).

3.3 RESULTS AND DISCUSSION

The genotypes differed in the agronomic characteristics assessed for FS, NL, FT, MW, and ITM (F test, $p < 0.05$) (Figure 1).

Figure 1 - Boxplot comparing the mean values of agronomic characteristics for fruit shape (FS), number of locules (NL), flesh thickness (FT), mean weight (MW), and number of internodes per linear meter (ITM). BC1: first backcrossing, BC2: second backcrossing, BC3: third backcrossing, RP: recurrent parent UFU-TOM-Mother 2, DP: donor parent UFU MC TOM1, Check: Santa Cruz Kada. Means followed by different letters in the column differed in Scott-Knott test at the 0.05 significance level. *Means in the column differed from the dwarf donor parent UFU MC TOM1 in Dunnett's test at the 0.05 probability level.



Source: Created by the author.

The dwarf tomato populations BC1, BC2, and BC3 were similar to the recurrent parent (UFU-TOM-Mother-2) and commercial control Kada, with slightly oblong fruit shapes smaller than < 1.5. The relationship between the transverse and longitudinal diameter of the fruit indicates that the dwarf tomato populations belong to the Santa Cruz type segment. The consumer market determines the preference for FS, and this segment has satisfactory acceptability for fresh consumption (Peixoto *et al*. 2017, Costa *et al*. 2020).

The recurrent parent (UFU-TOM-Mother-2) showed the highest value for NL, with an average of five locules. The fruits of the dwarf donor parent (UFU MC TOM1) had the smallest NL with two locules. The dwarf tomato populations evaluated showed intermediate values that differed from those of the recurrent and donor parents, except for in the UFU-Sci#12 population (Figure 1).

FT and NL strongly influence the fruit quality, with thicker flesh and fewer locules indicating greater firmness (Vieira *et al* 2019). The dwarf tomato populations showed a mean increase of 105% in FT compared to that of the donor parent (UFU MC TOM1), with the populations UFU-Sci#1 from the BC3 generation, UFU-Sci#9 from the BC2 generation, and UFU-Sci#11 and UFU-Sci#12 from the BC1 generation demonstrating the highest mean thickness of 3.75 mm (Figure 1).

In comparison to the donor parent (UFU MC TOM1), the dwarf tomato populations BC1, BC2 and BC3 showed a mean increase of 161.98% in fruit MW. The populations UFU-Sci#5 (BC3), UFU-Sci#9 (BC2), and UFU-Sci#12 (BC1) revealed the highest fruit production, with a MW of 18.28 g. As expected, the recurrent parent (UFU-TOM-Mother-2) and commercial control Kada showed the highest mean values for MW and FT.

For the fruit traits MW, FT, and NL, the dwarf tomato populations obtained through backcrossing were superior to the donor parent (UFU MC TOM1). The increases in BC2 and BC3 demonstrated the effectiveness of the crossing method used in this study. The results agree with those of Gomes *et al*. (2021), who showed that Santa Cruz type dwarf tomato populations revealed significant increases in mean fruit weight and flesh thickness after the first and second backcrossings.

Backcrossing enables the transfer of genes of interest to other parents and confers desirable agronomic characteristics (Finzi *et al*. 2020, Oliveira 2021). In the BC2 and BC3 generations, the populations are expected to contain means of 87.5% and 93.75%, respectively, of the recurrent parent's genome (Borém *et al*. 2021).

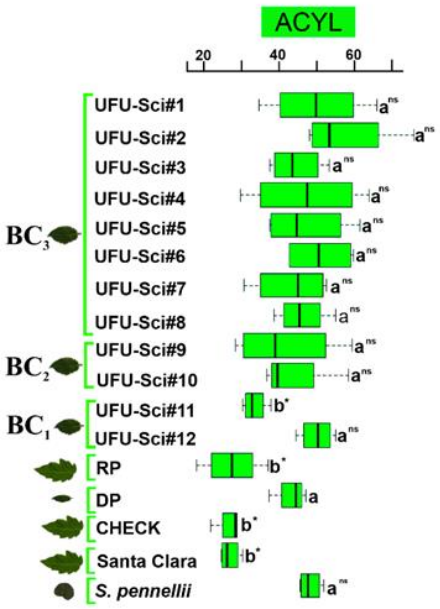
There was no significant difference in the fruit MW between BC1, BC2, and BC3, despite the significant difference between the backcrossed dwarf tomato populations and donor parent (UFU MC TOM1). This result may be related to the fact that the dwarf plant does not have the morphological structure or produce photoassimilates capable of generating the expected increases, thus limiting the increase in fruit MW. Because the fruit MW trait is a quantitative trait (Kouam *et al*. 2018), the third backcrossing can introduce as many effective alleles as possible into future lineages in order to maximize the probability of obtaining productive hybrids.

ITM in tomato plants is directly related to the plant architecture. Mini tomato hybrids from dwarf tomato populations have short internodes and large numbers of bunches per linear meter (Finzi *et al*. 2017). The donor parent (UFU MC TOM1) demonstrated the highest ITM, whereas the dwarf populations revealed higher values in the BC3 generation, highlighting the importance of successive backcrossing. However, as the backcrossing progressed, there was no significant variation was observed in ITM. Thus, hybrids with different backcrossing populations should be obtained to achieve the expected results.

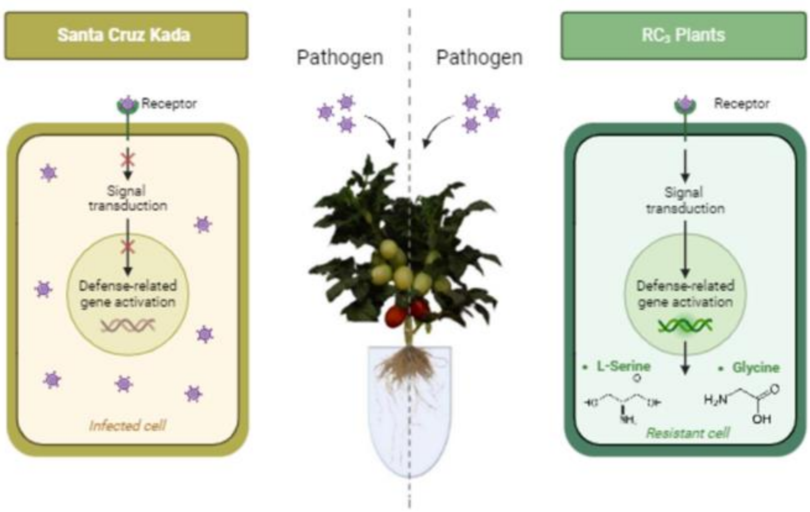
The allelochemical acylsugar is highly correlated with resistance to arthropod pests in tomato plants through antixenosis and antibiosis mechanisms (Marinke *et al.* 2022). There were significant differences in the acylsugar content between the genotypes evaluated (Figure 2A).

Figure 2- AcylSugar Comparison and Pathogen Resistance Enhancement. A. Boxplot comparing the average acylsugar values (ACYL) of the genotypes evaluated. BC1: first backcrossing, BC2: second backcrossing, BC3: third backcrossing, RP: recurrent parent UFU-TOM-Mother 2, DP: donor parent UFU MC TOM1, Check: Santa Cruz Kada. Means followed by different letters in the column differed in Scott-Knott test at the 0.05 significance level. *Means in the column differed from the control dwarf donor line UFU MC TOM1 in Dunnett's test at 0.05 probability. B. Potential enhanced resistance to pathogens in BC3 plants attributed to the elevated levels of glycine and L-serine.

A.



B.



Source: Created by the author.

The average levels of acylsugars in the dwarf tomato populations were 70% higher than those in the commercial control Kada and in the recurrent parent. The results agree with those of Oliveira *et al*. (2022) and Gomes *et al*. (2022) who found higher acylsugar values in dwarf tomato populations.

The wild accession *S. pennellii* is used for comparison of the acylsugar content (Maluf *et al*. 2010). In interspecific crossbreeding, tomato breeding programs currently use *S. pennellii* to introduce genes responsible for a high sugar content into commercial lines. However, successive backcrossings with the recurrent parent are necessary to re-establish desirable characteristics (Marinke *et al*. 2022).

Given the preliminary nature of research on the potential use of dwarf tomatoes for biotic stress resistance, the existence of other compounds in the leaflets of BC3 lines is suggested. In this regard, chromatographic analysis and metabolomic profiling have contributed to advancing knowledge. It was possible to observe the presence of other compounds of interest for further investigations. Notably, we highlight two of these compounds that showed a considerable increase in dwarf tomatoes in comparison to commercial ones. For instance, glycine exhibited an increase of over 24 times, while L-serine demonstrated a significant increase of 3.8 times at a $p < 0.01$. These results not only suggest the presence of these specific compounds, but also underscore their potential role in the resistance mechanisms of the BC3 lineage, providing valuable insights for future genetic improvement approaches.

Besides the presence of acylsugar, there are reports indicating that specific amino acids, such as glycine and L-serine, play a crucial role in promoting resistance to many types of stresses, both biotic and abiotic, in plants (Hildebrandt *et al*. 2015). These biochemical compounds are not only associated with defense against pathogens, but also have a substantial impact on essential physiological processes for plant development and survival. Their influence spans from protein synthesis to intracellular pH regulation, metabolic energy generation and resistance to a wide range of abiotic and biotic stresses (Hildebrandt *et al*. 2015). The accumulation of these amino acids, especially in locally infected leaves, can be seen as an adaptive strategy of the plant to strengthen its defense response by providing the necessary substrates for the quick synthesis of proteins and other compounds related to immunity against pathogens (Schwachtje *et al*. 2018).

Furthermore, another study demonstrated that just 8 hours after infection by Pseudomonas syringae pv. tomato, there was a significant increase in some amino acids in Arabidopsis leaves (Ward *et al*. 2010). These studies also highlight not only the complexity of plant metabolic response to pathogens, but also the dynamic adaptation of primary metabolism to efficiently modulate systemic resistance (Ward *et al.* 2010, Schwachtje *et al.* 2018). This intricate biochemical interaction underscores the importance of these amino acids not only in cellular homeostasis, but also as a key elements in plants' effective response to environmental challenges. A thorough understanding of the mechanisms by which glycine and L-serine contribute to plant resistance allows for the consideration of strategies aimed at harnessing these amino acids in the development of more resilient tomato varieties. The isolated or combined use of these compounds may represent an innovative approach to reduce pesticide dependence and promote sustainability in agriculture (Figure 2B).

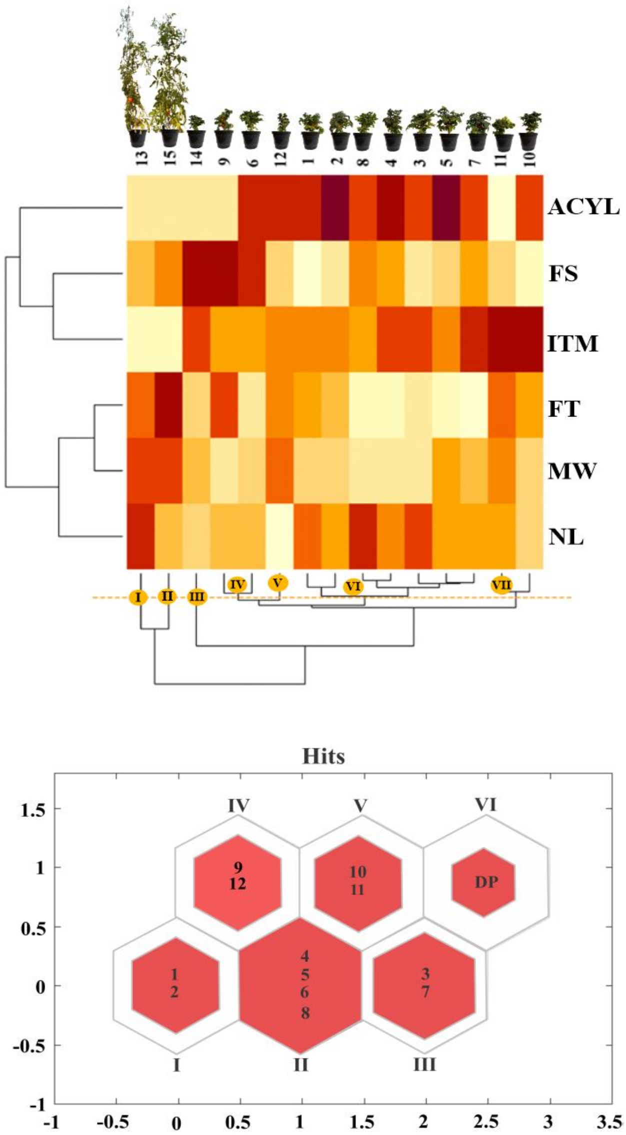
The donor parent (UFU MC TOM1) can transfers resistance genes to the progenies (Maciel *et al.* 2018, Finzi *et al*. 2022). The dwarf tomato populations and donor parent (UFU MC TOM1) did not differ from the wild accession in terms of the acylsugar content. Thus, dwarf tomato populations from backcrossings can be used in a similar manner as wild accessions (*S. pennellii*) to obtain populations with a high load of effective alleles. Thus, backcrossings after the initial crossing are not necessary to achieve resistance to arthropod pests. Dwarf tomato populations can be used to quickly and directly obtain hybrids with pest resistance traits.

The backcrossings provided significant gains for MW, FT e NL in comparison to those of the donor parent. Thus, genetic dissimilarity and selection indices must be used to select superior dwarf tomato populations. To visualize genetic dissimilarity between the individuals analyzed, a heat map was drawn, with a dendrogram obtained using the unweighted pair group method with arithmetic mean with the generalized Mahalanobis matrix and an Kohonen self-organizing map (SOM) (Figure 3).

Figure 3 - Visualizing Treatment Clusters with Dendrogram and Kohonen Self-Organizing Maps.A. Dendrogram and heat map of individuals and the characteristics of fruit shape (FS), number of lobes (NL), flesh thickness (FT), average weight (MW), number of internodes per linear meter (ITM), and acylsugar (ACYL). 1: UFU-Sci#1; 2: UFU-Sci#2; 3: UFU-Sci#3; 4: UFU-Sci#4; 5: UFU-Sci#5; 6: UFU-Sci#6; 7: UFU-Sci#7; 8: UFU-Sci#8; 9: UFU-Sci#9; 10: UFU-Sci#10; 11: UFU-Sci#1; 12: UFU-Sci#12; 13: UFU-TOM-Mother 2 - recurrent parent; 14: UFU MC TOM1 - donor parent; 15: commercial control Santa Cruz Kada. B. Kohonen self-organizing map (SOM), with the number of treatments in each neuron, clusters (3 × 2 of radius 1) using an artificial neural network.

A.

B.



Source: Created by the author.

A cut-off of 21.68% resulted in the formation of seven distinct groups based on genetic dissimilarity between the individuals. Groups I and II included the recurrent parent and commercial control, respectively. Group III included the donor parent (UFU MC TOM1), group IV included the UFU-Sci#6 (BC3) and UFU-Sci#9 (BC2) populations, and group V included the UFU-Sci#12 (BC1) population. Populations from BC3 formed group VI and the UFU-Sci#10 and UFU-Sci#11 populations from BC1 formed group VII (Figure 3A).

The distance between the dwarf tomato populations and donor parent ranged from 63.27 to 94.58, with the greatest distance observed in the UFU-Sci#2 population from BC3. The distance between the BC1 and BC3 populations showed variability between the dwarf tomato populations after successive backcrossings. The branches for the variables indicated similarity between the characteristics analyzed. In addition, the intense red color revealed a greater contribution to the response variable for the individuals.

Using Kohonen's SOM, the donor parent and dwarf populations were classified into six distinct classes (Figure 3B). Neuron I (row 1 column 1) included the UFU-Sci#1 and UFU-Sci#2 populations; neuron II (row 1 column 2) included the UFU-Sci#4, UFU-Sci#5, UFU-Sci#6, and UFU-Sci#8 populations; neuron III (row 1 column 3) included the UFU-Sci#3 and UFU-Sci#7 populations; neuron IV (row 2 column 1) included the UFU-Sci#9 and UFU-Sci#12 populations; neuron V (row 2 column 2) included the UFU-Sci#10, UFU-Sci#11 populations; and neuron VI included the donor parent (UFU MC TOM1).

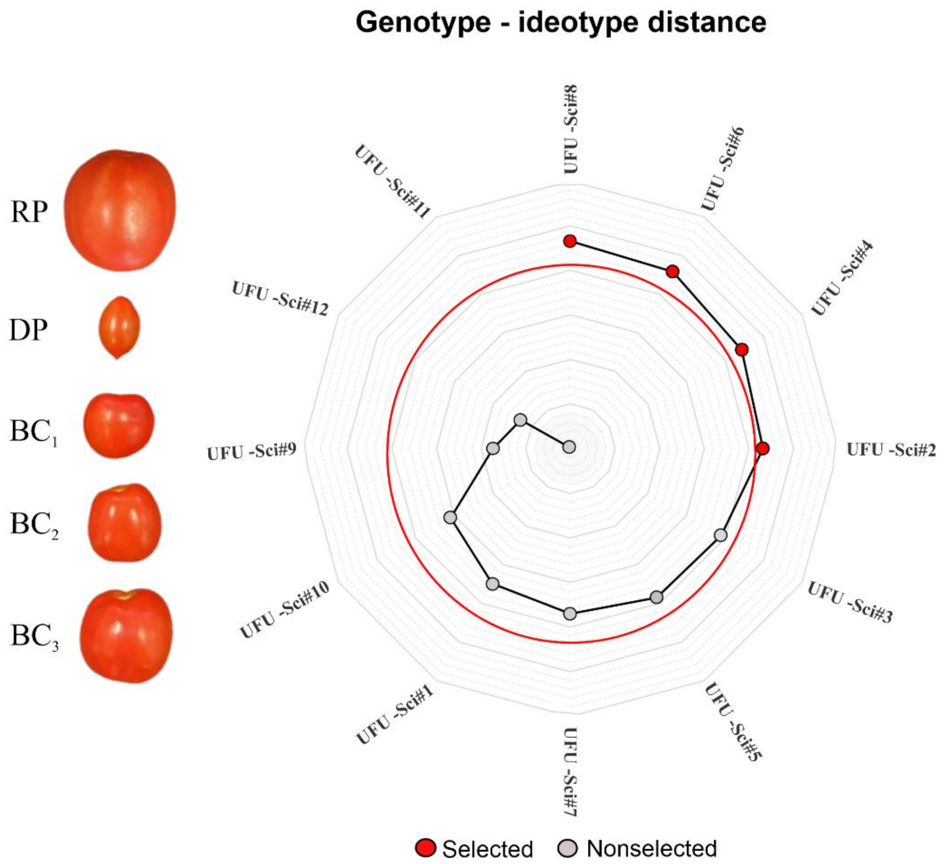
The dwarf tomato populations belonging to BC3 were organized into groups I, II, and III. The populations belonging to BC1 and BC2 were distributed in neurons IV and V. These results confirmed the increase in dissimilarity between the populations after backcrossing.

SOMs are considered as a type of artificial neural network trained to study genetic dissimilarity. This technique is considered as an essential tool for multivariate analysis and can organize dimensional data into groups according to similarity. The algorithm can also identify and distinguish close neurons in the network, which indicates greater similarity between individuals (Kohonen 2001, Ferreira *et al.* 2018). SOM maps were previously used to assess genetic dissimilarity between soybean cultivars in breeding programs (Sá *et al.* 2022). Additionally, Gomes *et al.* (2022) demonstrated that the SOM method was efficient in selecting contrasting populations of dwarf tomato with fruits of the Santa Cruz type belonging to BC1 and BC2, aiming to get the BC3 population.

The dwarf tomato populations belonging to BC3 formed their own clusters, diverging from the populations obtained in other backcrossings and from the donor parent, both by the unweighted pair group method with arithmetic mean clustering method and by the Kohonen self-organizing map (Figure 3). In fact, agronomic improvements in individuals with broad resistance to pests have been obtained through backcrossing. Gonçalves Neto *et al.* (2010) got commercial standard fruit through an interspecific cross between the wild accessions *S. pennellii* and S. *lycopersicum* followed by three backcrossings.

In addition to dissimilarity measures, the selection index is used to select superior individuals with high agronomic performance and elevated acyl levels de acylsugar. The dwarf tomato populations were selected based on the genotype-ideotype distance (Figure 4).

Figure 4 - Genotype-ideotype distance for selecting superior dwarf populations after backcrossing.



Source: Created by the author.

The genotype-ideotype index selected the UFU-Sci#8, UFU-Sci#6, UFU-Sci#4, and UFU-Sci#2 populations belonging to BC3. Thus, the smallest Mahalanobis distances were found between BC3 populations and defined genotype-ideotype. The other BC3, BC2, and BC1 populations showed intermediate values and greater distances. Ideotypes play a crucial role in achieving different objectives in plant breeding, helping breeders make decisions. In addition, determining an ideotype enables the selection of promising and superior populations (Lessa *et al.* 2017), as performed in this study.

The dwarf tomato plants revealed greatly improved fruit traits and broad resistance to pest arthropods after backcrossing. The selected populations can be used for the genetic improvement of tomato plants, with the potential to get compact, productive, and pest-resistant hybrids belonging to the Santa Cruz segment.

In conclusion, the dwarf tomato populations founded improved agronomic traits after the three backcrossings. The most prominent populations belonged to BC3 (UFU-Sci#8, UFU-Sci#6, UFU-Sci#4, and UFU-Sci#2). Most dwarf plants had high levels of acylsugars in the leaves, in addition, the significant increase of amino acids, notably L-serine and glycine, suggest the potential of obtaining pest-resistant hybrids.

REFERENCES

ADALJA, A.; LICHTENBERG, E. Implementation challenges of the food safety modernization act: evidence from a national survey of produce growers. *Food Control*, v. 89, p. 62-71, 2018. DOI:http://dx.doi.org/10.1016/j.foodcont.2018.01.024. Acesso em: 5 jun. 2023.

ALVARENGA, M. A. R. *Tomate:* produção em campo, em casa-de-vegetação e em hidroponia. Lavras: Editora UFLA, 2013. 455 p. Acesso em: 5 jun. 2023.

BORÉM, A.; MIRANDA, G. V.; FRITSCHE-NETO, R. *Melhoramento de plantas*. São Paulo: Oficina de Textos, 2021. 384 p.

COSTA, D. P. *et al*. Tomatoes used by industries have technological quality for fresh consumption. *Revista Caatinga*, v. 33, n. 3, p. 824-834, 2020. DOI: http://dx.doi.org/10.1590/1983-21252020v33n326rc. Acesso em: 5 jun. 2023.

FERREIRA, F. *et al.* SSR-based genetic analysis of sweet corn inbred lines using artificial neural networks. *Crop Breeding and Applied Biotechnology*, v. 18, n. 3, p. 309-313, 2018. DOI: http://dx.doi.org/10.1590/1984-70332018v18n3n45. Acesso em: 5 jun. 2023.

FILGUEIRA, F. A. R. *Novo manual de olericultura*: agrotecnologia moderna na produção e comercialização de hortaliças. Viçosa, MG: UFV, 2013. 421 p.

FINZI, R. R. *et al.* Growth habit in mini tomato hybrids from a dwarf line. *Bioscience Journal*, Uberlândia, v. 33, n. 1, p. 52-56, 2017. DOI: http://dx.doi.org/10.14393/BJ-v33n1a2017-35763. Acesso em: 10 jun. 2023.

FINZI, R. R. *et al.* Genetic gain according to different selection criteria for agronomic characters in advanced tomato lines. *Genetics and Molecular Research*, v. 19, p. 1-9, 2020. DOI: http://dx.doi.org/10.4238/gmr18462.

FLORES, P. *et al.* Genotypic variability of carotenoids in traditional tomato cultivars. *Food Research International*, v. 100, p. 510-516, 2017.DOI: http://dx.doi.org/10.1016/j.foodres.2016.07.014. Acesso em: 10 jun. 2023.

GOMES, D. A. *et al.* Dwarf tomato plants allow for managing agronomic yield gains with fruit quality and pest resistance through backcrossing. *Agronomy*, Basel, v. 12, p. 3087, 2022. DOI: http://dx.doi.org/10.3390/agronomy12123087. Acesso em: 10 jun. 2023.

GOMES, D. A. *et al.* Agronomic potential of BC1F2 populations of Santa Cruz type dwarf tomato plant. *Acta Scientiarum Agronomy*, v. 45, e56482, 2023. DOI: http://dx.doi.org/10.4025/actasciagron.v45i1.56482. Acesso em: 10 jun. 2023.

GOMES, D. A. *et al.* Selection of BC1F3 populations of Santa Cruz type dwarf tomato plant by computational intelligence techniques. *Bragantia*, Campinas, v. 80, e4821, 2021. DOI: https://doi.org/10.1590/1678-4499.20210046. Acesso em: 10 jun. 2023.

GONÇALVES-NETO, A. C. Resistência à traça-do-tomateiro em plantas com altos teores de acilaçúcares nas folhas. *Horticultura Brasileira*, v. 28, n. 2, p. 203-208, 2010. DOI: http://dx.doi.org/10.1590/S0102-05362010000200011. Acesso em: 10 jun. 2023.

HILDEBRANDT, T. M. *et al.* Amino acid catabolism in plants. *Molecular Plant*, v. 8, n. 11, p. 1563-1579, 2015. DOI: http://dx.doi.org/10.1016/j.molp.2015.09.005. Acesso em: 10 jun. 2023.

KOHONEN, T. *Self-organizing maps*. 3. ed. Berlin: Springer, 2001. 501 p.

KOUAM, E. B.; DONGMO, J. R.; DJEUGAP, J. F. Exploring morphological variation in tomato (Solanum lycopersicum): a combined study of disease resistance, genetic divergence and association of characters. *Agricultura Tropica et Subtropica*, v. 51, p. 71-82, 2018. DOI: http://dx.doi.org/10.2478/ats-2018-0008. Acesso em: 10 jun. 2023.

LESSA, L. S.; LEDO, C. A. S.; SANTOS, V. S. Seleção de genótipos de mandioca com índices não paramétricos. *Revista Raízes e Amidos Tropicais*, v. 13, n. 1, p. 1-17, 2017. DOI: https://doi.org/10.17766/1808-981X.2017v13n1p1-17. Acesso em: 10 jun. 2023.

LISEC, J. *et al.* Gas chromatography mass spectrometry-based metabolite profiling in plants. Nature Protocols, v. 1, p. 387-396, 2006. DOI: http://dx.doi.org/10.1038/nprot.2006.59. Acesso em: 10 jun. 2023.

MACIEL, G. M.; SILVA, E. C. Proposta metodológica para quantificação de acilaçúcares em folíolos de tomateiro. *Horticultura Brasileira*, Brasília, v. 32, n. 2, p. 174-177, 2014. https://doi.org/10.1590/S0102-05362014000200009. Acesso em: 10 jun. 2023.

MACIEL, G. M.; SILVA, E. C.; FERNANDES, M. A. R. Dwarfism occurrence in tomato plant type grape. *Revista Caatinga*, v. 28, n. 4, p. 259-264, 2015. DOI: http://dx.doi.org/10.1590/1983-21252015v28n429rc. Acesso em: 10 jun. 2023.

MACIEL, G. M. *et al.* Tomato genotypes with determinate growth and high acylsugar content presenting resistance to spider mite. *Crop Breeding and Applied Biotechnology*, v. 18, n. 1, p. 1-8, 2018. DOI: http://dx.doi.org/10.1590/1984-70332018v18n1a1. Acesso em: 10 jun. 2023.

MAGGIO, A. *et al.* Global drivers and megatrends in agri-food systems. *In*: SERRAJ, R.; PINGALI, P. (ed.). *Agriculture and food systems to 2050*: global trends, challenges and opportunities. [*S.l.*]: World Scientific Publishing, 2018. p. 47-83. Acesso em: 20 jun. 2023.

MALUF, W. R. *et al.* Broad-spectrum arthropod resistance in hybrids between high- and low-acylsugar tomato lines. *Crop Science*, v. 50, p. 439-450, 2010. DOI: http://dx.doi.org/10.2135/cropsci2009.01.0045. Acesso em: 20 jun. 2023.

MARINKE, L. S. *et al.* Selection of tomato genotypes with high resistance to Tetranychus evansi mediated by glandular trichomes. *Phytoparasitica*, v. 50, p. 629-643, 2022. DOI: http://dx.doi.org/10.1007/s12600-022-00984-6. Acesso em: 20 jun. 2023.

MATHWORKS. *MATLAB and Statistics Toolbox Release 2012*. Natick, MA: The MathWorks, 2012.

OLIVEIRA, C. S. *et al*. Selection of F2RC1 saladette-type dwarf tomato plant populations for fruit quality and whitefly resistance. *Revista Brasileira de Engenharia Agrícola e Ambiental*, Campina Grande, v. 26, n. 1, p. 28-35, 2022. DOI: http://dx.doi.org/10.1590/1807-1929/agriambi.v26n1p28-35. Acesso em: 20 jun. 2023.

OLIVEIRA, A. H. G. *et al.* Dynamics of herdability in different characters of lettuce. *Revista Caatinga*, v. 34, n. 3, p. 1-9, 2021. DOI: http://dx.doi.org/10.1590/1983-21252021v34n303rc. Acesso em: 20 jun. 2023.

PEIXOTO, J. V. M. *et al.* Productivity, acylsugar concentrations and resistance to the two-spotted spider mite in genotypes of salad tomatoes. *Revista Brasileira de Engenharia Agrícola e Ambiental*, Campina Grande, v. 24, n. 9, p. 596-602, 2020. DOI: http://dx.doi.org/10.1590/1807-1929/agriambi.v24n9p596-602. Acesso em: 20 jun. 2023.

PEIXOTO, J. V. M. *et al*. Tomaticultura: aspectos morfológicos e propriedades físico-químicas do fruto. *Revista Científica Rural*, Bagé, v. 19, n. 1, p. 108-131, 2017. Acesso em: 20 jun. 2023.

R CORE TEAM. R: a language and environment for statistical computing. s.l.: R Foundation for Statistical Computing, 2024. Disponível em: https://www.r-project.org/. Acesso em: 28 jan. 2023.

RESENDE, J. T. V. *et al.* Método colorimétrico para quantificação de acilaçúcar em genótipos de tomateiro. *Ciência e Agrotecnolog*ia, Lavras, v. 26, n. 6, p. 1204-1208, 2002. Acesso em: 20 jun. 2023.

SÁ, L. G. *et al.* Kohonen's self-organizing maps for the study of genetic dissimilarity among soybean cultivars and genotypes. *Pesquisa Agropecuária Brasileira*, v. 57, e02722, 2022. DOI: https://doi.org/10.1590/S1678-3921.pab2022.v57.02722. Acesso em: 20 jun. 2023.

SCHWACHTJE, J. *et al.* Primed primary metabolism in systemic leaves: a functional systems analysis. *Scientific Reports*, v. 8, art. 216, 2018. DOI: http://dx.doi.org/10.1038/s41598-017-18397-5. Acesso em: 20 jun. 2023.

VIEIRA, D. A. P. *et al.* Mechanical resistance, biometric and physicochemical characteristics of tomato cultivars for industrial processing. *Food Science and Technology*, v. 39, p. 363-370, 2019. DOI: http://dx.doi.org/10.1590/fst.32417. Acesso em: 20 jun. 2023.

WARD, J. L. *et al.* The metabolic transition during disease following infection of Arabidopsis thaliana by Pseudomonas syringae pv. tomato. *The Plant Journal*, v. 63, n. 3, p. 443-457, 2010. DOI: http://dx.doi.org/10.1111/j.1365-313X.2010.04254.x. Acesso em: 20 jun. 2023.

CHAPTER 2

GENOTYPIC AND ENVIRONMENTAL EFFECTS ON MORPHOAGRONOMIC PERFORMANCE IN TOMATO HYBRIDS DERIVED FROM DWARF MALE PARENTAL LINES [2]

---

[2] Artigo publicado na Revista. Ciência e Agrotecnologia
Ribeiro, A. L. A.; Maciel, G. M.; Siquieroli, A. C. S.; Pinto, F. G.; Ikehara, B. R. M.; Jacinto, A. C. P.; Pereira, L. M.; Oliveira, C. S. de . Genotypic and environmental effects on morphoagronomic performance in tomato hybrids derived from dwarf male parental lines. Ciência e Agrotecnologia 2025, 49, e009025. https://doi.org/10.1590/1413-7054202549009025

4 GENOTYPIC AND ENVIRONMENTAL EFFECTS ON MORPHOAGRONOMIC PERFORMANCE IN TOMATO HYBRIDS DERIVED FROM DWARF MALE PARENTAL LINES

ABSTRACT

The climatic scenario for the production of healthy and sustainable food faces significant challenges and the search for more productive cultivars with resilience is crucial. In this study, fifteen hybrids resulted from dwarf male parental lines were analyzed for morphoagronomic performance under field and greenhouse conditions. Initially, through metabolomic analysis of leaflets, efforts were made to identify the different compounds found among the commercial cultivar ('Santa Clara'), a wild accession (*Solanum pennellii*), and the dwarf donor parent ('UFU MC TOM1'). Subsequently, dwarf lines were obtained to produce the fifteen hybrids. The experiments were conducted in two environments in a randomized block design with three replications. The interaction between hybrids and environments was analyzed using the Scott-Knott test 5 for means, followed by a GGE biplot analysis. The dissimilarity between hybrids was analyzed by Mahalanobis distance. The acylsugar analysis and metabolomic profiling domonstrated that the donor parent is similar to the wild accession *S. pennellii*. The hybrids UFU#7 and UFU#12 exhibited highly compact plants and may serve as a novel technology aimed at optimizing space in field and greenhouse cultivation. 'UFU MC TOM1', the donor parent used to obtain the male parental lines of the hybrids, contains several metabolites in its leaflets that significantly differ from those found in the wild accession *S. pennellii* and the 'Santa Clara' cultivar. These metabolites are associated with key metabolic pathways that regulate various types of biotic and abiotic stress, paving the way for further studies focused on developing tomato plants with enhanced resilience.

Keywords: *Solanum lycopersicum* L.; sustainable production; genotype-environment interaction; food security.

4.1 INTRODUCTION

The demand for healthy eating has significantly contributed to the increased consumption of vegetables (Devirgiliis *et al*., 2024; Rosell & Fadnes, 2024). The tomato (*Solanum lycopersicum* L.) is considered a vegetable of great importance to the agricultural sector, widely cultivated and consumed worldwide (Furlaneto *et al*., 2022). Additionally, it plays a significant economic role (Sahu, Joshi, & Mishra, 2024). The fruits contain high levels of minerals, vitamins, and essential antioxidant substances, which may help prevent diseases (Leon-Calvario *et al*., 2020; Felföldi *et al*., 2021).

Tomato offers different varietal segments to meet various market demands and destinations, classified into Mini-tomato, Salad, Persimmon, Santa Cruz, and Saladette (Alvarenga, & Coelho, 2013; Dagade *et al*., 2015). The Santa Cruz group stands out for its longer post-harvest shelf life and high fruit firmness. The tomato cultivation occurs in open fields and greenhouses, and regardless of the cultivation environment, production is considered a high-risk activity due to vulnerability to pest and disease attacks (Flores *et al*., 2024; De Oliveira *et al*., 2024; Alvarenga, & Coelho, 2013).

To ensure sustainable production, high investment costs are necessary due to the application of large amounts of pesticides (Nascimento *et al.*, 2021). Therefore, it is essential to seek alternatives that increase productivity and ensure the economic viability of the crop (De Oliveira *et al.*, 2024). Irrigation management, spacing adjustments, fertilizer dosage, and different lighting strategies are among the approaches to increase tomato productivity (Nkansah *et al.*, 2021; Ali *et al.*, 2024; Campos *et al.*, 2025). However, techniques capable of modifying the morphology of hybrid plants are scarce. Dwarf tomato lines have emerged as promising parental candidates in genetic improvement, making it possible to increase productivity through hybridization (Maciel, Silva, & Fernandes, 2015; Pereira *et al.*, 2024b). The research has reported the development of more compact plants in mini-tomato hybrids using dwarf male parental lines, with changes in plant structure, higher productivity, pest and disease resistance, and improved fruit quality (Oliveira *et al*., 2024; Gomes *et al.*, 2023; Jacinto *et al*., 2024).

In mini-tomatoes, the strategy of hybridization between normal and dwarf lines to obtain hybrids was analyzed by Finzi *et al.* (2017) and confirmed in salad-type tomatoes (Pereira *et al*., 2024a) and saladette-type tomatoes (Pereira *et al*., 2024b). The authors suggest that productivity can be increased by reducing the internode distance of a normal phenotype, resulting in a higher number of bunches per linear meter of plant. Additionally, there are reports that the use of dwarf tomato lines has high levels of acylsugars and can be used as mitigants against herbivory damage caused by various pests

(Gomes *et al.*, 2021; Gomes *et al.*, 2023; Ribeiro *et al.*, 2024; Maciel *et al.*, 2024). These results are relevant to support further research aimed at sustainable production and reduced pesticide use for Santa Cruz-type tomatoes.

Notably, the climatic scenario strongly demands the search for genotypes with greater resilience to different production environments. We suggest that a recent discovery proposing the use of dwarf male parental lines to obtain hybrids with normal architecture (Finzi *et al.*, 2017; Pereira *et al.*, 2024a, 2024b) can bring new insights for future researches aimed at sustainable production and new technologies for immediate use by tomato producers. However, the genotypic and environmental effects on the morphophysiological performance, fruit quality, and agronomic traits in tomato hybrids derived from dwarf male parental lines remain unknown, which is the objective of this study.

4.2 MATERIAL AND METHODS

4.2.1 Comparative Metabolomic Analysis: commercial cultivar, wild accession, and dwarf tomato 'UFU MC TOM1'

The germplasm used in this research is part of the Tomato Genetic Improvement Program at the Federal University of Uberlândia (UFU), with all genealogy stored in the "BG α BIOFORT" software, registered under number BR512019002403-6 at INPI (Maciel *et al.*, 2019).

The genetic background of the dwarf male parental lines used to obtain the hybrids is derived from the donor parent 'UFU MC TOM1', a dwarf tomato (Maciel, Silva, & Fernandes, 2015). To conduct a broad approach regarding potential differences in compounds associated with many types of biotic and abiotic stress between a commercial cultivar 'Santa Clara', a wild accession *(Solanum pennellii*), and the dwarf donor parent ('UFU MC TOM1'), chromatographic analysis and metabolomic profiling of plant leaflets were performed. The wild accession *S. pennellii* and the 'Santa Clara' cultivar were used as controls to assess the potential of the donor parent 'UFU MC TOM1' compared to the wild accession and commercial check. The *S. pennellii* accession is a wild species widely known for its tolerance to biotic and abiotic stresses (Egea *et al.*, 2018).

In the summer of 2022, seeds of the commercial cultivar 'Santa Clara', the wild accession *S. pennellii*, and the donor parent 'UFU MC TOM1' were sown. The seedlings were transplanted into five-liter pots containing a commercial substrate based on coconut fiber. The experimental design was a randomized block design with five replications per treatment and ten plants per plot. The cultivation process was carried out in a greenhouse.

Non-target metabolomic analysis was performed using gas chromatography coupled with mass spectrometry (GC-MS) by the Metabolomics Research and Analysis Group (GPAM) at the Federal University of Viçosa (UFV), Rio Paranaíba Campus. Leaflets were ground in liquid nitrogen to obtain a fine powder, and extraction was performed using 100 mg of sample and 2 mL of extraction solution based on methanol, chloroform, and ultrapure water (3:1:1), with 50 µL/mL of Adonitol Purex as an internal standard. The samples, along with the extraction solution, were subjected to agitation in a cell disruptor (L-Beader 6 Loccus®), operating at 3500 rpm in cycles of 60 seconds of agitation interspersed with 30 seconds of rest. This process was assisted by stainless steel beads with a diameter of 2.8 mm. After agitation, 1 mL of the supernatant was transferred to new microtubes, and 300 µL of hexane (P.A.) was added. Then, the samples were left to rest for 3 minutes, and 500 µL of the lower portion were removed and placed in microtubes for drying in a sample concentrator at 40 °C for 16 hours.

The dried samples were derivatized by adding 50 µL of a solution of pyridine and methoxyamine hydrochloride (20 mg/mL), vortexed, and kept in a concentrator block at 37 °C for 90 minutes. Afterewards, the samples were cooled for 5 minutes in an ice bath, followed by the addition of 50 µL of BSTFA solution {[Bis(trimethylsilyl) trifluoroacetamide] - Sigma Aldrich}. The samples were heated again in the concentrator block for 30 minutes and then cooled. Finally, the derivatized aliquots were transferred to chromatographic vials containing 200 µL volume-reducing inserts, prepared for GC-MS analysis.

The analysis was performed using gas chromatography coupled with a mass spectrometer (GCMS-QP2010, Shimadzu, Kyoto, Japan), equipped with a DB-5MS capillary column (30 m × 250 µm internal diameter). The sample injection temperature was set at 280 °C, with a constant helium gas flow of 1.0 mL/min throughout the process. The initial temperature for chromatographic separation was 80 °C, maintained for 2 minutes. Later, the temperature was increased by 5 °C per minute until reaching a maximum temperature of 290 °C, which was maintained for 5 minutes.

The chromatograms were processed and corrected using MS-DIAL software (v. 4.9.2). The metabolites were identified based on the NIST 2014 library according to retention time and mass-to-charge ratio of the molecules and fragments. Statistical analyses and biochemical pathway construction were performed using MetaboAnalyst 6.0 software, and pathway enrichment was performed using the Kyoto Encyclopedia of Genes and Genomes (KEGG) considering $p < 0.05$.

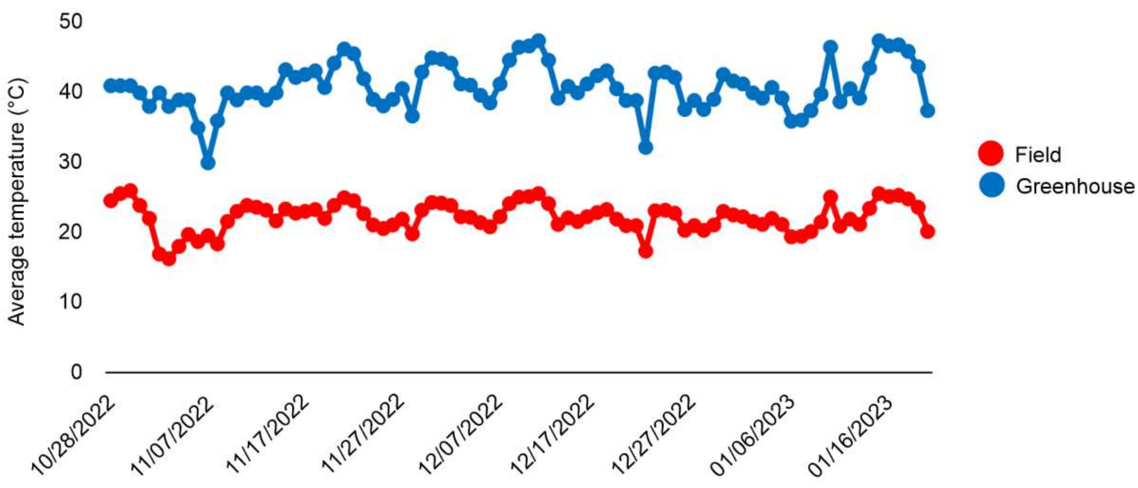
4.2.2 Plant Material and Growing Conditions

The experiments with the hybrids were conducted in two environments: field and greenhouse, both located at the Vegetable Experimental Station of the Federal University of Uberlândia (UFU), Monte Carmelo Campus, MG, Brazil (18° 42' 43.19" S, 47° 29' 55.8" W, altitude 873 m). The climatic conditions of the environments were monitored (Figure 1).

Figure 1- Climograph demonstrating the average temperature in the two cultivation environments (field and greenhouse) during the experimental period.

Source: Created by the author.

.



Soil sampling and chemical and physical analyses were conducted in both cultivation environments. The field analysis founded the following characteristics: clay texture; pH in CaCl2 = 4.9; MO = 3.9 dag kg-1; Pmeh = 79.1 mg dm-3; K = 0.29 cmol dm-3; Ca = 3.3 cmoldm-3; Mg = 1.3 cmol dm-3; H + Al = 4.9 cmol dm-3; SB = 4.9 cmol dm-3; CTC = 9.8 cmol dm-3; and V% = 50. The greenhouse analysis showed the following characteristics: pH in CaCl2 = 4.7; MO = 2.6. dag kg-1; Pmeh = 72.5 mg dm-3; K = 0.27 cmol dm-3; Ca = 3.21 cmoldm-3; Mg = 0.82 cmol dm-3; H + Al = 2.3 cmol dm-3; SB = 4.30 cmol dm-3; T = 6.6 cmol dm-3; e V% = 65.

Fifteen tomato hybrids with a Santa Cruz genetic background, obtained using dwarf male parental lines, were evaluated. To get dwarf lines with Santa Cruz-type fruits (used as male parents ♂ in the development of the hybrids), a cross was made in 2015 between the donor parent 'UFU MC TOM1'♂ and the recurrent parent UFU-TOM-Mother-2 ♀. 'UFU MC TOM1'♂ (donor parent) has a dwarf plant architecture with monogenic recessive inheritance (Maciel, Silva, & Fernandes, 2015), produces small fruits (< 5 g) and is capable of transferring internode-reduction traits to normal hybrid plants (Finzi *et al.*, 2017; Pereira *et al.*, 2024a, 2024b). It also has high levels of acylsugars with broad-spectrum pest resistance (Gomes *et al.*, 2022; Oliveira *et al.*, 2022, 2024; Maciel *et al.*, 2024). UFU-TOM-Mother-2 ♀, used as the recurrent parent, is a pre-commercial line with large fruits (280g), a Santa Cruz genetic background, but susceptible to various types of biotic and abiotic stress.

During the period 2018–2022, hybridization was carried out between 'UFU MC TOM1' ♂ *versus* UFU-TOM-Mother-2 ♀, followed by three backcrosses. The first backcross (BC1) was performed using the recurrent parent UFU-TOM-Mother-2, followed by self-pollination to obtain the F2BC1 generation. The second backcross (BC2) was derived from the selection of dwarf plants obtained in F2BC1, crossed again with the recurrent parent, followed by self-pollination to obtain the F2BC2 generation. Dwarf plants from the third backcross (BC3) were obtained by crossing selected dwarf plants from F2BC2 with the recurrent parent. In the F2BC1, F2BC2, and F2BC3 generations, normal-sized plants were eliminated at the seedling stage through visual observation, and only dwarf plants were selected (Pereira *et al.*, 2024b). After obtaining each backcross generation, two successive self-pollinations were performed to obtain the dwarf male parental lines in each backcross: F4BC1, F4BC2, and F4BC3.

The dwarf plant lines obtained through backcrossing, followed by two successive self-pollinations (F4BC__), were selected for use as male parents ♂ in the development of fifteen hybrids. The dwarf lines used were: BC1 = UFU-Sci#6.1.2,5.1.1; BC2 = UFU-Sci#6.1,2-2.1.1; BC3 = UFU-Sci#6.1,2-2.1.7. In 2023, with the dwarf lines (male parents ♂), crosses were performed with five pre-commercial lines with normal architecture (female parents ♀): 21TOM13303, 21TOM13381, 21TOM13304, 21TOM13382, and 21TOM13383, resulting in the fifteen experimental hybrids: 1 - UFU#1 (21TOM13303

♀ x UFU-Sci#6.1.2,5.1.1 ♂); 2- UFU#2 (21TOM13381 ♀ x UFU-Sci#6.1.2,5.1.1 ♂); 3 - UFU#3 (21TOM13304 ♀ x UFU-Sci#6.1.2,5.1.1 ♂); 4 - UFU#4 (21TOM13382 ♀ x UFU-Sci#6.1.2,5.1.1 ♂); 5 - UFU#5 (21TOM13383 ♀ x UFU-Sci#6.1.2,5.1.1 ♂); 6 - UFU#6 (21TOM13303 ♀ x UFU-Sci#6.1,2-2.1.1 ♂); 7 - UFU#7 (21TOM13381 ♀ x UFU-Sci#6.1,2-2.1.1 ♂); 8- UFU#8 (21TOM13304 ♀ x UFU-Sci#6.1,2-2.1.1 ♂); 9 - UFU#9 (21TOM13382 ♀ x UFU-Sci#6.1,2-2.1.1 ♂); 10 - UFU#10 (21TOM13383 ♀ x UFU-Sci#6.1,2-2.1.1 ♂); 11 - UFU#11 (21TOM13303 ♀ x UFU-Sci#6.1,2-2.1.7 ♂); 12 - UFU#12 (21TOM13381 ♀ x UFU-Sci#6.1,2-2.1.7 ♂); 13 - UFU#13 (21TOM13304 ♀ x UFU-Sci#6.1,2-2.1.7 ♂); 14 - UFU#14 (21TOM13382 ♀ x UFU-Sci#6.1,2-2.1.7 ♂); 15 - UFU#15 (21TOM13383 ♀ x UFU-Sci#6.1,2-2.1.7 ♂). The commercial cultivar 'Caniati' was added as a check, totaling 16 hybrids (treatments).

The hybrids and commercial check were sown in the spring of 2024 in polystyrene trays filled with a commercial substrate based on coconut fiber. After 40 days, the seedlings were transplanted to permanent beds in both environments (field and greenhouse). The experiment 1 was conducted in the field, while experiment 2 was conducted in a greenhouse covered with 150-micron UV-resistant polystyrene plastic and anti-aphid side curtains. Both experiments were conducted in a randomized block design (RBD) with three replications. The experimental plots consisted of eight plants, spaced 0.4 m apart within rows and 1.5 m between rows. The plants were trained to a single vertical stem, and cultural practices were performed according to recommendations for tomato cultivation (Filgueira, 2013).

4.2.3 Quantification of Acylsugar Levels

The evaluation of acylsugar levels (nmol cm^{-2} of leaf area) in the experimental hybrids and commercial check was conducted at the Seed and Genetic Resources Analysis Laboratory (LAGEN) of the Federal University of Uberlândia (UFU), following the methodology proposed by Resende *et al.* (2002) and adapted by Maciel and Silva (2014). The evaluation occurred 25 days after transplanting in the greenhouse, and eight leaf discs (equivalent to 4.2 cm^2) were collected from the upper third of each plant in the plot. The wild accession *S. pennellii* and the 'Santa Clara' cultivar were used as references for resistance evaluation.

4.2.4 Morphophysiological Performance, Fruit Quality, and Agronomic Traits in Cultivation Environments

In the field and greenhouse environments, agronomic evaluations were conducted at the beginning of fruit ripening, and fruit quality evaluations were performed at full ripening. Harvests were conducted weekly, totaling five harvests.

Agronomic characterization included the evaluation of the following traits: yield (kg/plant) (PROD), productivity (kg/ha) (PDT), number of fruits per plant (NF), fruit length (cm) (FL), fruit diameter (cm) (FD), number of locules (NL), pulp thickness (cm) (PT), plant height (m) (PH), internode length (m) (IL), and number of bunches per linear meter (NBM).

For fruit quality evaluation, the following traits were analyzed: the ratio of soluble solids (°Brix) to titratable acidity (AT) (BRIX/TA), with °Brix measured using a refractometer with a graduation of 0.2°Brix and titratable acidity determined according to the methodology adapted from AOAC. For the evaluation of β-carotene (BETA) and lycopene (LY) content (mg/100mg), extraction was performed from processed fruit pulp using petroleum ether and acetone (1:1) according to the methodology adapted from Rodriguez-Amaya (2001) and Rodriguez-Amaya, Kimura (2004).

4.2.5 Data Analysis

The data were subjected to analysis of variance (ANOVA), and means were compared using the Scott-Knott test ($p < 0.05$) to evaluate hybrids, environments, and the hybrid-environment interaction.

For the evaluations, hybrids were characterized as fixed effects, and environments as random effects. After identifying significant differences in the genotype-environment interaction, the GGE biplot method was used to analyze and evaluate the interaction and stability. The method was proposed for the analysis of Multi-Environment Trial (MET) data and uses a graphical representation based on the first two principal components (PC1 and PC2) (Yan, 2021). The data on fruit diameter (FD), number of locules (NL), β-carotene (BETA), and the ratio of soluble solids to titratable acidity (BRIX/TA) in the environments were analyzed using the GGE biplot, according to the model (Equation 1):

$$\boldsymbol{y^\wedge ij + \mu + \alpha i + \beta j + \phi ij} \qquad (1)$$

in which Yij: represents the value of the mixed effect of the overall mean (μ), the main effect of the genotype (αi), the main effect of the environment (βj), and the interaction between genotype i and environment j (θij) and the random error (εij).

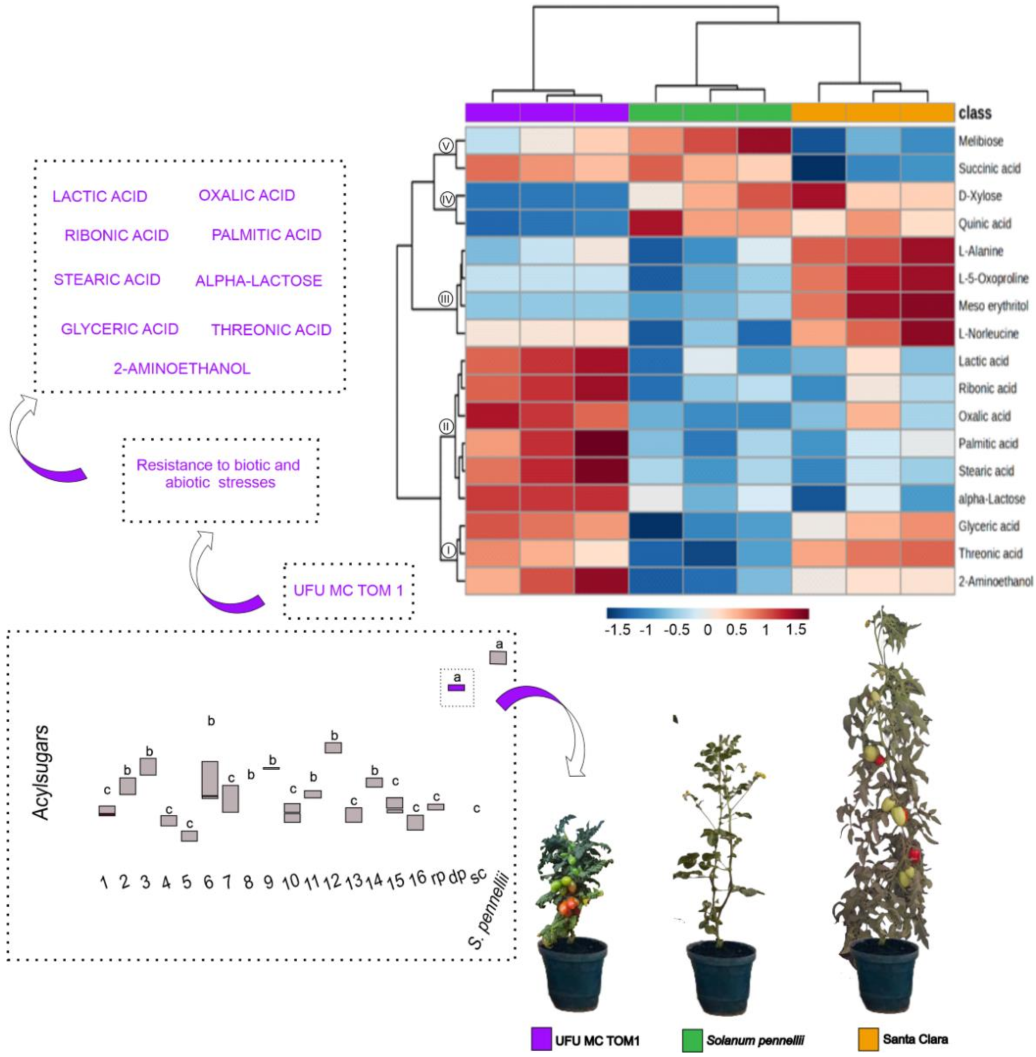
Thus, the GGE Biplot was used to generate the following graphs: "Which-Won-Where", "Discriminative vs. Representative," and "Examine a Genotype." The analysis was conducted using the GGE Biplot package in R software (R Core Team, 2024).

Multivariate analysis was used to characterize the dissimilarity between the hybrids and the evaluated traits in both the field and greenhouse, using a heat map and dendrogram. The dissimilarity matrix was obtained using the hierarchical method (UPGMA) and Mahalanobis distance. The analyses were performed using GENES software (Cruz, 2016) and R v. 4.2.1 (R Core Team, 2024).

4.3 RESULTS AND DISCUSSION

The previous study of acylsugar analysis, chromatography, and metabolomic profiling of leaves revealed that the donor parent ‘UFU MC TOM1’ did not differ from the wild accession *S. pennellii* used for comparison in terms of acylsugar levels and several other compounds associated with different types of biotic and abiotic stress (Figure 2).

Figure 2 - Measurements related to acylsugar quantification and metabolomic analysis for association with biotic and abiotic stresses. Legend: 1 - UFU#1; 2 - UFU#2; 3 - UFU#3; 4 - UFU#4; 5 - UFU#5; 6 - UFU#6; 7 - UFU#7; 8- UFU#8; 9 - UFU#9; 10 - UFU#10; 11 - UFU#11; 12 - UFU#12; 13 - UFU#13; 14 - UFU#14; 15 - UFU#15; 16 - commercial check; rp - recurrent parent; dp - donor parent; sc – 'Santa Clara'.



Source: Created by the author.

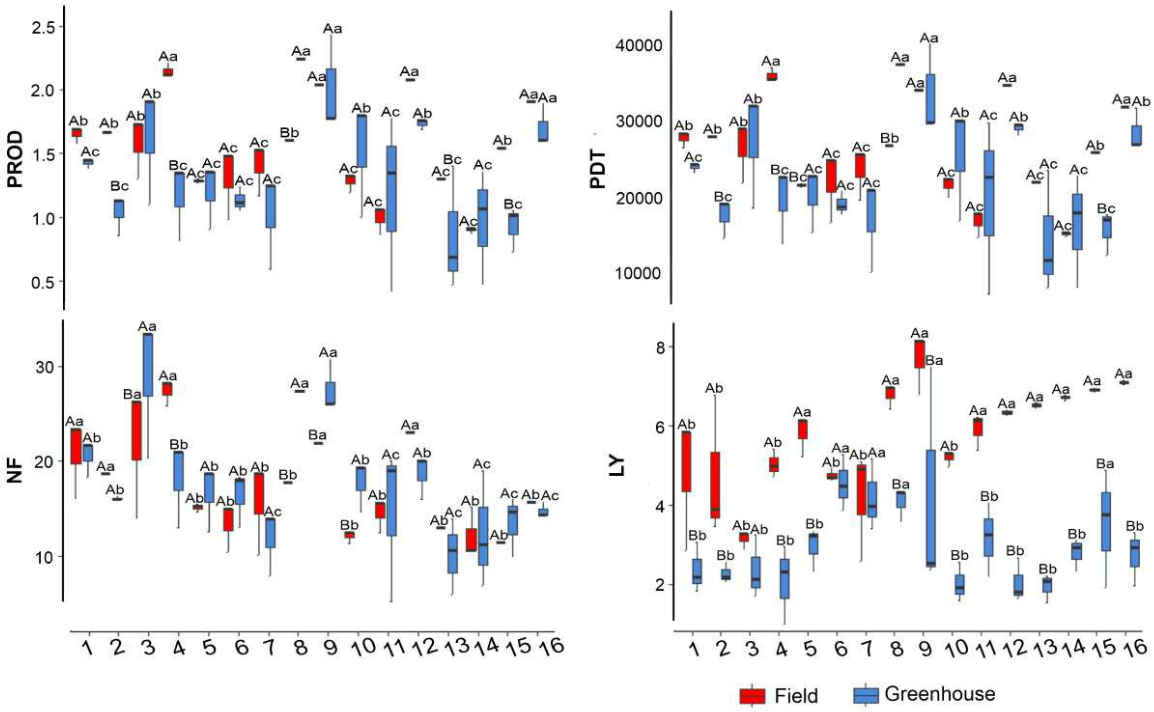
The comparison of metabolites among close relatives of cultivated tomatoes has been extensively studied for pest resistance (Vosman *et al.*, 2018), with limited information available on the use of dwarf tomatoes. Tomato plants with high acylsugar content exhibit pest resistance (Maluf *et al.*, 2010). The wild accession *S. pennellii* and the donor parent 'UFU MC TOM1' stand out for their high concentrations of this metabolite (Maciel *et al.*, 2024). The donor parent 'UFU MC TOM1' has been used for the introgression of pest resistance in tomatoes and has the potential to transfer resistance genes to hybrids (Finzi *et al.*, 2022; Maciel *et al.*, 2018; Pereira *et al.*, 2024b). This study demonstrated the performance of the wild accession *S. pennellii* and the donor parent 'UFU MC TOM1' in accumulating high levels of acylsugars (Figure 2). The hybrids UFU#2, UFU#3, UFU#6, UFU#8, UFU#9, UFU#11, and UFU#14 exhibited higher levels of acylsugars compared to the recurrent parent, cv. 'Santa Clara', and the commercial check. The hybrid UFU#12 stood out with values 100% higher than those found in the commercial check. These results provide valuable insights, demonstrating that the hybrids are promising for pest resistance, with more effective management strategies aimed at sustainability and the production of healthier products free from chemical pesticides.

Chromatographic analysis and metabolomic profiling contributed to the progress of research and the identification of additional compounds of interest in the donor parent 'UFU MC TOM1' (Figure 2). Groups I and II were formed by the compounds Glyceric Acid, Threonic Acid, 2-Aminoethanol, and Lactic Acid, Ribonic Acid, Oxalic Acid, Palmitic Acid, Stearic Acid, Alpha-Lactose, respectively. 'UFU MC TOM1' revealed superior results with intense colors and higher concentrations of the compounds in Group II in the leaflets compared to *S. pennellii* and the 'Santa Clara' cultivar. For Groups III and V, the donor parent was similar to *S. pennellii* and differed from the 'Santa Clara' cultivar in the compounds L-Alanine, L-5-oxoproline, Meso erythritol, L-Norleucine, and Melibiose and Succinic acid, respectively. Group IV was formed by the compounds D-Xylose and Quinic acid, and the donor parent showed cooler colors, indicating lower concentrations of these compounds compared to *S. pennellii* and the 'Santa Clara' cultivar.

Among the compounds found in the donor parent 'UFU MC TOM1', Glyceric Acid, Threonic Acid, Oxalic Acid, Palmitic Acid, and Stearic Acid stood out. Palmitic Acid contributes to plant growth, energy storage, cell signaling, and stress responses (Davis *et al.*, 1997; Abdel-Naime *et al.*, 2019). Stearic Acid reinforces cell membrane rigidity, providing protection against dehydration and pathogens (Song *et al.*, 2013). Oxalic Acid regulates pH, metabolism, and acts as a defense against pathogens (Franceschi & Nakata, 2005; Kumar, Irfan, & Datta, 2019). Glyceric Acid and Threonic Acid assist plants in oxidative stress responses. Additionally, Glyceric Acid plays a role in photosynthesis and cellular respiration, while Threonic Acid aids plants in ascorbic acid metabolism (Kleczkowski & Igamberdiev, 2024; Agarrwal, Bentur, & Nair, 2014). Notably, 'UFU MC TOM1' has great potential to foster future breeding programs aimed at plants with greater resilience to different types of biotic and abiotic stress.

Regarding hybrids derived from dwarf male parental lines, a significant effect was observed in the interaction between tomato hybrids and cultivation environments for agronomic and fruit quality traits: yield, productivity, number of fruits per plant, and lycopene content (Figure 3).

Figure 3 - Means related to agronomic and fruit quality evaluations for yield (PROD), productivity (PDT), number of fruits per plant (NF), and lycopene (LY) for significant interaction. Means followed by distinct letters differ from each other by the Scott-Knott test at 0.05 significance. Lowercase letters compare treatments within each environment, and uppercase letters compare environments within each treatment. Legend: 1 - UFU#1; 2 - UFU#2; 3 - UFU#3; 4 - UFU#4; 5 - UFU#5; 6 - UFU#6; 7 - UFU#7; 8- UFU#8; 9 - UFU#9; 10 - UFU#10; 11 - UFU#11; 12 - UFU#12; 13 - UFU#13; 14 - UFU#14; 15 - UFU#15; 16 - commercial check.



Source: Created by the author.

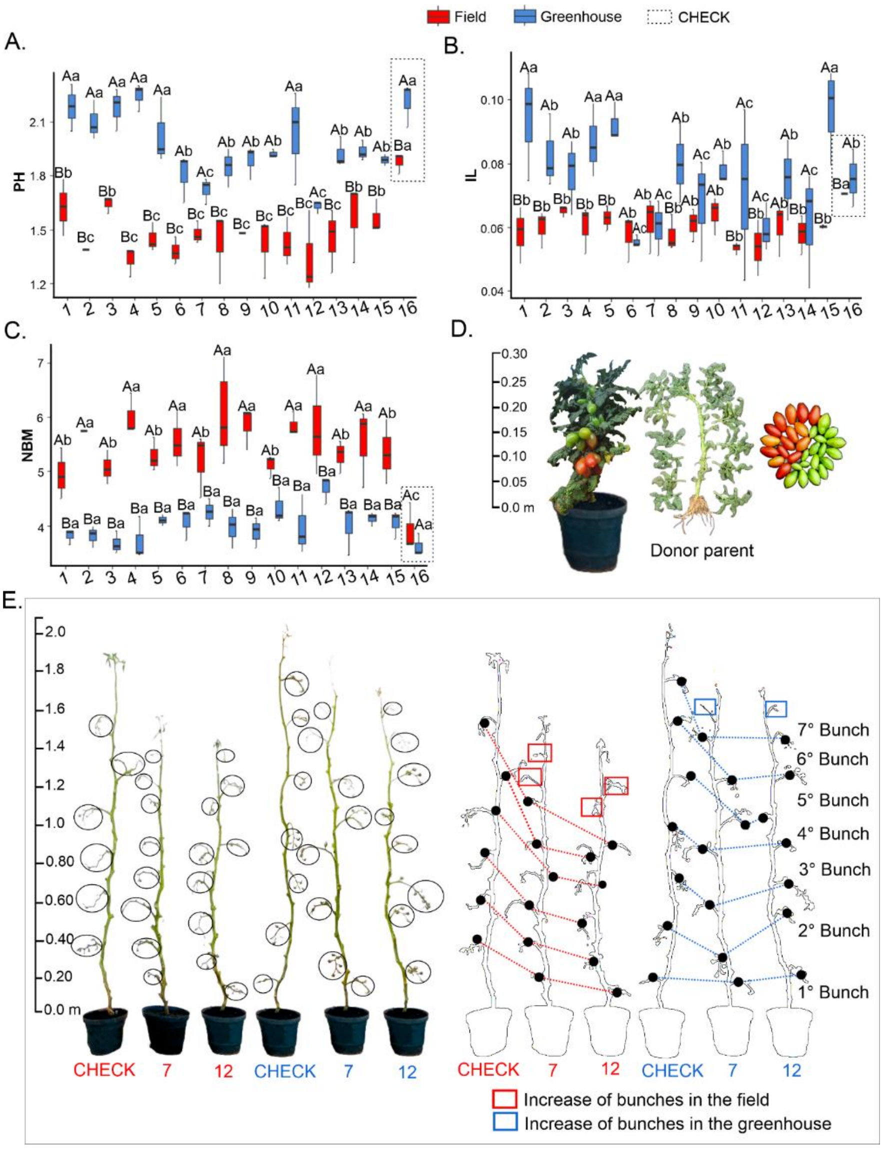
The hybrids UFU#4, UFU#2, UFU#8, UFU#13, and UFU#15 stood out for yield and productivity in the field compared to the greenhouse, except for UFU#8. In the field, the hybrids UFU#4, UFU#9, UFU#12, and the commercial check were superior. In the greenhouse, the hybrids UFU#8 and UFU#9 revealed superiority over the commercial check, with increases of 31.25% and 19.53% for yield and 31.70% and 19.65% for productivity, respectively. This indicates that the performance of the hybrids was influenced by the different cultivation systems adopted.

However, regardless of the cultivation system, there was an increase in yield and productivity in Santa Cruz-type hybrids derived from a dwarf parent. Through strategies in tomato breeding, the use of combinations with dwarf plants resulted in significantly productive hybrids with agronomic advantages (Finzi *et al.*, 2017; Pereira *et al.*, 2024b). Regarding the number of fruits, the greenhouse demonstrated superior performance in 31.5% of the hybrids analyzed. The hybrids UFU#1, UFU#2, UFU#3, UFU#4, UFU#9, and UFU#12 stood out in the field, while the hybrids UFU#8 and UFU#9 stood out in the greenhouse, both with superior performance to the commercial check.

In both environments, the hybrid UFU#9 stood out for high yield, productivity, and number of fruits, demonstrating the potential of the research in obtaining high-performance hybrids. In addition to productivity, the hybrid UFU#9 stood out in the field with a lycopene content of 7.6 mg/100 g^{-1}, 8.31% higher than the commercial check. In the greenhouse, the hybrids UFU#6, UFU#7, UFU#8, UFU#9, and UFU#15 showed higher lycopene content than the commercial check. Between the environments, the field demonstrated superior performance in 81.25% of the hybrids evaluated. The high lycopene content in the fruits is of great importance to consumers, as lycopene has essential antioxidant properties for human health (Mirondo & Barringer, 2015). The consumer market has shown a preference for more sustainable agriculture (Meng *et al.*, 2022) and the production of food with higher nutritional quality. Tomato breeding programs have prioritized the development of hybrids that combine high productivity and enhanced nutritional value of the fruits (Ilahy *et al.*, 2017). Thus, developing biofortified hybrids for bioactive compounds such as lycopene becomes essential.

Morphological traits such as plant height, internode length, and number of bunches per linear meter showed a significant interaction effect (Figure 4).

Figure 4 - (A, B, C) - Means related to morphological evaluations for plant height (PH), internode length (IL), and number of bunches per linear meter (NBM) for significant interaction. Means followed by distinct letters differ from each other by the Scott-Knott test at 0.05 significance. Lowercase letters compare treatments within each environment, and uppercase letters compare environments within each treatment. (D) – donor parent 'UFU MC TOM1'. (E) – Comparison of plant height and bunch development in field and greenhouse conditions. On the left, highlighted circles on the plants indicate the insertion points of the bunches. On the right, red and blue squares represent bunch development in the field and greenhouse, respectively. Legend: 1 - UFU#1; 2 - UFU#2; 3 - UFU#3; 4 - UFU#4; 5 - UFU#5; 6 - UFU#6; 7 - UFU#7; 8- UFU#8; 9 - UFU#9; 10 - UFU#10; 11 - UFU#11; 12 - UFU#12; 13 - UFU#13; 14 - UFU#14; 15 - UFU#15; 16 – commercial check.



Source: Created by the author.

The donor parent 'UFU MC TOM1' was used as a male parent to obtain promising dwarf lines through successive backcrosses (Maciel, Silva, & Fernandes, 2015) (Figure 4D). The cross between normal and dwarf lines resulted in Santa Cruz-type hybrids with modifications in plant architecture (Figure 4E). These results corroborate the study by Finzi *et al.* (2017) in mini-tomatoes, where compact plants were presented aiming to increase productivity.

Plant height and internode length were higher in the greenhouse, both in the hybrids and the commercial check. The results indicate etiolation caused by solar radiation and increased temperature in the greenhouse compared to the field (Seleguini *et al.*, 2016). Despite the etiolation, the commercial check showed greater height in all hybrids evaluated in the field and greenhouse, with average increases of 27.89% and 12.7%, respectively (Figure 4A). The hybrids UFU#7 and UFU#12 stood out in the environments for having lower heights, with 1.48 and 1.4 m in the field and 1.72 and 1.63 m in the greenhouse (Figure 4A).

The hybrids revealed reducing internode length in both environments. In the field, the commercial check showed higher values compared to all hybrids evaluated (Figure 4B). The lowest value was observed in the hybrid UFU#12, with a 31% reduction compared to the commercial check. In the greenhouse, 40% of the hybrids showed values lower than the commercial check, including the hybrids UFU#6, UFU#7, UFU#9, UFU#11, UFU#12, and UFU#14, which had an average internode length of 0.062 m. The structural modification in internode length and plant height provided an increase in the number of bunches per linear meter for both environments (Figure 4E).

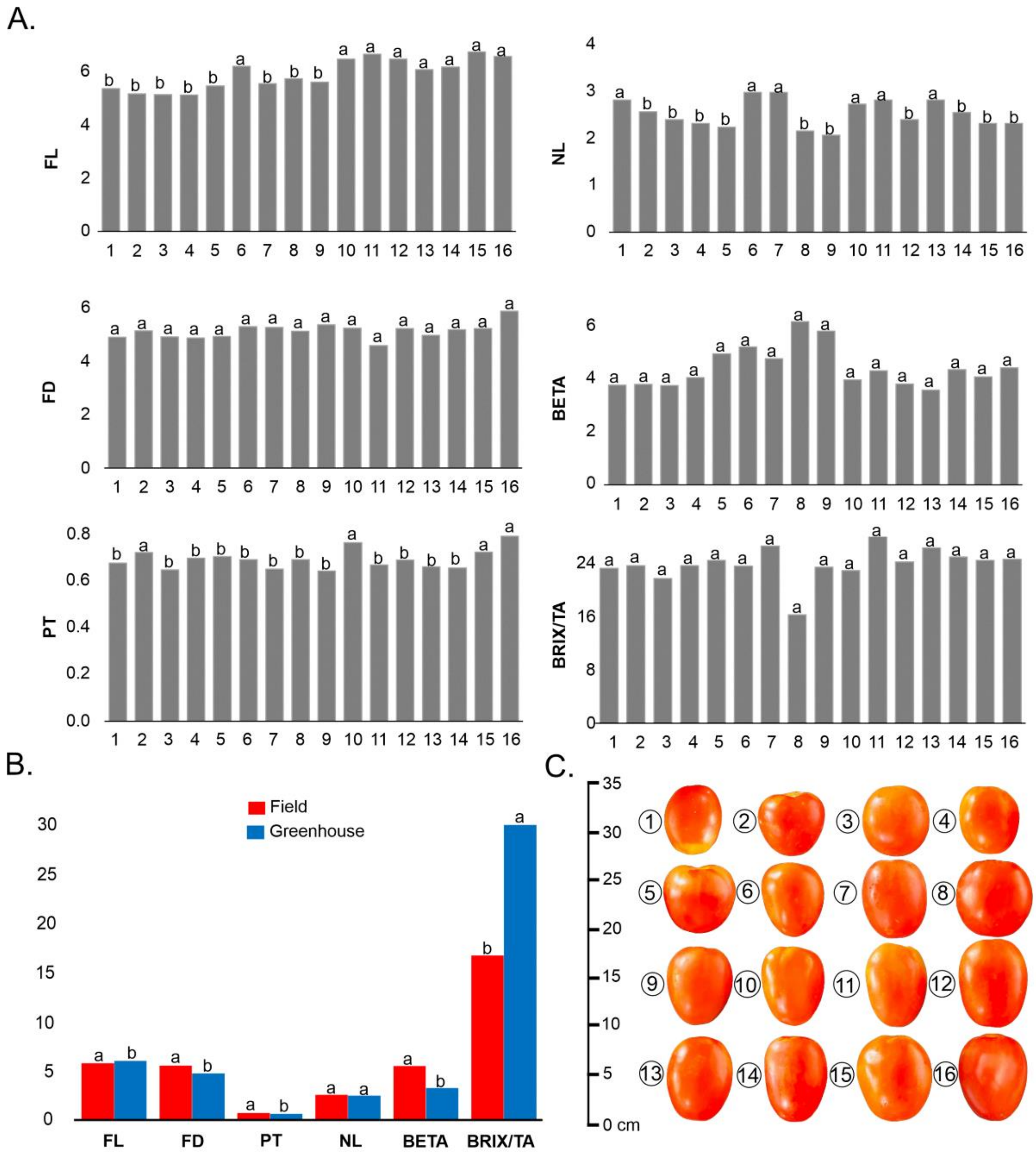
The field environment was superior to the greenhouse regarding the number of bunches per linear meter for all hybrids, except for the commercial check. This demonstrates that the field provided a higher density of bunches compared to the greenhouse at the time of evaluation. However, it cannot be concluded that the cultivation in the greenhouse was unfavorable, as the hybrids UFU#12 and UFU#7 showed an increase of 29.5% and 17.40%, respectively, compared to the commercial check in the greenhouse. In the field, the hybrids UFU#8, UFU#4, UFU#9, UFU#11, UFU#12, UFU#2, UFU#6, and UFU#14 demonstrated an average of 5.81 bunches per linear meter, representing a 48.5% increase compared to the commercial check, which had 3.91 bunches per linear meter.

As shown in Figure 4E, the hybrids UFU#7 and UFU#12 revealed an increase of two bunches per plant in the field and one bunch per plant in the greenhouse. According to recommendations by Silva *et al.* (2019), when the tomato plant reaches about 1.8 m, apical pruning is performed. After this pruning, the hybrids UFU#7 and UFU#12 had about 8.09 and 8.49 bunches in the greenhouse and 9.32 and 10.30 in the field, respectively. In comparison, the commercial check had 6.51 bunches in the greenhouse and 7.01 bunches in the field after apical pruning. These results demonstrate a significant increase in the number of bunches per plant, resulting in increased productivity due to the use of dwarf lines for hybrid formation.

This strategy proves effective in optimizing production, both in the field and greenhouse. The hybrids derived from dwarf lines in this study found differentiated morphology, with more compact plants and short internodes. Research aimed at increasing tomato productivity through structural modifications without altering crop management is scarce. Studies on increasing productivity focus on adopting cultural practices, spacing adjustments, and fertilization, which require management adjustments and high production costs (Campos *et al.*, 2025; Niu *et al.*, 2024).

There was no significant effect between environments and treatments on fruit length, fruit diameter, pulp thickness, number of locules, β-carotene, and BRIX/TA (Figure 5).

Figure 5 - Means related to evaluations of fruit length (FL), fruit diameter (FD), pulp thickness (PT), number of locules (NL), β-carotene (BETA), and BRIX/TA of fruits between environments and treatments. Non-significant interaction in isolation between treatments (A). Non-significant interaction in isolation between environments (B). Means followed by distinct letters differ from each other by the Scott-Knott test at 0.05 significance. Legend: 1 - UFU#1; 2 - UFU#2; 3 - UFU#3; 4 - UFU#4; 5 - UFU#5; 6 - UFU#6; 7 - UFU#7; 8- UFU#8; 9 - UFU#9; 10 - UFU#10; 11 - UFU#11; 12 - UFU#12; 13 - UFU#13; 14 - UFU#14; 15 - UFU#15; 16 – commercial check.



Source: Created by the author.

The fruits were superior in the field compared to the greenhouse for the variables fruit length, fruit diameter, pulp thickness, number of locules, and β-carotene, except for BRIX/TA of fruits (Figure 5).

The hybrids differed for the traits fruit length, number of locules, and pulp thickness. The hybrids UFU#6, UFU#10, UFU#11, UFU#12, UFU#13, UFU#14, and UFU#15 showed an average fruit length of 6.30 cm, similar to the commercial check. The fruit shape confirms that the hybrids belong to the Santa Cruz type (Figure 5C) (Resende *et al.*, 2020). The diversity in fruit size and shape highlights the importance of selecting parental lines in breeding. This choice allows the selection of hybrids with desirable traits for the market (Mattedi *et al.*, 2015).

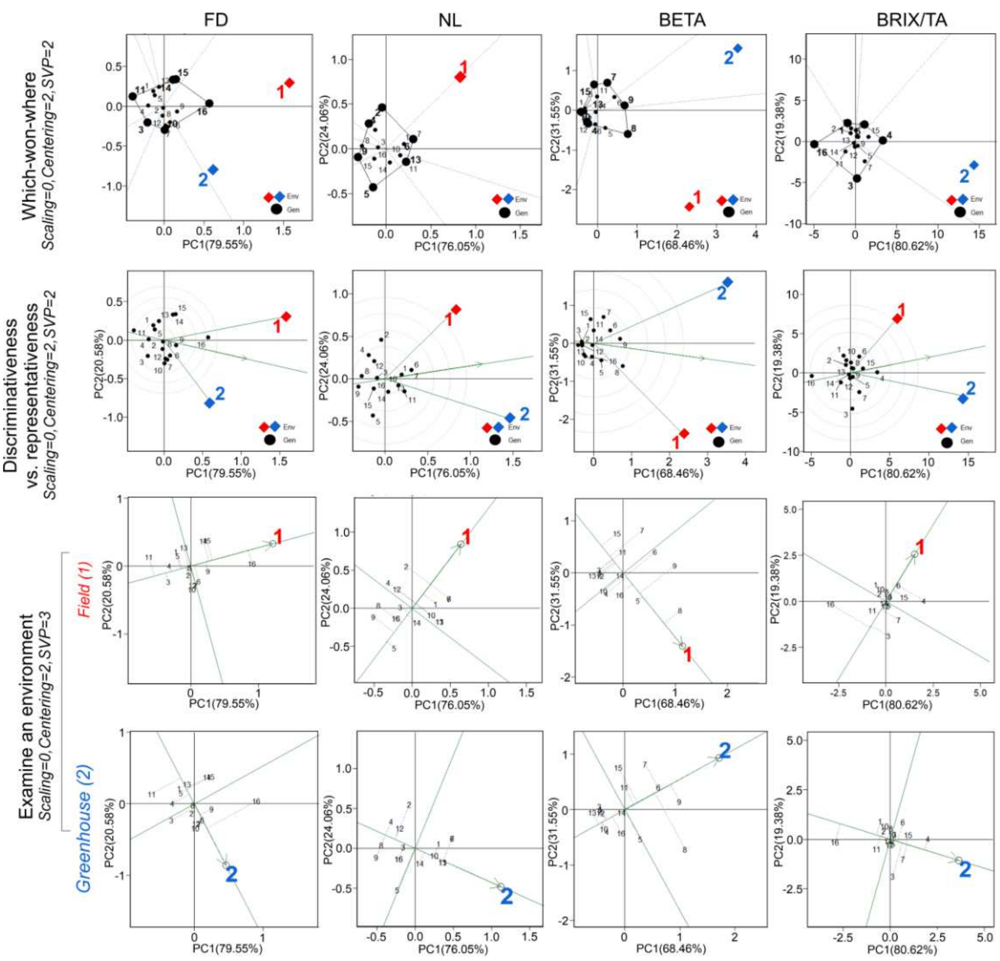
The hybrids UFU#2, UFU#10, and UFU#15 were similar to the commercial check regarding pulp thickness, with an average of 0.74 cm. For the number of locules, 37% of the hybrids evaluated were superior to the commercial check, which had an average of 3 locules per fruit. The hybrids UFU#2 and UFU#15 had fewer locules and thicker pulp, resulting in firmer fruits and a longer shelf life (Pavan *et al.*, 2022).

No significant differences were observed for the traits fruit diameter, BRIX/TA, and β-carotene (BETA) (Figure 5A). The results indicate that the fruits of the hybrids demonstrate promising quality compared to commercial standards, showing potential to achieve satisfactory consumer acceptability (Adegbola *et al.*, 2019). The BRIX/TA is related to fruit flavor, with higher values indicating sweeter and less acidic fruits (Araujo *et al.*, 2014).

The tomato fruit is considered a functional food, because contains carotenoids and other compounds with antioxidant and anti-inflammatory activity, such as phenolic acids, and flavonoids, which contribute to cancer prevention (Chaudhary *et al.*, 2018; Fernandes *et al.*, 2021). Regarding β-carotene content, 31.25% of the hybrids showed values higher than the commercial check. It is worth noting that dwarf tomato lines have shown higher levels of lycopene and β-carotene (Oliveira *et al*., 2024). Thus, the hybrids reveal promise for obtaining biofortified fruits.

After identifying significant differences in the genotype-environment interaction for the traits fruit diameter, number of locules, β-carotene, and BRIX/TA, the Genotype-vs-Environment interaction (GGE biplot) method was employed to analyze the interaction and stability (Yan *et al.*, 2007) (Figure 6).

Figure 6 - GGE Biplot (Genotype-vs-Environment interaction). Legend: 1 - UFU#1; 2 - UFU#2; 3 - UFU#3; 4 - UFU#4; 5 - UFU#5; 6 - UFU#6; 7 - UFU#7; 8- UFU#8; 9 - UFU#9; 10 - UFU#10; 11 - UFU#11; 12 - UFU#12; 13 - UFU#13; 14 - UFU#14; 15 - UFU#15; 16 - commercial check. FD - fruit diameter; NL - number of locules; BETA - β-carotene; BRIX/TA - Brix/titratable acidity ratio; PC1-first principal components; PC2-second principal components; Field: in red; Greenhouse: in blue.



Source: Created by the author.

The conventional G x E method is considered limited, as it emphasizes main effects, making it difficult to select superior genotypes (Coelho *et al.*, 2024). Therefore, it is essential to use effective methods that consider the genotype (G) and the genotype + environment interaction (GE). The GGE Biplot model allows understanding how genotypes behave in different environments through graphs and explains the evaluation of performance and stability individually (Divéky-Ertsey *et al.*, 2022).

The principal components explained 100% of the variation observed in the experiment. For fruit diameter, PC1 represents 79.55% of the variation, while PC2 represents 20.45%. For the number of locules, PC1 explains 76.04%, and PC2 explains 23.98%. For β-carotene, the variation is composed of 68.46% PC1 and 31.54% PC2. For BRIX/TA, PC1 explains 79.5%, and PC2 explains 20.45%.

The "which-won-where" graphs show the ability of genotypes to respond to environments (Alves *et al.*, 2020). The generated polygon represents the most distant and responsive genotypes, i.e., those that demonstrate superior performance. The lines dividing the biplot into sectors contain a vertex genotype, and within this sector, environments are divided into groups. For fruit diameter, the commercial check stood out in both environments, with a value of 5.88 cm. Regarding the number of locules, UFU#7 was superior in the field, while for BRIX/TA, the treatment UFU#4 was superior in the greenhouse. For β-carotene, UFU#9 and UFU#8 stood out in the greenhouse and field, respectively.

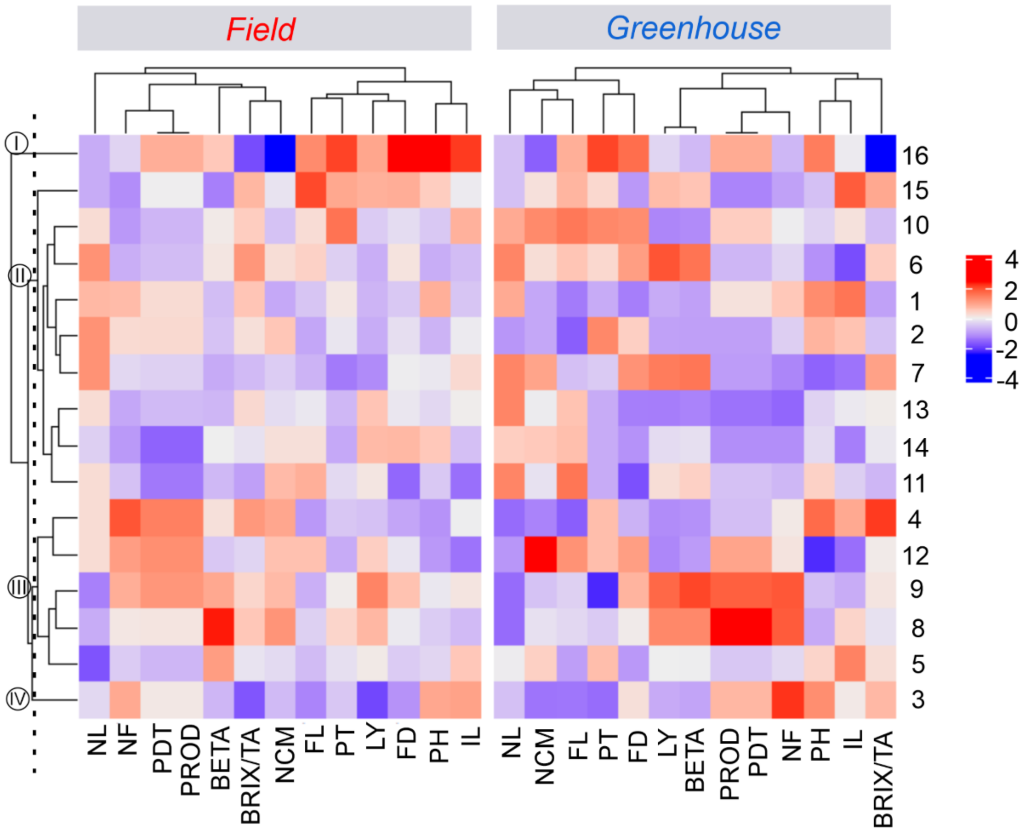
The visualization of the Discriminative *vs*. Representative biplot shows the comparison between the two environments (Kumar *et al.*, 2020). As the vector increases, environmental discrimination is greater. Thus, the farther the vector, the more superior the environment can be considered for a given trait. If the vectors are short and less discrepant, the genotypes tend to be similar, indicating no differences between locations. In this study, the vectors were long for the evaluated environments, with the greenhouse having the longest vector among the analyzed variables, except for fruit diameter.

To identify the genotypes most adapted to a given environment, the "examine the environment" graphs are used individually (De Meyer *et al.*, 2024). The genotypes are classified by mean and stability and are represented in the biplot by coordinates. Regarding fruit diameter, the commercial check and the hybrids UFU#16, UFU#15, and UFU#14 stood out in the field, while in the greenhouse, the hybrids UFU#12 and UFU#10 and the commercial check stood out. For the number of locules, the hybrids UFU#6 and UFU#7 were superior in both environments, followed by UFU#2 in the field and UFU#12 in the greenhouse.

For β-carotene, the hybrids UFU#9 and UFU#8 stood out in both environments, followed by UFU#5 in the field and UFU#9 in the greenhouse. Regarding BRIX/TA, the hybrids UFU#15 and UFU#4 stood out in both environments. However, the hybrids UFU#4 and UFU#7 were superior in the field and greenhouse, respectively.

The hybrids found significant gains compared to those available in the market. Although, it is necessary to study the dissimilarity between the hybrids to understand their potential in the environments. To visualize the genetic dissimilarity of the hybrids and the differences between the analyzed environments, a heat map complemented by a dendrogram obtained by the UPGMA method and the generalized Mahalanobis matrix was used (Figure 7).

Figure 7 - Heat map for the evaluation of hybrid dissimilarity. Intense red coloration indicates a greater contribution of the response variable in each hybrid and environment. Legend: 1 - UFU#1; 2 - UFU#2; 3 - UFU#3; 4 - UFU#4; 5 - UFU#5; 6 - UFU#6; 7 - UFU#7; 8- UFU#8; 9 - UFU#9; 10 - UFU#10; 11 - UFU#11; 12 - UFU#12; 13 - UFU#13; 14 - UFU#14; 15 - UFU#15; 16 - commercial check. PH - plant height; IL - internode length; NBM - number of bunches per linear meter; PROD - yield; PDT – productivity; NF - number of fruits per plant; LY – lycopene; FL - fruit length; FD - fruit diameter; PT- pulp thickness; NL - number of locules; BETA - β-carotene; and BRIX/TA - Brix/titratable acidity ratio.



Source: Created by the author.

The dendrogram resulted in the formation of four groups. The group I was composed of the commercial check, the group II by the hybrids UFU#15, UFU#10, UFU#6, UFU#1, UFU#2, UFU#7, UFU#13, UFU#14, and UFU#11, the group III by the hybrids UFU#14, UFU#12, UFU#9, UFU#8, and UFU#5, and the group IV by the hybrid UFU#3. The definition of the groups is based on a cutoff line where abrupt changes occur in the dendrogram levels and through the breeder's prior knowledge (Cruz, Carneiro, & Regazzi, 2014).

The greatest distances between the hybrids and the commercial check were 517.9 for hybrid 11 in the field and 105.7 for hybrid 3 in the greenhouse. The distances highlight the variability between the hybrids and the commercial check. In the field, 68.7% of the hybrids demonstrated greater distances in comparison to the commercial check, while in the greenhouse, 11% of the hybrids did. The heat map confirms the variability between the hybrids and the commercial check in both environments.

The colors represent the influence of each variable on the individuals. Intense blue indicates extremes with less prominence, and intense red indicates extremes with greater prominence. In the field and greenhouse, the commercial check showed red colors, signaling higher values for plant height and internode length. Regarding the number of bunches per linear meter (NBM), the commercial check showed blue colors, indicating lower values in both environments. These results confirm what was shown earlier and highlight the potential of the research in both environments (Figure 4).

The introduction of dwarfism genes through dwarf lines resulted in more compact plants, high productivity, and higher fruit quality, which can be considered biofortified.

CONCLUSIONS

In conclusion, the study shows that tomato hybrids obtained from crosses between normal and dwarf lines resulted in structural changes in the plants, including reduced internode length and a higher number of bunches per linear meter of plant, both in the field and greenhouse. The hybrids found biofortified fruits and high levels of acylsugars aimed at pest resistance. ‘UFU MC TOM1’, the donor parent contains several metabolites pathways that regulate various types of biotic and abiotic stress.

REFERENCES

ABDEL-NAIME, W. A. *et al.* Antibacterial, antifungal, and GC-MS studies of Melissa officinalis. *South African Journal of Botany*, v. 124, p. 228-234, 2019. DOI: https://doi.org/10.1016/j.sajb.2019.05.011. Acesso em: 2 dez. 2024.

ADEGBOLA, Y. P. *et al.* Consumer preferences for fresh tomatoes in Benin using a conjoint analysis. *Journal of International Food & Agribusiness Marketing*, v. 31, n. 1, p. 1-21, 2019. DOI: http://dx.doi.org/10.1080/08974438.2018.1469448. Acesso em: 2 dez. 2024.

AGGARWAL, R.; BENTUR, J. S.; NAIR, S. Gas chromatography mass spectrometry-based metabolic profiling reveals biomarkers involved in rice-gall midge interactions. *Journal of Integrative Plant Biology*, v. 56, n. 9, p. 515-524, 2014. DOI: https://doi.org/10.1111/jipb.12244. Acesso em: 2 dez. 2024.

ALI, A. *et al.* Quality and physiological evaluation of tomato subjected to different supplemental lighting systems. Scientia Horticulturae, v. 323, p. 112469, 2024. DOI: http://dx.doi.org/10.1016/j.scienta.2023.112469. Acesso em: 2 dez. 2024.

ALVARENGA, M. A. R.; COELHO, F. S. Exigências climáticas. *In*: ALVARENGA, M. A. R. *Tomate*: produção em campo, casa-de-vegetação e em hidroponia. Lavras: Editora UFLA, 2013. p. 31-37.

ALVES, M. V. *et al*. Desempenho agronômico e qualitativo de cultivares de feijoeiro dos grupos comerciais carioca e especial na época de inverno. *Revista de La Facultad de Agronomía*, v. 119, n. 1, p. 46, 2020. DOI: https://doi.org/10.24215/16699513e046. Acesso em: 2 dez. 2024.

ARAUJO, J. C. *et al.* Physico-chemical and sensory parameters of tomato cultivars grown in organic systems. *Horticultura Brasileira*, v. 32, n. 2, p. 205-209, 2014. DOI: http://dx.doi.org/10.1590/S0102-05362014000200015. Acesso em: 2 dez. 2024.

CAMPOS, C. M. A. *et al.* Plant density and planting arrangement for tomato plants of determinate growth. *Revista Brasileira de Engenharia Agrícola e Ambiental*, Campina Grande, v. 29, n. 1, e278914, 2025. DOI: http://dx.doi.org/10.1590/1807-1929/agriambi.v29n1e278914. Acesso em: 5 dez. 2024.

CHAUDHARY, P. *et al.* Bioactivities of phytochemicals present in tomato. *Journal of Food Science and Technology*, v. 55, p. 2833-2849, 2018. DOI: https://doi.org/10.1007/s13197-018-3221-z. Acesso em: 5 dez. 2024.

COELHO, F. G. T. *et al.* Analysis of combining ability to obtain tropical carrot hybrids for production traits. *Horticulturae*, v. 10, n. 5, p. 442, 2024. DOI: https://doi.org/10.3390/horticulturae10050442. Acesso em: 5 dez. 2024.

CRUZ, C. D.; CARNEIRO, P. C. S.; REGAZZI, A. J. *Modelos biométricos aplicados ao melhoramento genético*. 3. ed. Viçosa, MG: Editora UFV, 2014. v. 2. 668 p.

CRUZ, C. D. Genes software extended and integrated with the R, MATLAB and Selegen. *Acta Scientiarum. Agronomy*, v. 38, n. 4, p. 547-552, 2016. DOI: https://doi.org/10.4025/actasciagron.v38i4.32629. Acesso em: 5 dez. 2024.

DAGADE, S. B. *et al.* Estimating combining ability effect of the Indian and exotic lines of tomatoes by partial diallel analysis. *Turkish Journal of Agriculture - Food Science and Technology*, v. 3, n. 9, p. 715-720, 2015. DOI: http://dx.doi.org/10.24925/turjaf.v3i9.715-720.319. Acesso em: 5 dez. 2024.

DAVIS, E. L. *et al.* Nematicidal activity of fatty acid esters on soybean cyst and root-knot nematodes. *Journal of Nematology*, v. 29, n. 4S, p. 677-684, 1997. Acesso em: 5 dez. 2024.

DE MEYER, E. *et al.* Evaluating genetic diversity and seed composition stability within Pan-African soybean variety trials. *Crop Science*, v. 64, n. 6, p. 3272-3292, 2024. DOI: http://dx.doi.org/10.1002/csc2.21356. Acesso em: 5 dez. 2024.

OLIVEIRA, M. P. G. *et al.* Tomato plants' growth observations obtained from multiple sources in a production-like setting. *SciELO Preprints*, 2024. DOI: https://doi.org/10.1590/SciELOPreprints.7667. Acesso em: 5 dez. 2024.

DEVIRGILIIS, C. *et al.* Effect of fruit and vegetable consumption on human health: An update of the literature. *Foods*, v. 13, n. 19, p. 3149, 2024. DOI: https://doi.org/10.3390/foods13193149. Acesso em: 5 dez. 2024.

DIVÉKY-ERTSEY, A. *et al.* Tomato landraces may benefit from protected production—evaluation on phytochemicals. *Horticulturae*, v. 8, n. 10, p. 937, 2022. DOI: https://doi.org/10.3390/horticulturae8100937. Acesso em: 5 dez. 2024.

EGEA, I. *et al.* The drought-tolerant Solanum pennellii regulates leaf water loss and induces genes involved in amino acid and ethylene/jasmonate metabolism under dehydration. *Scientific Reports*, v. 8, p. 2791, 2018. DOI: https://doi.org/10.1038/s41598-018-21187-2. Acesso em: 5 dez. 2024.

FELFÖLDI, Z. *et al.* Physico-chemical, nutritional, and sensory evaluation of two new commercial tomato hybrids and their parental lines. *Plants*, v. 10, n. 11, p. 2480, 2021. DOI: https://doi.org/10.3390/plants10112480. Acesso em: 5 dez. 2024.

FERNANDES, I. *et al.* Influence of crop system fruit quality, carotenoids, fatty acids and phenolic compounds in cherry tomatoes. *Agricultural Research*, v. 10, p. 56-65, 2021. DOI: https://doi.org/10.1007/s40003-020-00478-z. Acesso em: 5 dez. 2024.

FILGUEIRA, F. A. R. *Novo manual de olericultura: agrotecnologia moderna na produção e comercialização de hortaliças*. 3. ed. Viçosa, MG: Editora UFV, 2013. 402 p.

FINZI, R. R. *et al.* Agronomic performance of mini-tomato hybrids from dwarf lines. *Ciência e Agrotecnologia*, v. 41, n. 1, p. 15-21, 2017. DOI: http://dx.doi.org/10.1590/1413-70542017411021416. Acesso em: 5 dez. 2024.

FINZI, R. R. *et al.* Agronomic potential, pest resistance, and fruit quality in BC1F3 dwarf round tomato populations. *Comunicata Scientiae*, v. 13, p. e3759, 2022. DOI: https://doi.org/10.14295/cs.v13.3759. Acesso em: 5 dez. 2024.

FLORES, F. *et al.* Adaptability and yield performance of introduced tomato lines under greenhouse and open field conditions in Honduras. *HortScience*, v. 59, n. 8, p. 1041-1048, 2024. DOI: https://doi.org/10.21273/HORTSCI17753-24. Acesso em: 5 dez. 2024.

FRANCESCHI, V. R.; NAKATA, P. A. Calcium oxalate in plants: formation and function. *Annual Review of Plant Biology*, v. 56, p. 41-71, 2005. DOI: https://doi.org/10.1146/annurev.arplant.56.032604.144106. Acesso em: 6 dez. 2024.

FURLANETO, F. P. B. *et al.* Quality of tomato fruits in protected growth. *Research, Society and Development*, v. 11, n. 11, p. e417111133938, 2022. DOI: http://dx.doi.org/10.33448/rsd-v11i11.33938. Acesso em: 6 dez. 2024.

GOMES, D. A. *et al.* Selection of BC1F3 populations of Santa Cruz type dwarf tomato plant by computational intelligence techniques. *Bragantia*, v. 80, p. e4821, 2021. DOI: https://doi.org/10.1590/1678-4499.20210046. Acesso em: 6 dez. 2024.

GOMES, D. A. *et al.* Dwarf tomato plants allow for managing agronomic yield gains with fruit quality and pest resistance through backcrossing. *Agronomy*, v. 12, n. 12, p. 3087, 2022. DOI: https://doi.org/10.3390/agronomy12123087. Acesso em: 6 dez. 2024.

GOMES, D. A. *et al.* Agronomic potential of BC1F2 populations of Santa Cruz type dwarf tomato plant. *Acta Scientiarum. Agronomy*, v. 45, n. 1, p. e56482, 2023. DOI: https://doi.org/10.4025/actasciagron.v45i1.56482. Acesso em: 6 dez. 2024.

ILAHY, R. *et al.* A focus on high-lycopene tomato cultivars: horticultural performance and functional quality. *Acta Horticulturae*, v. 1159, p. 57-64, 2017. DOI: https://doi.org/10.17660/ActaHortic.2017.1159.9. Acesso em: 6 dez. 2024.

JACINTO, A. C. P. *et al*. Reaction of tomato lineages and hybrids to Xanthomonas euvesicatoria pv. perforans. *Agronomy,* v. 14, n. 6, p. 1211, 2024. DOI: https://doi.org/10.3390/agronomy14061211. Acesso em: 6 dez. 2024.

KLECZKOWSKI, L. A.; IGAMBERDIEV, A. U. Multiple roles of glycerate kinase—From photorespiration to gluconeogenesis, C4 metabolism, and plant immunity. *International Journal of Molecular Sciences*, v. 25, n. 6, p. 3258, 2024. DOI: https://doi.org/10.3390/ijms25063258. Acesso em: 6 dez. 2024.

KUMAR, V.; IRFAN, M.; DATTA, A. Manipulação do metabolismo do oxalato em plantas para melhoria da qualidade e produtividade dos alimentos. *Phytochemistry*, v. 158, p. 103-109, 2019. DOI: https://doi.org/10.1016/j.phytochem.2018.10.029. Acesso em: 6 dez. 2024.

KUMAR, V. *et al.* G × E models for yield adaptation and target environment analysis in barley (Hordeum vulgare). *Indian Journal of Agricultural Sciences*, v. 90, n. 1, p. 128-132, 2020. DOI: https://doi.org/10.56093/ijas.v90i1.98590. Acesso em: 6 dez. 2024.

LEON-CALVARIO, I. *et al.* Tomato grafted and cultivated in saline medium and its relation on nutraceutical compounds of the fruits. *Pakistan Journal of Botany*, v. 52, n. 3, p. 811-819, 2020. DOI: https://doi.org/10.30848/PJB2020-3(6). Acesso em: 6 dez. 2024.

MACIEL, G. M.; SILVA, E. C. Methodological proposal to quantify acylsugars in tomato leaflets. *Horticultura Brasileira*, v. 32, n. 2, p. 174-177, 2014. DOI: http://dx.doi.org/10.1590/S0102-05362014000200009. Acesso em: 6 dez. 2024.

MACIEL, G. M.; SILVA, E. C.; FERNANDES, M. A. R. Dwarfism occurrence in tomato plant type grape. *Revista Caatinga*, v. 28, n. 4, p. 259-264, 2015. Acesso em: 6 dez. 2024.

MACIEL, G. M. *et al.* Multivariate techniques in the determination of genetic diversity in pest-resistant mini tomato genotypes. *Horticultura Brasileira*, v. 36, n. 4, p. 504-509, 2018. DOI: http://dx.doi.org/10.1590/S0102-053620180413. Acesso em: 6 dez. 2024.

MACIEL, G. M. *et al.* BG a BIOFORT (programa de computador).[*s.l*]: Universidade Federal de Uberlândia-UFU, 2019. Registro BR512019002403-6, 2019.

MACIEL, G. M. *et al.* New insights into the use of dwarf tomato plants for pest resistance. *Bragantia*, v. 83, e20240066, 2024. DOI: https://doi.org/10.1590/1678-4499.20240066. Acesso em: 6 dez. 2024.

MALUF, W. R. *et al.* Broad-spectrum arthropod resistance in hybrids between high- and low-acylsugar tomato lines. *Crop Science*, v. 50, n. 2, p. 439-450, 2010. DOI: https://doi.org/10.2135/cropsci2009.01.0045. Acesso em: 6 dez. 2024.

MATTEDI, A. P. *et al.* Genetic divergence of tomato subsamples. *Revista Ceres*, v. 61, n. 1, p. 70-76, 2015. DOI: http://dx.doi.org/10.1590/S0034-737X2014000100009. Acesso em: 6 dez. 2024.

MENG, F. *et al.* Carotenoid biofortification in tomato products along the whole agro-food chain from field to fork. *Trends in Food Science & Technology*, v. 124, p. 296-308, 2022. DOI: https://doi.org/10.1016/j.tifs.2022.04.023. Acesso em: 6 dez. 2024.

MIRONDO, R.; BARRINGER, S. Improvement of flavor and viscosity in hot and cold break tomato juice and sauce by peel removal. *Journal of Food Science*, v. 80, n. 1, p. 171-179, 2015. DOI: https://doi.org/10.1111/1750-3841.12725. Acesso em: 6 dez. 2024.

NASCIMENTO, F. A. *et al.* Farmers exposed to pesticides have almost five times more DNA damage: A meta-analysis study. *Environmental Science and Pollution Research*, v. 29, p. 805-816, 2021. DOI: https://doi.org/10.1007/s11356-021-15573-z. Acesso em: 6 dez. 2024.

NIU, H. *et al.* Optimal irrigation and fertilization enhanced tomato yield and water and nitrogen productivities by increasing rhizosphere microbial nitrogen fixation. *Agronomy*, v. 14, n. 9, p. 2111, 2024. Acesso em: 6 dez. 2024.

NKANSAH, G. O. *et al.* Influence of topping and spacing on growth, yield, and fruit quality of tomato (Solanum lycopersicum L.) under greenhouse condition. *Frontiers in Sustainable Food Systems*, v. 5, p. 659047, 2021. DOI: https://doi.org/10.3389/fsufs.2021.659047. Acesso em: 6 dez. 2024.

OLIVEIRA, C. S. *et al.* Selection of F2RC1 saladette-type dwarf tomato plant populations for fruit quality and whitefly resistance. *Revista Brasileira de Engenharia Agrícola e Ambiental*, v. 26, n. 1, p. 28-35, 2022. DOI: https://doi.org/10.1590/1807-1929/agriambi.v26n1p28-35. Acesso em: 6 dez. 2024.

OLIVEIRA, C. S. *et al.* Saladette-type dwarf tomato introgression lines with agronomic potential, improved fruit quality, and biotic stress tolerance. *Ciência e Agrotecnologia*, v. 48, e002624, 2024. DOI: https://doi.org/10.1590/1413-7054202448002624. Acesso em: 6 dez. 2024.

PAVAN, M. P. *et al.* Heterosis and combining ability studies by line × tester analysis for fruit biochemical, morpho-physiological, and yield traits governing shelf life in tomato (Solanum lycopersicum L.). *Euphytica*, v. 218, p. 90, 2022. DOI: https://doi.org/10.1007/s10681-022-03038-4. Acesso em: 6 dez. 2024.

PEREIRA, L. M. *et al.* Additional advantages for agronomic performance and fruit quality in tomato hybrids of the Saladette type derived from a dwarf male parent. *Horticulturae*, v. 10, n. 11, p. 1145, 2024. DOI: https://doi.org/10.3390/horticulturae10111145. Acesso em: 6 dez. 2024.

PEREIRA, L. M. *et al.* Introgression of the self-pruning gene into dwarf tomatoes to obtain salad-type determinate growth lines. *Plants*, v. 13, n. 11, p. 1522, 2024. DOI: https://doi.org/10.3390/plants13111522. Acesso em: 6 dez. 2024.

R CORE TEAM. R: a language and environment for statistical computing. s.l.: R Foundation for Statistical Computing, 2024. Disponível em: https://www.r-project.org/. Acesso em: 28 jan. 2026.

RESENDE, J. T. V. *et al.* Colorimetric method for quantifying acylsugars in tomato genotypes. *Ciência e Agrotecnologia*, v. 26, p. 1204-1208, 2002. Acesso em: 6 dez. 2024.

RESENDE, N. C. V. *et al.* Selection of tomato lines and populations for fruit shape and resistance to tomato leafminer. *Horticultura Brasileira*, v. 38, n. 2, p. 671-676, 2020. DOI: https://doi.org/10.1590/S0102-053620200202. Acesso em: 6 dez. 2024.

RIBEIRO, A. L. A. *et al.* Genetic variation, agronomic potential, and acylsugar content in Santa Cruz dwarf tomato after backcrossings. *Crop Breeding and Applied Biotechnology*, v. 42, n. 3, e48722438, 2024. DOI: http://dx.doi.org/10.1590/1984-70332024v24n3a33. Acesso em: 9 dez. 2024.

RODRIGUEZ-AMAYA, D. B. *A guide to carotenoid analysis in foods*. Washington: International Life Sciences Institute Press, 2001.

RODRIGUEZ-AMAYA, D. B.; KIMURA, M. *Handbook for carotenoid analysis*. Washington: HarvestPlus, 2004.

ROSELL, M.; FADNES, L. T. Vegetables, fruits, and berries A scoping review for Nordic Nutrition Recommendations 2023. *Food & Nutrition Research*, v. 68, 2024. DOI: https://doi.org/10.29219/fnr.v68.10455. Acesso em: 9 dez. 2024.

SAHU, S. P.; JOSHI, R. K.; MISHRA, R. Genome editing technologies towards tomato improvement: recent advances and future perspectives. *Journal of Experimental Biology and Agricultural Sciences*, v. 12, n. 4, p. 537-556, 2024. DOI: https://doi.org/10.18006/2024.12(4).537.556. Acesso em: 9 dez. 2024.

SELEGUINI, A. *et al.* Paclobutrazol effect on plant growth and tomato (Solanum lycopersicum L.) production in protected environment. *Scientia Agropecuaria*, v. 7, n. 4, p. 351-358, 2016. DOI: https://doi.org/10.17268/sci.agropecu.2016.04.04. Acesso em: 9 dez. 2024.

SILVA, R. V. *et al.* Production of tomato Santa Cruz in function of organic fertilization in Nova Xavantina-MT. *Revista Brasileira de Ciências Agrárias*, v. 14, n. 1, p. 10-21, 2019. Acesso em: 9 dez. 2024.

SONG, N. *et al*. Overexpression of a wheat stearoyl-ACP desaturase (SACPD) gene TaSSI2 in Arabidopsis ssi2 mutant compromises its resistance to powdery mildew. *Gene*, v. 524, n. 2, p. 220-227, 2013. DOI: https://doi.org/10.1016/j.gene.2013.04.019. Acesso em: 9 dez. 2024.

VOSMAN, B. *et al.* Broad spectrum insect resistance and metabolites in close relatives of the cultivated tomato. *Euphytica*, v. 214, p. 46, 2018. DOI: https://doi.org/10.1007/s10681-018-2124-4. Acesso em: 9 dez. 2024.

YAN, W. *et al*. GGE biplot vs. AMMI analysis of genotype-by-environment data. *Crop Science*,v. 47, n. 2, p. 643-653, 2007. DOI: https://doi.org/10.2135/cropsci2006.06.0374. Acesso em: 9 dez. 2024.

YAN, W. A systematic narration of some key concepts and procedures in plant breeding. *Frontiers in Plant Science*, v. 12, p. 724517, 2021. DOI: https://doi.org/10.3389/fpls.2021.724517. Acesso em: 9 dez. 2024.