UNIVERSIDADE ESTADUAL PAULISTA – UNESP
FACULDADE DE CIÊNCIAS AGRÁRIAS E VETERINÁRIAS
CÂMPUS DE JABOTICABAL

INIBIÇÃO DO BROTAMENTO DE BATATAS (*Solanum Tuberosum* L.) COM USO DE LED DURANTE O ARMAZENAMENTO PROLONGADO

Vanessa Maria Dantas Pedrosa
Engenheira Agrônoma

2025

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Discente: Vanessa Maria Dantas Pedrosa
Orientador: Prof. Dr. Gustavo Henrique de Almeida Teixeira
Coorientadores: Prof. Dr. Arthur Bernardes de Cecílio Filho
Prof. Dr. Rogério Falleiros Carvalho

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IMPACTO POTENCIAL DESTA PESQUISA

O estudo propõe as luzes LED como alternativa sustentável ao uso de tóxicos no controle de brotamento de batatas, alinhando-se aos ODS 2, 3, 9 e 12, objetivando reduzir uso de químicos, perdas pós-colheita e riscos à saúde/ambiente, promovendo segurança alimentar e agricultura limpa.

POTENTIAL IMPACT OF THIS RESEARCH

The study proposes LED lights as a sustainable alternative to the use of toxic chemicals to control potato sprouting, aligning with SDGs 2, 3, 9, and 12. The aim is to reduce chemical use, post-harvest losses, and health/environmental risks, promoting food security and clean agriculture.

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TÍTULO DA TESE: INIBIÇÃO DO BROTAMENTO DE BATATAS (*Solanum Tuberosum* L.) COM USO DE LED DURANTE O ARMAZENAMENTO PROLONGADO

AUTORA: VANESSA MARIA DANTAS PEDROSA
ORIENTADOR: GUSTAVO HENRIQUE DE ALMEIDA TEIXEIRA
COORIENTADOR: ARTHUR BERNARDES CECILIO FILHO
COORIENTADOR: ROGÉRIO FALLEIROS CARVALHO

Aprovada como parte das exigências para obtenção do Título de Doutora em Agronomia (Produção Vegetal), pela Comissão Examinadora:

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GUSTAVO HENRIQUE DE ALMEIDA TEIXEIRA
Data: 02/06/2025 11:52:01-0300
Verifique em https://validar.iti.gov.br

Prof. Dr. GUSTAVO HENRIQUE DE ALMEIDA TEIXEIRA (Participaçao Virtual)
Department of Plant Sciences / University of Idaho (UIDHAO) - Kimberly/EUA

Documento assinado digitalmente
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FERNANDO ANGELO PIOTTO
Data: 02/06/2025 13:14:50-0300
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Prof. Dr. FERNANDO ÂNGELO PIOTTO (Participaçao Virtual)
Departamento de Produção Vegetal / ESALQ USP Piracicaba/SP

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POLIANA CRISTINA SPRICIGO
Data: 29/05/2025 17:16:51-0300
Verifique em https://validar.iti.gov.br

Profa. Dra. POLIANA CRISTINA SPRICIGO (Participaçao Virtual)
Departamento de Biotecnologia Agropecuária e Ambiental / FCAV UNESP Jaboticabal

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Data: 29/05/2025 15:38:21-0300
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Pesquisador Dr. ALEX GUIMARÃES SANCHES (Participaçao Virtual)
Supperfruits Global / Belém/PA

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LUCIANA MARIA SARAN
Data: 29/05/2025 17:36:43-0300
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Profa. Dra. LUCIANA MARIA SARAN (Participaçao Virtual)
Departamento de Biotecnologia Agropecuaria e Ambiental / FCAV UNESP Jaboticabal

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DADOS CURRICULARES DO AUTOR

VANESSA MARIA DANTAS PEDROSA - Nasceu em 09 de março de 1995 no município de Mamanguape, Paraíba. Ingressou no curso de Agronomia em 2014 na Universidade Federal da Paraíba (UFPB), Campus de Areia. Neste período iniciou seus estudos na área de tecnologia pós-colheita de frutos sob orientação da Profa. Dra. Silvanda de Melo e Silva enquanto bolsista PIBIC (2 anos). Após a obtenção do título de Engenheira Agrônoma, em 2018, ingressou no Mestrado do Programa de Pós-Graduação em Agronomia (Produção Vegetal) da Universidade Estadual Paulista (UNESP), Faculdade de Ciências Agrárias e Veterinárias (FCAV), Campus de Jaboticabal, em março de 2019, como bolsista da Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP). Durante o Mestrado se dedicou ao desenvolvimento de recobrimentos contendo micosporina tipo aminoácido (MAA) visando ao controle da escaldadura em frutos de laranjeira, bem como, no entendimento do metabolismo oxidativo sob a orientação do Prof. Dr. Gustavo Henrique de Almeida Teixeira. Atualmente Doutora em Agronomia, através do referido programa de pós-graduação.

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"*It is not our abilities that show what we truly are. It is our choices*." - Albus Dumbledore.

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INIBIÇÃO DO BROTAMENTO DE BATATAS (*SOLANUM TUBEROSUM* L.) COM USO DE LED DURANTE O ARMAZENAMENTO PROLONGADO

RESUMO - Tradicionalmente, a inibição do brotamento em tubérculos de batatas (*Solanum tuberosum* L.) durante o armazenamento é realizada com a aplicação de carbamatos (clorprofame), também conhecidos como CIPC. Estes produtos são bastante efetivos no controle do brotamento, porém sua aplicação tem gerado questionamentos tanto do ponto de vista ambiental quanto da saúde humana. Desta forma, muitos países não estão re-cetificando o uso do CIPC para esta finalidade. O início do processo de brotamento nos tubérculos de batata está relacionado ao fim da endo-dormência, sendo afetado por fatores ambientais e fisiológicos. Dentre estes fatores ambientais, a luz desempenha um papel fundamental no alongamento dos brotos dos tubérculos, especialmente nos comprimentos de onda próximos do vermelho-vermelho distante (700–730 nm) e do azul (400 e 450 nm). Todavia, não foram encontrados resultados do uso de diodo emissores de luz (LED) visando à inibição do brotamento. Assim, a hipótese deste trabalho foi a de que o uso de luz LED na região do vermelho, vermelho distante e do azul irá inibir o brotamento dos tubérculos de batatas armazenadas por longos períodos. Para isso, batatas da cultivar Asterix foram colhidas e utilizadas em diversos experimentos, visando: i. determinar a melhor qualidade luminosa (vermelho, vermelho distante e azul) e fluências (0,1, 1,0 ou 5,0 μmol m^{-2} s^{-1}) para a inibição do brotamento em comparação à aplicação do CIPC, ii. determinar a duração da exposição à luz (curta ou contínua) para a efetiva inibição do brotamento em comparação à aplicação do CIPC, e iii. determinar o efeito do tratamento com LED durante o armazenamento prolongado dos tubérculos no desenvolvimento dos brotos, bem como, dos parâmetros químicos e bioquímicos relacionados à qualidade da batata. Visando avaliar a melhor qualidade luminosas e fluências para inibição de brotação, no primeiro estudo batatas ‘Asterix’ foram irradiadas continuamente com luzes LED no azul (0,1 μmol m^{-2} s^{-1}), no vermelho (1,0 μmol m^{-2} s^{-1}) e vermelho distante (1,0 μmol m^{-2} s^{-1}) por 30 dias a 15°C. O tratamento com CIPC e com as luzes LED não inibiram o desenvolvimento inicial dos brotos, mas as luzes LED no vermelho e vermelho distante foram eficazes no controle do crescimento dos brotos, semelhante ao observado em batatas-semente. Além disso, as luzes LED no azul e vermelho distante causaram uma redução no valor b* da cor dos tubérculos, indicando possíveis efeitos de esverdeamento. Desta forma, apesar das luzes LED influenciarem o desenvolvimento dos brotos, seu potencial efeito inibitório e depende dos parâmetros luminosos, bem como do estado fisiológico dos tubérculos, mais especificamente de seu estádio fisiológico. O segundo estudo buscou identificar as alterações fisiológicas e bioquímicas em batatas tratadas com luzes LED durante o armazenamento prolongado. Tubérculos da cultivar ‘Asterix’ foram expostos a luzes LED no vermelho (5 μmol m^{-2} s^{-1}), vermelho distante (5 μmol m^{-2} s^{-1}) e no azul (1 μmol m^{-2} s^{-1}) por até 75 dias a 15°C. Os tratamentos com luzes LED no azul e vermelho distante prolongaram a dormência dos tubérculos, resultando em menos brotos e brotos de menor tamanho. Os níveis de carboidratos não foram afetados pelos tratamentos luminosos, principalmente quando comparamos aos tratamentos controle e com luz LED no vermelho distante. Utilizando-se das informações obtidas nos experimentos anteriores, o terceiro estudo visou verificar o efeito da aplicação da luz LED no vermelho distante (5 μmol m^{-2} s^{-1}) antes e

continuamente durante o armazenamento das batatas. Os tubérculos foram expostos à luz LED no vermelho distante por 0 (controle), 2 ou 4 minutos antes do armazenamento, ou continuamente durante o armazenamento a 15°C. A exposição contínua à luz LED no vermelho distante reduziu significativamente o número e o desenvolvimento dos brotos, sendo seu efeito regulatório mais eficiente em relação à exposição pré-armazenamento. No entanto, a luz LED no vermelho distante não inibiu completamente o surgimento das brotações. Em relação à qualidade dos tubérculos, os tratados com luz LED no vermelho distante apresentaram menor teor de matéria seca, amido e açúcar solúvel total em comparação com o CIPC, mas não houve diferenças nos níveis de açúcares redutores. Concluiu-se que, embora promissor, o uso de luz LED no vermelho distante não foi totalmente eficaz para a inibição da brotação. Apesar disso, as luzes LED podem ser uma alternativa viável ao CIPC para o controle da brotação, mas ainda são necessários mais estudos para otimizar os protocolos de aplicação e entender os mecanismos fisiológicos envolvidos.

Palavras-chave: *Solanum Tuberosum* L., carboidratos, dormência, diodo emissor de luz

Sprouting inhibition in potatoes (*Solanum tuberosum* L.) using LED during prolonged storage

ABSTRACT - Traditionally, sprouting inhibition in potato tubers (*Solanum tuberosum* L.) during storage is achieved by applying carbamates (chlorpropham), also known as CIPC. These products are quite effective in controlling sprouting, but their application has raised questions from both an environmental and human health point of view. Therefore, many countries are not re-accepting the use of CIPC for this purpose. The onset of the sprouting process in potato tubers is related to the end of endodormancy and is affected by environmental and physiological factors. Among these environmental factors, light plays a fundamental role in the elongation of tuber sprouts, especially at wavelengths close to red-far red (700–730 nm) and blue (400 and 450 nm). However, no results were found for the use of light-emitting diodes (LED) to inhibit sprouting. Thus, the hypothesis of this study was that the use of LED light in the red, far-red, and blue regions will inhibit sprouting of potato tubers stored for long periods. For this purpose, potatoes of the Asterix cultivar were harvested and used in several experiments, aiming to: i. determine the best light quality (red, far-red, and blue) and fluences (0.1, 1.0, or 5.0 μmol m^{-2} s^{-1}) for sprouting inhibition compared to the application of CIPC; ii. determine the duration of light exposure (short or continuous) for effective sprouting inhibition compared to the application of CIPC; and iii. Determine the effect of LED treatment during prolonged storage of tubers on sprout development, as well as the chemical and biochemical parameters related to potato quality. In order to evaluate the best light quality and fluences for sprouting inhibition, in the first study, 'Asterix' potatoes were continuously irradiated with blue (0.1 μmol m^{-2} s^{-1}), red (1.0 μmol m^{-2} s^{-1}), and far-red (1.0 μmol m^{-2} s^{-1}) LED lights for 30 days at 15 °C. Treatment with CIPC and LED lights did not inhibit initial sprout development, but red and far-red LED lights were effective in controlling sprout growth, similar to that observed in seed potatoes. In addition, blue and far-red LED lights caused a reduction in the b* value of tuber color, indicating possible greening effects. Thus, although LED lights influence sprout development, their potential inhibitory effect depends on the light parameters as well as on the physiological state of the tubers, more specifically their physiological stage. The second study sought to identify the physiological and biochemical changes in potatoes treated with LED lights during prolonged storage. Tubers of the 'Asterix' cultivar were exposed to red (5 μmol m^{-2} s^{-1}), far-red (5 μmol m^{-2} s^{-1}), and blue (1 μmol m^{-2} s^{-1}) LED lights for up to 75 days at 15 °C. Treatments with blue and far-red LED lights prolonged tuber dormancy, resulting in fewer and smaller sprouts. Carbohydrate levels were not affected by the light treatments, especially when compared to the control and far-red LED light treatments. Using the information obtained in the previous experiments, the third study aimed to verify the effect of applying far-red LED light (5 μmol m^{-2} s^{-1}) before and continuously during potato storage. Tubers were exposed to far-red LED light for 0 (control), 2 or 4 minutes before storage, or continuously during storage at 15 °C. Continuous exposure to far-red LED light significantly reduced the number and development of sprouts, with its regulatory effect being more efficient compared to pre-storage exposure. However, far-red LED light did not completely inhibit sprouting. Regarding tuber quality, those treated with far-red LED light had lower dry matter, starch, and total soluble sugar content

compared to CIPC, but there were no differences in the levels of reducing sugars. It was concluded that, although promising, the use of far-red LED light was not fully effective in inhibiting sprouting. Despite this, LED lights may be a viable alternative to CIPC for sprouting control, but further studies are still needed to optimize application protocols and understand the physiological mechanisms involved.

Keywords: *Solanum Tuberosum* L., carbohydrates, dormancy, light emitting diode

CAPÍTULO 1 – Considerações gerais

1. INTRODUÇÃO

A batateira (*Solanum tuberosum* L.) é uma das espécies cultivadas mais importantes do mundo, tendo grande expressão produtiva e comercial (FAOSTAT, 2023; IBGE, 2023). A produção de batata em alguns países pode ocorrer em múltiplas safras ao longo do ano, como a exemplo do Brasil, enquanto em outros países, principalmente os de climas temperados, há predominância de uma única safra bem definida, sendo necessário o armazenamento dos tubérculos de batata por longos períodos (8 a 12 meses) para atender as diferentes demandas de produção e as exigências de diferentes mercados, *in natura* e indústria (Nasir e Toth, 2022).

O armazenamento dos tubérculos por longos períodos é possível com o uso de baixas temperaturas (4 a 9 °C) e alta umidade relativa (95–97%), sendo o manuseio pós-colheita dependente do uso dos tubérculos (Pringles, 2009). Ao se associar estas tecnologias à fisiologia dos tubérculos, é possível o armazenamento por longos períodos, ou seja, até 12 meses.

Fisiologicamente, os tubérculos de batata no momento da colheita apresentam dormência, que é a ausência de crescimento visível de qualquer estrutura vegetal que contenha um meristema (Lang et al., 1987). A dormência é um mecanismo natural que visa a conservação de energia até que as condições ideais para o crescimento de uma nova planta ocorram (Zhu et al., 2023). A dormência suprime temporariamente o brotamento, que é um processo indesejado na pós-colheita dos tubérculos de batata, visto que sua ocorrência leva ao consumo das reservas nutricionais, principalmente de carboidratos, levando a perda de massa, murchamento, formação de estruturas e compostos indesejáveis, comprometimento da qualidade geral e, consequentemente, na redução de seu valor de mercado. Desta forma, o brotamento ainda é um dos principais problemas durante o armazenamento dos tubérculos (Giri et al., 2020; Hu et al., 2023; Nyankanga et al., 2018).

Tradicionalmente, o brotamento em tubérculos de batatas é inibido com o uso de produtos químicos, principalmente com o uso do clorprofam (isopropyl N-(3chlorophenyl) carbamate) ou CIPC. Este produto é um herbicida que impede a

divisão celular, e vem sendo empregados para inibir o brotamento de batatas na fase pós-colheita, principalmente daquelas destinadas à indústria de batatas pré-fritas, onde o período de armazenamento pode ser de quatro meses até quase um ano (ABBA, 2020; Visse-Mansiaux et al.; 2022). Apesar da efetividade deste produto no controle do brotamento, tem-se relatado uma crescente preocupação quanto aos resíduos químicos e impactos ambientais que o uso destes produtos pode causar, levando a uma série de restrições ao seu uso em várias regiões do mundo, como na União Europeia, Japão e Coreia do Sul (Goffart et al., 2022; Vijay et al., 2018).

Nesse contexto, alternativas mais seguras e que sejam tão eficientes quanto ao CIPC têm sido pesquisadas, como o uso de outros produtos químicos, irradiação com raios gama, aplicação de óleos essenciais, além de abordagens mais recentes, como tratamentos com radiação luminosa (Dhaif Allah et al., 2018; Etemadinasab et al., 2020). A radiação luminosa (luz), especialmente em comprimentos de onda específicos, mostra um grande potencial na modulação de processos fisiológicos que inibem o crescimento dos brotos sem afetarem a qualidade dos tubérculos, abrindo novas possibilidades para a conservação pós-colheita de batatas (Abelenda et al., 2016).

Estudos recentes sugerem que o uso de diodo emissor de luz (LED), na faixa do comprimento de onda do vermelho, vermelho distante e do azul tiveram impacto significativo na redução do crescimento dos brotos de batatas sementes, sem comprometer a qualidade dos tubérculos (McGee et al., 1987; Mølmann & Johansen, 2020). No entanto, a implementação do uso da luz como um método de controle do brotamento requer considerações técnicas específicas. A intensidade e a duração da exposição à luz devem ser cuidadosamente mensuradas para se evitar efeitos adversos, como o estresse fisiológico nos tubérculos e comprometimento da qualidade do produto (Baur et al., 2022). Além disso, a uniformidade da iluminação e sua aplicação no ambiente de beneficiamento e armazenamento é crucial para garantir resultados consistentes. Estudos adicionais são necessários para otimizar os parâmetros de uso de luz LED, como a combinação ideal de comprimentos de onda e a frequência de exposição. Soma-se a isso o fato do uso de luz LED ter apenas diminuído o crescimento dos brotos (Pedrosa et al., 2025), não tendo inibido o brotamento.

Neste contexto, a hipótese deste trabalho foi de que o uso de luz LED na região do vermelho, vermelho distante e do azul poderia inibir o brotamento dos tubérculos de batatas armazenadas por longos períodos. Para isso, o presente estudo buscou investigar o uso de luzes LED em diferentes comprimentos de onda e durações da exposição à luz LED, visando a inibição do brotamento de batatas da cultivar Asterix sem afetar a qualidade dos tubérculos. Este trabalho visou oferecer uma alternativa ao uso de CIPC, contribuindo para práticas mais sustentáveis e seguras na conservação de batatas para a indústria alimentícia.

2. REVISÃO DE LITERATURA

2.1. Importância alimentar e econômica da batata

A batateira (*Solanum tuberosum* L.) é a quarta cultura alimentar cultivada em todo o mundo, cuja produção é inferior apenas ao cultivo do arroz, do trigo e do milho (Adekanmbi et al., 2024; FAOSTAT, 2023; IBGE, 2023).

Em 2023, a produção mundial de tubérculos de batatas ultrapassou um volume de 383 milhões de toneladas (FAOSTAT, 2023), com um aumento de pouco mais de 2,5% na produtividade em relação ao ano anterior. Neste mesmo ano, a produção brasileira de batata foi de mais de 4.1 milhões de toneladas (t) de tubérculos (FAOSTAT, 2023), sendo esta produção distribuída ao longo de três safras, ou seja, a safra das secas, de invernos e das águas (Figueiredo et al., 2011). A batateira é a segunda espécie de hortaliças mais procurada e consumida no mercado brasileiro (HORTIFRUTI BRASIL, 2024). Devido à possibilidade de se cultivar batatas em diferentes safras ao longo e em diferentes regiões do Brasil, implica que o armazenamento dos tubérculos de batatas para o mercado *in natura*, quando realizado, é feito por períodos muito curtos. Por outro lado, para o mercado de batatas chips e pré-fritas, há a necessidade de se armazenar este produto por longos períodos, quatro meses ou mais (ABBA, 2020) . Já em países de clima temperado, onde as condições climáticas permitem o cultivo de apenas uma safra por ano, o armazenamento dos tubérculos é necessário para suprir o mercado *in natura* e de processamento ao longo de todo o ano (Adekanmbi et al., 2024; Goffart et al., 2022).

Dentre as cultivares existentes, as principais cultivares de batatas cultivadas no

Brasil são a ‘Ágata’ e ‘Orchestra’ para o mercado *in natura,* a ‘Atlantic’ e ‘Markies’ para a indústria de batatas chips, e a ‘Asterix’ para o mercado de pré-fritas (ABBA, 2024). Do volume de tubérculos produzidos ao longo do ano, a maioria se destina ao mercado *in natura* (60%), sendo direcionado quase que diretamente, em um curto espaço de tempo, para os consumidores. Por outro lado, os tubérculos destinados à indústria de batata chips, à indústria de batatas pré-fritas congeladas e à produção de batatas semente representam 15%, 15% e 10%, respectivamente, deste volume (ABBA, 2020; ABBA, 2024). Para estas finalidades, os tubérculos são armazenados conforme a necessidade de produto e do atendimento ao mercado.

Diante da necessidade de armazenamento e da manutenção da qualidade dos tubérculos que se destinam a indústria, o uso adequado e eficiente de tecnologias pós-colheita é fundamental para a conservação dos tubérculos, especialmente devido a sua perecibilidade e visando reduzir a ocorrência de perdas pós-colheita. As principais perdas pós-colheita durante o armazenamento de tubérculos de batatas são causadas pelo surgimento de doenças, perda de massa fresca e o brotamento (Pringles, 2009; Jia et al., 2019; Lal et al., 2023; Upadhyayam et al., 2021). Dentre estes, o brotamento e talvez o principal problema associados a deterioração da qualidade dos tubérculos (Jaiswal et al., 2023), especialmente para as cultivares cujo período de dormência é mais curto, como o da principal cultivar utilizada como batata pré-frita no Brasil, a ‘Asterix’, que é de apenas 60 dias.

2.2. Aspectos fisiológicos dos tubérculos

Os estádios fisiológicos dos tubérculos de batata são caracterizados por modificações físicas, químicas e bioquímicas que se desenvolvem ao longo do ciclo produtivo da batateira. As diferentes fases de desenvolvimento da planta levam a estas modificações que são mais significativas a partir do momento de formação dos tubérculos via crescimento dos estolões, até o momento da colheita dos tubérculos no estádio final de maturação (del Socorro Sánchez-Correa et al., 2024). As alterações ambientais, como variação de fotoperíodo e temperatura, influenciam mais significativamente na qualidade dos tubérculos na fase final de desenvolvimento e

maturação dos tubérculos, influenciando a capacidade de armazenamento dos mesmos (Di et al., 2024).

Dentre as alterações ambientais, o fotoperíodo, tanto dias longos quanto curtos, assim como a variação de temperatura, temperaturas mais baixas ou mais altas, são responsáveis por induzir nas plantas, e consequentemente nos tubérculos, diferentes respostas, como na atuação de genes responsáveis pela tuberização, a exemplo do StSP6A (parálogo da proteína móvel FLOWERING LOCUS T (FT) - SELF-PRUNING 6A), e translocação e acúmulo de carboidratos, sendo estes processos particularmente sensíveis a ocorrência de dias longos e altas temperaturas (Laumer et al., 2025). Como resultado, tem-se o comprometimento da qualidade e avanço na idade fisiológica dos tubérculos, que em alguns casos, ao serem colhidos, já apresentam o desenvolvimento inicial das gemas ou estruturas germinativas nos tubérculos de batata, sugerindo que esse material já não apresenta dormência ou que está será mais curta, inviabilizando seu armazenamento (Visse-Mansiaux et al., 2021; del Socorro Sánchez-Correa et al., 2024)

Após colhidos, os tubérculos de batatas apresentam um período de dormência no qual não ocorre o desenvolvimento das gemas e formação de brotos devido à supressão da atividade meristemática das gemas (Haider et al., 2021). Todavia, conforme ocorrem alterações das condições ambientais e nos aspectos endógenos dos próprios tubérculos (Jakubowski e Królczyk, 2020), são observadas alterações fisiológicas nos níveis hormonais e os meristemas retornam a apresentar atividade fisiologica e as gemas passam a se desenvolver, o que é comumente chamado de brotamento, sendo este um dos principais problemas pós-colheita durante o armazenamento das batatas (Giri et al., 2020; Grzesik et al., 2022; Nyankanga et al., 2018).

A dormência é uma característica inerente à sobrevivência de algumas espécies vegetais como uma resposta adaptativa às condições ambientais, ao possibilitar o repouso, neste caso dos tubérculos, em períodos desfavoráveis de crescimento da planta (Eljebbawi et al., 2024). A ocorrência da dormência suprime e suspende temporariamente processos relacionados ao crescimento vegetativo, como o aumento da taxa respiratória, transcrição e tradução de genes relacionadas aos ciclos celulares, regulação de fito hormônios, resposta ao estresse, metabolismo dos

carboidratos e a produção de energia (Dogramaci et al., 2024). Desta forma, a dormência permite que os vegetais lidem mais facilmente com as variações e suportem os extremos ambientais, evita gastos de energéticos desnecessários e garante que em condições propícias ocorra a ativação da atividade fisiológica para desenvolvimento do vegetal, de modo a assegurar a perpetuação da espécie (Olsen, 2009; Suttle, 2004; Wang et al., 2024).

Na batateira, foram descritos e classificados três tipos ou estádios distintos de dormência, ou seja, a endo dormência, a eco dormência e a para dormência (Olsen, 2009). A endo dormência ou dormência verdadeira (Dogramaci et al., 2024) é caracterizada pela inibição de natureza fisiológica, ou seja, é regulada por sinais endógenos que suprimem o desenvolvimento meristemático, mesmo em condições ideais, durante a pós-colheita (Sonnewald e Sonnewald, 2014; Wasserman et al., 2023). A eco dormência é regulada por sinais exógenos, onde as condições ambientais induzem modificações e resposta de modo a impedir ou induzir a germinação, sendo este o tipo de dormência mais comumente manipulada durante o armazenamento prolongado dos tubérculos (Gong et al., 2021; Sheikh et al., 2022). Já a para dormência, sendo está também de natureza fisiológica, é induzida por uma parte diferente da estrutura vegetal, geralmente o broto apical que suprime o crescimento dos brotos laterais, este fenômeno e conhecido também por dominância apical (Dogramaci et al., 2024; Olsen, 2009; Sheikh et al., 2022).

Os tubérculos, órgãos de armazenamento de compostos energéticos, quando em processo de germinação, atuam como sumidouros de suas próprias reservas para suprir as demandas energéticas que incluem a divisão celular, a germinação de brotos, o alongamento de caule, a formação das folhas, a formação de raízes, entre outros processos até o estabelecimento de uma nova planta (Li et al., 2023; Sheikh et al., 2022). Com a quebra da dormência ocorre a mobilização de diferentes compostos, principalmente compostos de reserva como o amido, açúcares simples e seus derivados, além de proteínas, vias de sinalização da hexoquinase, trealose-6-fosfato (T6P) e alvo da rapamicina (Target of Rapamycin–TOR) (Nwogha et al., 2023). Além disso, o processo de metabolismo dos carboidratos é um dos pré-requisitos para a sinalização que desencadeia o início da germinação, em resposta a fatores como a

radiação luminosa (luz), em determinados comprimentos de onda, umidade e temperatura (Haider et al., 2021; Li et al., 2023; Shukla et al., 2019).

A ocorrência do brotamento nos tubérculos de batata envolve processos metabólicos acompanhados de modificações estruturais e indução da expressão de genes relacionados às proteínas quinases não fermentadoras de sacarose (SnRK–sacarose non-fermenting-1 kinases), regulada pelo conteúdo de açúcar e sinais hormonais, especialmente pelo catabolismo do ácido abscísico (ABA), que pode atuar na conexão entre as vias de sinalização hormonal e de glicose (Sonnewald e Sonnewald, 2014; Zhu et al., 2024), figura 1.

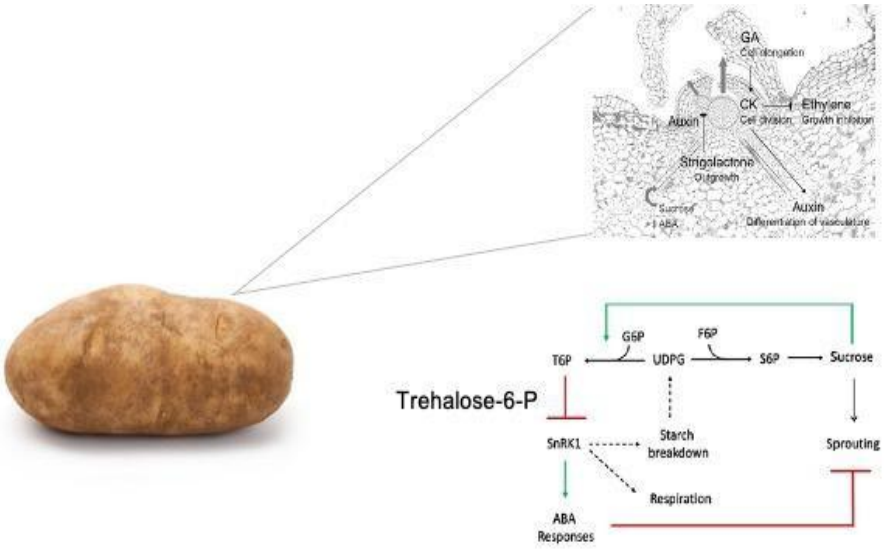

Figura 1. Modelo de regulação metabólica do brotamento do tubérculo de batata. Adaptado de Sonnewald e Sonnewald (2014). O baixo teor de T6P pode estimular uma maior mobilização das reservas e respiração por ativação da via de sinalização SnRK (linhas pontilhadas). A ativação da sinalização SnRK1 tem sido associada à ativação do catabolismo de ABA. Níveis baixos de ABA são necessários para a progressão da dormência e indução do brotamento. As setas verdes indicam o controle positivo e as vermelhas a regulação negativa.

Segundo Sonnewald e Sonnewald (2014), o transporte de sacarose para as gemas dos tubérculos é um pré-requisito para a indução do brotamento. Enquanto Zhu et al. (2024) relataram como a sinalização via T6P pode suprimir a atividade do SnRK1 para estimular os processos de consumo de energia em resposta à disponibilidade de sacarose, pode-se então relacionar que nas células do parênquima

os níveis de sacarose diminuem durante o período de dormência e por conseguinte, o teor de sacarose se correlaciona com o nível do sinal metabólito da trealose-6fosfato (T6P), que diminui com a progressão da dormência (Gong et al., 2021). Considerando os relatos de Debast et al. (2011), um baixo teor de T6P pode estimular uma maior mobilização dos compostos de reserva e, a respiração, pela ativação da via de sinalização SnRK (Figura 1). Além disso, a ativação da sinalização SnRK1 também foi associada à ativação do catabolismo do ABA (Hasan et al., 2022). Destacando-se que níveis baixos de ABA são necessários para a quebra da dormência e indução do brotamento (Figura 1).

Compreender os processos fisiológicos relacionados à dormência e ao desenvolvimento dos brotos nos tubérculos de batata possibilita um melhor ajuste das condições necessárias para garantir a qualidade e longevidade pós-colheita dos tubérculos armazenados por longos períodos, tanto os que se destinam ao mercado *in natura* quanto para o processamento, pois o brotamento é ainda um dos principais problemas observados durante o armazenamento prolongado.

2.3. Controle do brotamento na pós-colheita dos tubérculos de batata

O controle do brotamento na pós-colheita de tubérculos de batata ainda é um grande desafio a ser superado para a manutenção da qualidade e viabilidade comercial do produto *in natura* destinado ao armazenamento prolongado. O procedimento padrão de armazenamento de batata para a indústria, refere-se ao recebimento de tubérculos recém-colhidos com terra aderida ou escovados, pré-limpeza para retirada de sujidades e torrões de terra, empilhamento (Figura 2A) ou transferência para bins (Figura 2B) dentro de câmaras de armazenamento. O controle das condições ambientais, com a regulação de temperatura (4 a 9 °C) e umidade relativa (95-97%), é um processo amplamente adotado na indústria para retardar o metabolismo dos tubérculos e inibir o brotamento, além de prolongando sua vida útil pós-colheita (Liu et al., 2021; Hu et al., 2023). Embora seja necessário o armazenamento refrigerado para preservação dos tubérculos a longo prazo, somente o controle ambiente não é eficiente em retardar efetivamente o desenvolvimento dos brotos, sendo necessário a utilização de tratamentos visando o controle do brotamento

(Thoma e Zheljazkov, 2022). Ademais, assim como qualquer outro tratamento, a refrigeração exige certos cuidados, pois a utilização de temperaturas muito baixas (4°C), pode levar ao acúmulo de açúcares, induzir o adoçamento e levar ao escurecimento de batatas destinadas a industrialização (Datir, 2020).

Figura 2. Formas de armazenamento de tubérculos destinados a indústria. **A**. Armazenamento dos tubérculos em pilha em galpões; **B**. Armazenamento dos tubérculos em bins/ caixotes plásticos, metálicos ou de madeira. Fonte: Pedrosa, 2023.

Tradicionalmente, a aplicação de inibidores químicos de brotamento, como o clorprofame (isopropil N-cloro-fenilcarbamato, CIPC), é uma prática amplamente difundida na indústria. O CIPC é um herbicida inibidor da germinação também empregado na pós-colheita de batatas, promovendo alterações na estrutura dos microtúbulos, resultando na inibição da mitose celular (Guo, 2021). Além de seu uso estar relacionado a redução da degradação do amido e do acúmulo de açúcar, promove também a manutenção dos parâmetros de qualidade, como a coloração de chips e batatas pré-fritas, mesmo durante longos períodos de armazenamento (Visse-Mansiaux et al., 2021; Thomas et al., 2022; Dobry e Campbell; 2024). No entanto, seu

uso tem resultado em preocupações quanto aos efeitos ambientais e à saúde humana, o que levou à decisão, em 2020, da União Europeia em não re-registrar o CIPC para esta finalidade.

No que diz respeito aos tratamentos usualmente empregados na pós-colheita de tubérculos de batata, dentre os produtos químicos mais utilizados, para além do CIPC, destaca-se o 1–4 dimetil naftaleno (1-4 DMN) (Boivin et al., 2020; Campbell et al., 2010; Gong et al., 2021). O 1-4 DMN é um composto volátil orgânico, inicialmente isolando em batata e apresenta potencial ação na inibição da germinação e crescimento de brotos em tubérculos de batata (Visse-Mansiaux et al., 2021; Drogamaci et al., 2024).

Enquanto o mecanismo de ação do 1-4 DMN ou mesmo informações claras quanto ao seu potencial tóxico ainda não tenham sido completamente esclarecidos, é sabido que sua capacidade na atuação do controle da germinação e desenvolvimento dos brotos não é contínuo, processo reversível ao longo do tempo, sendo sugerido por alguns autores que sua atuação, interferindo na expressão de genes, distinguisse da promovida pela atuação do CIPC (Campbell et al., 2010; Campbell et al., 2019; de Weerd et al., 2010). Além de seu potencial no controle do brotamento, o 1-4 DMN pode influenciar na regulação do metabolismo de carboidrato ou ainda na prevenção do escurecimento (Krause et al., 2023; Mendonça Neto et al., 2021; Siddiqui et al., 2022). Embora seja considerado seguro para uso na pós-colheita de tubérculos, o 1– 4 DMN, dado ao seu efeito momentâneo de supressão da germinação, há necessidade de aplicações múltiplas ou utilização de maiores concentrações do produto, podendo, consequentemente, aumentar a concentrações de resíduo nos tubérculos após o armazenamento (EFSA et al., 2023; Thoma e Zheljazkov, 2022). O seu efeito também e variável em função das cultivares de batatas a serem armazenadas(Krause et al., 2023).

A aplicação de etileno exógeno também tem sido utilizado como uma alternativas ao uso de CIPC durante o armazenamento prolongado de tubérculos de batatas. O etileno e um fito hormônio gasoso, relativamente barato, que não deixa resíduos e pode ainda atuar como um regulador de crescimento, inibindo ou induzindo a brotação (Rylski et al., 1974; Gong et al., 2021), além de modular o amadurecimento dos tubérculos (Dako et al., 2021). O etileno atua nas membranas de organelas

intracelulares, ligando-se a receptores e interferindo na resposta transcricional de genes dependentes de etileno (transcrição das famílias EIN3/EIL1-Ethylene Insensitive3 / Ethylene Insentitive3-Like1) (Maltsev, 2021). Atuando em rotas diversas, de vias metabólicas complexas, a inibição da germinação e do desenvolvimento dos brotos mediante ação do etileno, pode ainda acarretar desordens outras que comprometem a qualidade posterior dos tubérculos, como a interferência no metabolismo de carboidratos, levando ao acúmulo de açúcares (adoçamento), ou ainda, comprometendo o conteúdo de compostos fenólicos (Chen et al., 2024; Dako et al., 2021).

A utilização do etileno como inibidor da brotação pode ser contraditória, principalmente mediante necessidade de exposição continua e prolongada dos tubérculos ao etileno para ocorrer de fato a inibição e não o efeito contrário, uma interrupção precoce da dormência e indução da germinação (Di et al., 2024), além de dificultar sua aplicação na pós-colheita. Em se tratando de questões relacionadas à possível toxicidade residual e aos impactos ambientais o uso de fitoquímicos, como os reguladores vegetais, via aplicação exógena, como a exemplo também do ácido abscísico (ABA), tem sido investigados por sua capacidade de modular a dormência dos tubérculos sem comprometer a segurança do produto (Zhang et al., 2022).As preferências dos consumidores por produtos com menor conteúdo de resíduos químicos e as novas limitações impostas pelas agências governamentais que requerem novas alternativas e exigem cada vez menos o uso de compostos químicos, principalmente no que se refere ao uso de produtos com alto risco de contaminação, seja ela ambiental ou animal, faz com que as pesquisas tenham avançado em busca de alternativas menos danosas como o uso de óleos essenciais (Bruno et al., 2023; Das e Chaudhari, 2025; Thoma e Zheljazkov, 2022), ou com menor geração de resíduos, como o uso da radiação luminosa (Ionica et al., 2023; Lemessa et al., 2022; Mølmann & Johansen, 2020; Pedrosa et al., 2025).

2.4. Fotomorfogênese

A radiação luminosa exerce papel primordial e fundamental nos processos fisiológicos e bioquímicos dos vegetais, sendo a principal via de energia para ocorrer

o processo fotossintético, que permite às plantas a produção de energia química necessária para seu crescimento e desenvolvimento (Ali et al., 2021; Razzaq e Du 2024). Estes processos estão condicionados por características como os comprimentos de onda específicos, quantidade e qualidade luminosa, bem como pela variação do fotoperíodo (Carvalho et al., 2011; Lin et al., 2017).

O fotoperíodo é um dos fatores determinantes no desenvolvimento das plantas e seus efeitos estão ligados à eficiência de diferentes fotorreceptores foliares, como os fitocromos e criptocromos (Griffin e Toledo-Ortiz, 2022). Além disso, a luz também exerce importante papel na ativação de sinalizadores sistêmicos para a ativação e/ou inibição de genes, estando esses envolvidos nas respostas fisiológicas aos estímulos luminosos, que induzem as modificações para a ocorrência da floração, formação de órgãos de armazenamento e, consequente, a tuberização das batatas (Abelenda et al., 2016; Bao et al., 2025; Desta et al., 2021).

Até o momento, é sabido que, quando as plantas de batata são expostas a dias longos, o fitocromo tipo B estabiliza o StCOL1 (CONSTANS-LIKE1) no início da manhã, e este controla negativamente a tuberização pela ativação transcricional do StSP5G (SELF PRUNING 5G), que suprime a expressão do sinal de StSP6 (Lázaro et al., 2015; Guillemette et al., 2024; Romero et al., 2024). Em dias curtos, o StCOL1 é desestabilizado e o StSP5G não é expresso, permitindo a ativação de StSP6A (SELF-PRUNING 6A) (Zhang et al., 2024). Sintetizado nas folhas, o sinal móvel StSP6A é transportado via floema para os estolões, onde induz a tuberização por associação com um ou mais reguladores adicionais que controlam a expressão dos genes de identidade do tubérculo (Abelenda et al., 2016; Dutta et al., 2024).

Durante o armazenamento, os tubérculos de batata apresentam respostas morfogênicas amplamente controladas pela incidência de luz ou por sua ausência (Hu et al., 2023). Ambientes escuros estimulam a brotação dos tubérculos de batata e causam alongamento excessivo dos brotos. Por outro lado, armazenar batatas na presença de luz de baixa intensidade inibe a foto morfogênese, diminui a velocidade de crescimento dos brotos e inibe a senescência dos tubérculos (Gong et al., 2021).

O brotamento de batatas do tipo sementes pode ser estimulado ou inibido pela mudança da irradiação luminosa, sendo este processo mais dependente da energia total incidida do que pela sua duração (Di et al., 2024; Mølmann e Johansen, 2020).

Assim como a incidência luminosa, durante o armazenamento de batatas semente, a temperatura também é controlada de modo a garantir a pré-germinação dos tubérculos e a formação de brotos que facilitem o plantio, além de suprimir temporariamente o envelhecimento do tubérculo e induzir maior vigor aos rebentos formados (Johansen e Mølmann, 2018; Mølmann e Johansen, 2020).

Da mesma forma, a luz estimula a ocorrência de processos fisiológicos, seja pelas reações bioquímicas naturais do vegetal ou pelo aumento da expressão de genes que induzem a geminação e o brotamento (Abelenda et al., 2011; Gendron et al., 2021). Em batata semente, por exemplo, para a formação de propágulos, a luminosidade, quando trabalhada corretamente, pode ser utilizada inibindo a atividade vegetativa no período de armazenamento e, consequentemente, a incidência de excesso de germinação na produção de partes vegetativas para a propagação (Gachangosup et al., 2008; Mou et al., 2024), ou ainda, pode permitir a manutenção da qualidade pós-colheita de batatas destinadas ao mercado consumidor (Cools et al., 2014).

2.5. Regulação Luminosa na Pós-colheita

Na fase pós-colheita, os tubérculos de batata são mantidos a baixas temperaturas e na ausência de luz, pois esta leva ao esverdeamento dos tubérculos, que pode estar associado à produção de glicoalcaloides (Pringles, 2009; Dhalsamant et al., 2022). O estímulo luminoso induz a modificação de amiloplatos, estrutura de reserva de amido, em cloroplastos, onde se acumulam moléculas de clorofila, nos tecidos do parênquima cortical nos tubérculos de batata (Dhalsamant et al., 2022), podendo além de comprometer a qualidade visual dos tubérculos.

Os glicoalcaloides são compostos neurotóxicos de sabor amargo, naturalmente presentes em plantas da família Solanaceae, como a batata (*Solanum tuberosum*), o tomate (*Solanum lycopersicum*) e berinjela (*Solanum melongena*) (Zhao et al., 2021). Em batatas cultivadas, 95% dos glicoalcaloides totais (TGAs) são constituídos pela α-solanina e α-chaconina, que derivam da mesma aglicona (solanidina) e diferem apenas em suas cadeias de açúcares (Chen et al., 2024; Liu et al., 2024). Sua biossíntese ocorre a partir do colesterol, por meio de reações

enzimáticas envolvendo hidroxilações, glicosilações e transaminações, com suas vias metabólicas reguladas geneticamente e sua síntese induzida por diferentes fatores ambientais, comprometendo assim a qualidade do produto (Akiyama et al., 2025).

A presença de luz, que pode estimular o crescimento de brotações em tubérculos de batatas, induzir o esverdeamento e o acúmulo de glicoalcaloides (Edwards et al., 1998; Pringles et al., 2009), pode ser um problema no varejo quando os tubérculos são expostos à luz artificial ou durante o armazenamento quando as luzes são inadvertidamente deixadas ligadas. Por esta razão, durante o armazenamento, as batatas são mantidas no escuro e, após a quebra de dormência e falta de supressão de crescimento dos brotos, estes alongam-se especialmente em ambientes quentes (Morris, 1966).

Apesar dos aspectos deletérios da luz à qualidade dos tubérculos, esta tem se mostrado uma tecnologia promissora na manutenção da qualidade na pós-colheita de outros produtos hortícolas, influenciando processos fisiológicos e morfofisiológicos. Indispensável para o funcionamento de diversas atividades metabólicas, a luz, em comprimentos de onda específicos, pode exercer funções distintas (Simkin et al., 2022; Yang et al., 2018). Por exemplo, a luz vermelha promove o desenvolvimento do aparato fotossintético e regula transformações no sistema fotocrômico, impactando a morfogênese (Kazemi et al., 2024).

O regime luminoso desempenha papel central na regulação de diversos processos, desde a germinação até o amadurecimento dos frutos. Os órgãos vegetais percebem a luz por meio de fotorreceptores especializados, que permitem respostas à intensidade, qualidade e duração da luz, além de monitorarem as consequências metabólicas da fotossíntese (Borbély et al., 2022; Wong et al., 2020). Ao longo da vida pós-colheita, vários mecanismos como o relógio circadiano, mecanismo genético endógeno, que permite que estas estruturas se adaptem às mudanças ambientais, podem regular processos biológicos como o brotamento, o desenvolvimento de pigmento, a abertura estomática e o acúmulo de compostos secundários (Inoue et al., 2018; Patnaik et al., 2022).

Dentre os fatores ambientais, a luz modula o acúmulo de compostos bioativos por meio da ativação de fotorreceptores, como fitocromos e criptocromos, que

desencadeiam uma cascata de sinalização em rotas específicas (Bhatla e Lal, 2023; Bao et al., 2024; Kharshiing et al., 2022). Esses sinais regulam a expressão gênica e o metabolismo de flavonoides, açúcares solúveis e carotenoides, elementos essenciais para a cor, o sabor e os benefícios nutricionais dos frutos (Li et al., 2024). Recentemente, o uso de diodo emissor de luz (LED) para manipular espectros luminosos tem sido explorado como uma ferramenta inovadora para melhorar a qualidade e o valor agregado dos frutos (Appolloni et al., 2023; Martínez-Zamora et al., 2023; Meiramkulova et al., 2023).

Os tubérculos de batata percebem a luz por meio de fitocromos (phy), principalmente o phy A e phy B. Os fitocromos existem em duas formas, a forma inativa quando expostos à luz vermelha (660 nm) e a forma ativa quando expostos à luz vermelho distante (730 nm) (Rockwell e Lagarias, 2010; Zhou et al., 2019). Withrow (1941) foi pioneiro nos estudos sobre os efeitos da qualidade da luz no desenvolvimento de brotos em tubérculos de batatas e relatou que a luz vermelho distante inibiu o alongamento dos brotos. McGee et al. (1987) controlaram o crescimento de brotos em batatas-semente usando luz azul (400–500 nm) a baixa irradiância (10–20 μmol m^{-2} s^{-1}).

Apesar da luz estimular o brotamento, o crescimento de brotos presentes nas batatas-semente foi inibido pela exposição dos tubérculos a diodo emissor de luz (LED) no vermelho (660 nm) a baixa irradiância (10–100 ηmol m^{-2} s^{-1}) e luz LED no vermelho distante a alta irradiância (1.000 ηmol m^{-2} s^{-1}) sem desenvolvimento de esverdeamento (Mølmann e Johansen, 2020). Essas respostas estão relacionadas com as respostas de fluência muito baixa do phy A à luz vermelha e sensibilidade em irradiância mais alta à luz vermelha distante, mas também com respostas de baixa fluência do phy B (Xie et al., 2007).

Recentemente, foi relatado que o crescimento das brotações existentes em batatas sementes foi inibido quando estas foram expostas a LED na região do vermelho (660 nm), as baixas irradiâncias (10–100 nmol m^{-2} s^{-1}) e no vermelho distante (735 nm), as altas irradiâncias (Mølmann & Johansen, 2020). Um estudo anterior em mudas de batata relatou que, em uma baixa intensidade de luz de 49 μmol m^{-2} s^{-1}, a luz verde resultou em comprimentos de brotos mais longos com boa aptidão, enquanto a luz azul levou a brotos mais curtos (Grishchenko et al., 2022).

Quanto às batatas destinadas ao consumo, Cools et al. (2014) utilizaram a radiação ultravioleta (UV-C) nas doses de 5–20 $kJ.m^{-2}$ por 1,5 minutos no momento em que as batatas se encontravam na esteira que as transportava para o interior da câmera de armazenamento. Estes autores relataram que este tratamento foi eficiente para inibir o crescimento dos brotos e a incidência de brotamento dos tubérculos. Todavia, não foram encontrados relatos quanto ao uso de LED visando a inibição do brotamento em batatas destinadas ao consumo *in natura* ou pré-fritas durante o armazenamento por longos períodos.

Com a crescente demanda por processos e produtos agrícolas com menor potencial a apresentarem riscos aos consumidores, os tratamentos tradicionais como o uso de CIPC para o controle do brotamento durante o armazenamento das batatas tem sido restrito em diversos países, como os da União Europeia (EU) entre outros (Shukla et al., 2019; Vijay et al., 2018). Neste sentido, o uso de luz pode ser uma alternativa a inibição do brotamento em batatas destinadas ao consumo *in natura* ou pré-fritas , pois esta tem sido efetiva no controle do crescimento de brotos em batatas sementes (Mølmann e Johansen, 2020; Hu et al., 2023; Mou et al., 2024).

3. OBJETIVOS

Como não foram encontrados informações quanto ao uso da radiação luminosa na região do visível para a inibição de brotamento de batatas destinadas à indústria de batata pré-fritas, e da necessidade de se desenvolver métodos que substituam o uso do CIPC, este projeto teve por objetivo geral desenvolver um método que iniba o brotamento em batata ‘Asterix’ com uso de LED durante o armazenamento prolongado e, por objetivos específicos: i. Determinar a melhor qualidade luminosa (vermelho, vermelho distante e azul) para o controle do brotamento em comparação à aplicação do CIPC, ii. Determinar a duração da exposição à luz (curta ou contínua) para o efetivo controle do brotamento em comparação à aplicação do CIPC, e iii. Determinar o efeito do tratamento com LED durante o armazenamento prolongado dos tubérculos, e iv. Avaliar o desenvolvimento dos brotos, bem como os parâmetros químicos e bioquímicos relacionados à qualidade da batata.

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CAPÍTULO 2 – CIPC and LED lights are not effective in controlling sprout growth and development in potato with advanced physiological age

ABSTRACT - In seed potatoes, low irradiance blue LED light (400-500 nm) has been reported to inhibit sprout growth. Recently, similar effect of low irradiance red (660 nm) and high irradiance far-red LED (735 nm) lights have been reported. However, there is no information regarding the inhibitory effect of LED lights on sprout development in table potato tubers. Therefore, the objective of this study was to evaluate the efficacy of blue, red, and far-red LED lights on sprout development and growth on potatoes with advanced physiological age. Potato tubers of Asterix cultivar were harvested at advanced physiological age and cured at 15°C, 95% RH for 15 days. After that, the tubers were submitted to the following treatments: dark (negative control), 20 mg L-1, CIPC (positive control), blue LED light (0.1 µmol m^{-2} s^{-1}), red LED light (1.0 µmol m^{-2} s^{-1}), and far-red LED light (1.0 µmol m^{-2} s^{-1}). The storage was carried out in a cold room at 15°C, 95% RH for up to 30 days. Neither CIPC nor LED light treatments inhibit the sprout development and the number of sprouts (≥ 2 mm) increased during storage. On the other hand, the LED lights controlled the growth of sprouts, with red and far-red lights been more effective. The color parameter a* was not affected by the treatments, but the b* value reduced on tubers treated with blue and far-red LED lights, probably due to greening. Concluding, CIPC as well as LED lights did not control the development of sprouts in table potatoes at advanced physiological age; however, red and far-red LED lights did control sprout growth similar to seed potatoes.

Keywords: *Solanum tuberosum* L., photomorphogenesis, postharvest, quality, storage.

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1. INTRODUCTION

Worldwide, isopropyl N-(3-chlorophenyl) carbamate (CIPC) is the most used sprout suppressant on potatoes. This product is very effective in controlling sprouting, but the recent lack of registration and subsequent use of CIPC in European countries have caused global potato industries to evaluate alternative means for sprout control.

During storage, potatoes are kept in the dark, and after dormancy break and lack of sprout suppression, sprouts will elongate especially in warm environments (Morris, 1966). The presence of light can stimulate sprouting growth, induce greening and glycoalkaloid (GA) accumulation (Edwards et al., 1998; Pringles et al., 2009), which can be a problem at retail condition when tubers are exposed to natural and/or artificial light or in all storages where lights are inadvertently left on. The negative concerns in the exposure to light coincides with the increased use of LED lights in the industry.

Tubers perceive light via different phytochromes (phy), mainly phyA and phyB. Phytochromes exist in two forms, the red-light (R) absorbing inactive form (660 nm) and the far-red (FR) absorbing active form (730 nm), Rockwell and Lagarias (2010). Withrow (1941) pioneered the studies regarding the effects of light quality on potato sprout development and they reported FR light inhibited sprout elongation. Regarding LED light, McGee et al. (1987) controlled sprouting growth in seed potatoes using low irradiance (10-20 ηmol m^{-2} s^{-1}) blue (400-500 nm) LED light.

Recently, the growth of sprouts present on seed potatoes was inhibited by exposing the tubers to low irradiance (10-100 ηmol m^{-2} s^{-1}) red (660 nm) LED, and high irradiance (1,000 ηmol m^{-2} s^{-1}) far-red (735 nm) LED lights with no greening development (Mølmann and Johansen, 2020). These responses are related with the very low fluence responses of phytochrome A (phyA) to red light and sensitivity at higher irradiance to far-red light, but also to low fluence responses of phyB (Xie et al., 2007). Therefore, previous research indicates that the use of LED light has the potential for sprout suppression.

In tropical countries, the warm climate results in higher average soil temperatures and it affects the physiological age of the tubers, which ultimately will have reduced period of dormancy (Pringles, 2009). Therefore, it is important to

question whether LED light (red, farred, and blue) can be used to inhibit sprouting on table potatoes with advanced physiological age produced in warm tropical summers.

2. MATERIAL AND METHODS

2.1 Plant material

Potato tubers of 'Asterix' cultivar were harvested at advanced physiological age in a commercial farm located in Casa Branca (21°46'26'' South, 47°05'11'' West, 684 meters a.s.l.) São Paulo state, Brazil. Potatoes were cured at 15°C, 95% RH for 15 days. After the wound healing process, the tubers were submitted to the following treatments: i. dark (negative control), ii. 20 mg L-1, CIPC (positive control), iii. blue LED light (0.1 µmol m^{-2} s^{-1}), iv. red LED light (1.0 µmol m^{-2} s^{-1}), and v. far-red LED light (1.0 µmol m-2 s-1). These light radiance fluences were chosen based on a study carried out by Pedrosa et al. (in press). The light treatments were intermittent throughout the storage period, monitored and adjusted with the aid of a spectroradiometer (SpectraPen, LM 510, España), and potatoes were stored in a cold room at 15°C, 95% RH for up to 30 days.

2.2 Evaluations

Fresh weight loss (FWL): FWL was calculated based on change in tubers' mass after different storage periods by weighing the potatoes on a semi-analytical balance with an accuracy of 0.01 g (Mars, model AS 2000, São Paulo, Brazil). The results were expressed as percentage (%).

Color: Pericarp color was determined using a colorimeter (Minolta, model CR-400, Osaka, Japan) using parameters L*, a*, and b* proposed by the Commission Internationale de l' Éclairage (McGuirre ,1992).

Sprouting evaluation: The size of sprouts (≥2 mm) and the number of sprouts were determined at reception and every 10 days during the storage following the method described by Benedetti et al., (2005).

2.3 Statistical design and analysis

The experiment was carried out according to a completely randomized design (CRD) with a factorial arrangement of 5 treatments (negative control - dark, positive control – CIPC, red, blue, and far-red LED lights) × 4 storage periods (reception - 0, 10, 20, and 30 days) with four replicates of five potatoes for each storage period, totaling 400 tubers. Data was subjected to analysis of variance (ANOVA) using AGROSTAT software (Barbosa and Maldonado Jr., 2015) and the means compared using Tukey's test, with a significance threshold of 0.05%.

3. RESULTS AND DISCUSSION

During storage (15°C and 95% RH), a significant interaction between treatments and storage period was observed for fresh weight loss (FWL), Table 1. The FWL increased during storage and reached 1.91% at 30 days. The LED light treatments, especially the blue light, resulted in higher FWL in relation to the negative control (dark) and CIPC treatment (Table 1).

The higher FWL of the potatoes treated with LED lights might be related to the interaction between the tubers and the different light wavelengths, as irradiation induces physiological modifications, such as increments the respiratory activity, and gas exchange rates (Kim and Lee, 2019). These modifications are related to the photostimulation responses, and the more energetic blue wavelength, might have induced a greater carbohydrate consumption to fulfill the metabolic demands (Finger et al., 2018). However, as 98% of the moisture that leaves the tubers is lost through its skin by evaporation (Pringles, 2009), the LED light treatments might have generated enough heat to reduce the relative humidity (RH) of the air, leading to a higher FWL (Table 1).

The increase of FWL might have also been related to sprouting, as when sprouts start to develop, both respiration and FWL increase rapidly (Burton et al., 1955). The LED light treatments did not inhibit sprouting, neither the CIPC treatment (Table 1). The number of sprouts (≥2 mm) increased during storage and after 20 days at 15°C and 95% RH it was possible to see the first sprouts on the tubers (Table 1). By the end of the storage period, an average of 2.23 sprouts were observed per tuber (Table 1). Although Harper (2020) reported that 'Asterix' has a dormancy period varying from 162

to 175 days, in Brazil this period is of only 60 days (ABBA, 2021). However, ‘Asterix’ potatoes at advanced physiological age had even shorter period of dormancy, 30 days (Table 1). Therefore, the warm conditions of the harvest season reduced the period of dormancy, resulting in potatoes at advanced physiological age, and even the CIPC treatment, which is very effective in controlling sprouting, could not inhibit sprouts to develop (Table 1).

On the other hand, the sprouts growth was controlled by the LED light treatments (Table 1). It was observed a significant interaction between treatments and storage period, and once present, the sprouts developed during the storage and reached 10 mm by 30 days (Table 1). The potatoes maintained in the dark (negative control) and treated with CIPC (positive control) had bigger sprouts (5.61-5.74 mm) in relation to LED light treated tubers (1.22-2.21 mm), Figure 1.

These results were similar to McGee et al. (1987) and Mølmann and Johansen (2020) studying seed potatoes. Thus, low irradiance (0.10 µmol m^{-2} s^{-1}) blue LED and high irradiance (1.0 µmol m^{-2} s^{-1}) red and far-red LED lights can be used to control sprout development in both, seed and table potatoes (Table 1 and Figure 1). However, at advanced physiological age table potatoes, red and far-red LED lights were more efficient in controlling sprout growth (Figure 1). These responses might be related to the phytochrome activation and deactivation mechanism of photomorphogenesis via red/far-red signaling regulation process (Quail et al., 1995; Rockwell and Lagarias, 2010). Although Withrow (1941) reported that far-red light inhibited sprout elongation, sprouting inhibition on potatoes by light is still to be proved.

Despite the fact that the presence of light can induce greening (Edwards et al., 1998; Pringles et al., 2009), the LED light treatments did not have big impact on the color of the periderm (Table 1). The a* value, which can range from +a (red color) to -a (green color), did not present any significant different between LED light treatments and the negative (dark) and positive (CIPC) controls (Table 1). Mølmann and Johansen (2020) also did not report greening on seed potatoes treated with low irradiance (0.10 µmol m^{-2} s^{-1}) blue LED and high irradiance (1.0 µmol m^{-2} s^{-1}) red and far-red LED lights. However, Pedrosa et al. (in press) observed changes in color (greening) of ‘Asterix’ potatoes exposed to intermittent blue and far-red LED lights with high fluence

irradiance (5.0 μmol m^{-2} s^{-1}). Then, light might still be a concern depending on the quality and fluence of the light which tubers are exposed to.

4. CONCLUSIONS

CIPC as well as LED light treatments did not inhibit sprouting in table potatoes at advanced physiological age; however, red and far-red LED lights (1.0 μmol m^{-2} s^{-1}) did control sprout growth similar to seed potatoes, demonstrating a strong photomorphogenic response.

More studies are necessary to fully understand the effect of LED light on sprouting and on other physiological aspects of table potatoes.

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6. LITERATURE CITED

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Tables

Table 1. Effect of dark (negative control), chlorpropham (CIPC - positive control), blue, red, and far-red LED intermittent light treatments on fresh weight loss (FWL), number of sprouts, size of sprouts, color parameters (luminosity – L*, a*, b*) of 'Asterix' potatoes at advanced physiological age stored at 15°C and 95% RH for up to 30 days.

Factors	FWL	Number of	Size of sprouts	L*	a*	b*
	(%)	Sprouts	(mm)			
Treatments (A)						
Dark	0.84 b	0.89 a	5.74 a	56.68 a	13.57 a	17.73 b
CIPC	0.78 b	0.90 a	5.61 a	54.89 a	13.56 a	18.47 a
Blue	1.27 a	0.90 a	2.21 b	54.62 a	13.30 a	18.24 a
Red	0.90 ab	1.00 a	2.02 b	54.86 a	12.98 a	18.17 ab
Far Red	0.86 ab	0.75 a	1.22 b	54.89 a	13.36 a	18.39 a
Evaluation Days (B)						
Reception	0.00 c	0.00 c	0.00 c	56.32 a	21.71 a	18.96 a
Day 10	1.01 b	0.00 c	0.00 c	55.85 a	10.26 b	17.50 c
Day 20	1.90 a	1.32 b	3.45 b	53.68 a	10.77 b	18.28 b
Day 30	1.91 a	2.23 a	10.00 a	86.92 a	10.69 b	18.06 b
Interaction A x B	0.002*	NS	0.001**	NS	0.001**	0.001**
C.V.(%)	18.86	90.68	47.53	117.64	5.19	2.63

Means followed by the same letter within each column do not differ statistically from each other by the Tukey test (P<0.05). Non-significant interaction (NS), significant interaction at P<0.05 (**) and significant interaction at P<0.01 (*).

Figures

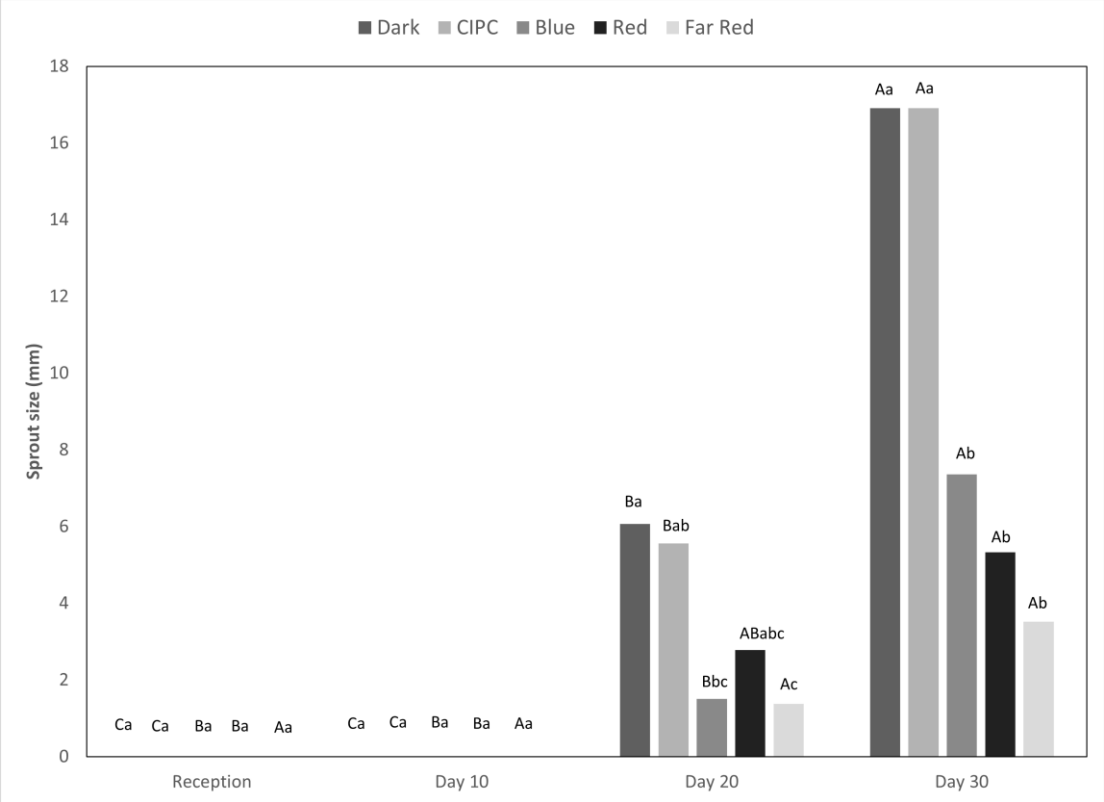

Figure 1. Effect of dark (negative control), chlorpropham (CIPC - positive control), blue, red, and far-red LED intermittent light treatments on size of sprouts of 'Asterix' potatoes at advanced physiological age stored at 15°C and 95% RH for up to 30 days. Means followed by the same lowercase letters do not statistically differ from each other within storage periods using the Tukey test ($P < 0.05$). Means followed by the same uppercase letters do not statistically differ from each other across the storage period using the Tukey test ($p < 0.05$)

CAPÍTULO 3 - Sprouting Control Treatment with LED Lights Does Not Affect the Biochemical Aspects of ‘Asterix’ Potatoes

ABSTRACT - Recently, it was observed that red, blue and far-red lights and different intensities (0.1 and 1.0 μmol m^{-2} s^{-1}) of light-emitting diode (LED) reduced potato sprout growth but did not effectively inhibit sprouting in physiologically aged tubers. Therefore, this study aimed to identify the physiological and biochemical changes and sprout development in potatoes treated with LED lights or with 3-chlorophenyl carbamate (CIPC). To achieve this, ‘Asterix’ potatoes were harvested, cured at 15 °C (90–93% RH) for 15 days and treated with red (5 μmol m^{-2} s^{-1}), far-red (5 μmol m^{-2} s^{-1}) and blue (1 μmol m^{-2} s^{-1}) LED lights, in addition to the negative control (dark) and positive control (0.022 g L^{-1} of CIPC) treatments. Potatoes from the light treatments were exposed to LED lights 24 h a day throughout the storage period, under optimal conditions for sprout development (16.7 ± 1 °C and 91.5 ± 1% RH). Tubers treated with blue and far-red LED light exhibited longer dormancy, fewer sprouts and smaller sprouts over the storage period. The carbohydrate content (starch and reducing sugars) was not affected by light treatments; however, total soluble sugar content was lower in tubers kept in the dark and higher in those treated with far-red LED light, which was not related to sprouting control. Therefore, it is suggested that other signalling mechanisms may be involved in sprout control using LED lights.

Keywords Blue light, carbohydrates, far-red light, red light, potato dormancy, sprouting

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1. INTRODUCTION

Light can stimulate sprout growth in potato tubers, induce greening and lead to the accumulation of glycoalkaloids (Pringles, 2009; Okamoto et al., 2020). This can become problematic in retail when tubers are exposed to artificial light or during storage when lights are inadvertently left on. Potatoes are typically stored in the dark to prevent sprout growth, but after dormancy break and when sprout suppression is lacking, sprouts tend to elongate, especially in warm environments (Morris 1966). Sprouting is, therefore, one of the main causes of post-harvest losses during potato storage (Pringles, 2009; FAOSTAT, 2023).

After harvest, potatoes enter a dormancy period during which bud growth is suppressed in response to endogenous factors (endodormancy) and environmental conditions (ecodormancy) (Koornneef et al., 2002; Olsen, 2009). The initiation of germination induction and subsequent activity of meristematic tissues for bud development commence upon the dormancy break in tubers, triggered by the mobilization of reserve compounds such as carbohydrates, predominantly starch and sugars. This response is influenced by abiotic factors or the inherent characteristics of the tubers (Shukla et al., 2019; Gong et al., 2021). Sprouting involves metabolic processes, morphological changes and the induction of gene expression. The key starting point is the transport of sugars such as sucrose to the buds, thereby supplying the energy required for shoot development. Additionally, sugars serve as signalling molecules for metabolites trehalose-6-phosphate (T6P) (Sonnewald and Sonnewald, 2014; Gong et al., 2021). The decrease in T6P concentration as dormancy progresses is associated with the activity of sucrose non-fermenting-related kinase (SnRK) and the subsequent catabolism of abscisic acid (ABA), which collectively regulate the sprouting process (Hu et al., 2023).

Light, being a crucial abiotic factor, is detected by potato tubers through phytochromes, with a primary emphasis on phytochromes (Phy), Phy A and Phy B. Phytochromes exist in two forms, the inactive form when exposed to red light (660 nm) and the active form when exposed to far-red light (730 nm) (Zhou et al., 2019). Withrow (1941) pioneered the study of light quality effects on sprout development in potato tubers and reported that farei light inhibited sprout elongation. Concerning

light-emitting diodes (LEDs), McGee et al. (1987) controlled sprout growth in seed potato tubers using blue LED light at low irradiance (0.01–0.02 μmol m^{-2} s^{-1}). However, traditional industry practices employ carbamates, such as isopropyl- N (3-chlorophenyl carbamate) or chlorpropham (CIPC), for sprout control during potato storage. Nevertheless, this herbicide is highly toxic to the environment and living organisms, leading the European Union (EU) and other countries not to re-register this product despite its high efficiency (Vijay et al., 2018; Shukla et al., 2019). Therefore, alternative sprout control methods have been explored, such as the use of ethylene (Thoma and Zheljazkov, 2022), 1,4-dimethylnaphthalene or 1,4-DMN (Sousa Santos et al., 2023) and essential oils (Chen et al., 2024).

It has recently been reported that various qualities of LED light, including red, blue and far-red, at different intensities (0.1 and 1.0 μmol m^{-2} s^{-1}) resulted 2019). Therefore, alternative sprout control methods have been explored, such as the use of ethylene (Thoma and Zheljazkov, 2022), 1,4-dimethylnaphthalene or 1,4-DMN (Sousa Santos et al., 2023) and essential oils (Chen et al., 2024).

It has recently been reported that various qualities of LED light, including red, blue and far-red, at different intensities (0.1 and 1.0 μmol m^{-2} s^{-1}) resulted in a reduction of potato sprout growth in physiologically aged tubers (Pedrosa et al., 2023). However, these LED treatments did not effectively suppress sprouting in advanced aging tubers. Consequently, the objective of this investigation is to discern the physiological and biochemical changes and sprout development in physiologically mature tubers, recently harvested potatoes subjected to LED treatments, after the curing period, in comparison with the conventional industry control method employing CIPC, as well as possible correlations between the evaluated parameters.

2. MATERIALS AND METHODS

2.1 Plant Material

‘Asterix’ potato (*Solanum tuberosum* L.) tubers, which is the main cultivar produced for the pre-fried potato processing industry in Brazil, were used in this study. This cultivar has a semi-late growth cycle with semi-long dormancy (60 days) and is suitable for both fresh market and processing. Physiological mature tubers were used

in this study after sorting as Class II (> 45 and < 85 mm long) or special, according to Companhia de Entrepostos e Armazéns Gerais de São Paulo (CEAGESP 2023). Tubers were obtained from a commercial farm located at Vargem Grande do Sul (21° 50′ 9″ S, 46° 52′ 50″ W, at an altitude of 730 m) in the state of São Paulo, Brazil.

2.2 Experiment Setup

The freshly harvested potato tubers, with a maximum of 24 h between harvesting and entering the cold chamber for curing, underwent cleaning and removal of field dirt on conveyors through brushing, without undergoing a washing process to preserve their storage characteristics used in the industry. Potatoes were sorted out based on the absence of injuries, sprouting and tuber size to ensure sample uniformity. After sorting, tubers were stored in a dark cold room, set at 15 ± 1 °C and 90–93% relative humidity (RH) for 15 days to complete the curing process. After this period, the tubers were placed in plastic boxes (experimental units) prepared for the application of the light treatments (Supplementary material — S1).

The light irradiance levels were selected based on previous results (Pedrosa et al., 2023), namely i. red LED (660 nm — irradiance of 5 μmol m^{-2} s^{-1}), ii. far- red LED (735 nm — irradiance of 5 μmol m^{-2} s^{-1}) and iii. blue LED (450 nm — irradiance of 1 μmol m^{-2} s^{-1}). The other treatments included iv. the negative control (potatoes kept in the dark) and v. the positive control (potatoes treated with CIPC by spraying a solution containing 0.022 g L^{-1} of isopropyl-n-(3-chlorophenyl)carbamate in 50% (v/v) ethanol 20 days after harvest. Potatoes in the light treatments were exposed to LED lights 24 h a day throughout the storage period under ideal conditions for sprout development, at temperatures of 16.7 ± 91 °C and 91.5 ± 1% RH (Johansen, 2010). The tubers were stored for up to 75 days, a period exceeding the dormancy of ‘Asterix’.

The irradiances were checked periodically in each of the storage units, to guarantee the same incidence of light on the tubers throughout the storage period, according to the treatments established.

The experiment was set up following a completely randomized design in a factorial arrangement consisting of 5 treatments by 8 evaluation days (0, 15, 25, 35,

45, 55, 65 and 75 days), with 4 replicates of 4 tubers for morphological, physical and chemical evaluations and 3 replicates of 4 tubers for physiological and biochemical analyses.

2.3 Evaluations

The tubers were assessed at 10-day intervals until the end of the storage period for various morphological, physical and chemical parameters, including:

2.3.1 Fresh weight loss (FWL): The weight loss was calculated based on the variation in tuber mass at different storage times using a semi-analytical balance (Marte, model AS 2000, São Paulo, Brazil) with a precision of 0.01 g and results were expressed as a percentage (%).

2.3.2 Dry matter content (DM): Dry matter was determined by drying the tuber without skin (pulp) in a forced-air circulation oven (Lucadema, model LUCA-82/27, Brazil) at 105 °C until a constant weight was achieved (Zarzecka et al., 2021), with results expressed in grams (dry matter) per kilogram (fresh weight) (g kg^{-1}).

2.3.3 Firmness; Firmness was assessed on opposite sides of each tuber using an electronic texture analyser (Bishop, model FT 327, Italy), with results expressed in Newtons (*N*) as described by Watkins and Harman (1981).

2.3.4 Number of sprouts per tuber: This determination considered the number of sprouts with at least 2 mm in length on each tuber (Benedetti et al., 2005).

2.3.5 Sprout size (> 2 mm and < 2 mm): Sprout size was determined by measuring vegetative structures using a digital calliper, with a measuring range of 0–150 mm and accuracy of 0.02 mm (Caliper, Brazil), with sprouts considered structures greater than 2 mm in length and piping as white bud structures smaller than 2 mm (Benedetti et al., 2005).

As for physiological and biochemical analyses, these were performed at 10-day intervals until the end of the storage. For biochemical analyses, the periderm and pulp were immediately frozen with liquid nitrogen and stored at − 20 °C until analysis.

2.3.6 Respiratory activity: The respiratory activity was determined using a gas chromatograph (Thermo Scientific, model Trace 1310, USA) to measure the concentration of carbon dioxide (CO_2) produced by the tubers. Tubers were kept in a hermetically sealed container (2.4 L) for 24 h, and the amount of CO_2 in the container was determined before and after this period. This information was used to calculate the respiration rate, which was expressed in mg CO_2 kg^{-1} h^{-1} (Kader and Saltveit, 2003).

2.3.7 Starch contente: For this analysis, 0.5 g of pulp, fresh ground material, was homogenized with 50 mL of distilled water, then potassium acetate buffer solution (1.0 mL, 4.0 M, pH 4.5) and 100 µL of a 50% (v/v) alpha-amylase solution were added. The samples were then heated at 90 °C (water bath) for 2 h with constant agitation. After this period, 100 µL of amyloglucosidase (10 mg mL^{-1}) was added to the samples, followed by returning to a water bath at 55 °C for 2 h. The extract was filtered, diluted with distilled water and neutralized with 4 N NaOH solution. Sugar content was determined according to Nelson (1944) and Somogyi (1952). Starch content was expressed in g kg^{-1}.

2.3.8 Reducing sugars: For the extraction of these sugars, 4.5 g of pulp, fresh ground material, was diluted in 50 mL of distilled water and heated at 60 °C in a stirred bath for 30 min. After cooling, the samples were diluted in 100 mL of distilled water and filtered. For sugar determination, 100 µL aliquots were used following the methodology of Nelson (1944) and Somogyi (1952), and the content was expressed in g kg^{-1}.

2.3.9 Total soluble sugars: The total soluble sugar content was determined using the method of Nelson (1944) and Somogyi (1952). For sugar extraction, 3.5 g of pulp, fresh ground material, diluted in 60 mL of 50% (v/v) ethanol was heated at

60–65 °C in a stirred bath for 1 h. To each sample, 1 mL of hydrochloric acid was added, and samples were heated for another 1 h. After this period, the samples were cooled and neutralized with 4 N NaOH. From the final neutralized extract, 100 µL was used for absorbance determination at 535 nm (KASVI, model K37-UVIS). The results were expressed in g kg^{-1}.

2.4 Statistical Analysis

The data were subjected to analysis of variance using the AGROSTAT program (Barbosa and Maldonado Junior, 2015), and means were compared using the Tukey test with a significance level of 0.05. As necessary, given the nature of the characteristics, data for the variables number of sprouts, sprouts (> 2 mm) and sprouts (< 2 mm) were transformed to arcsine [sqrt(× /100)]. Pearson correlation analyses were also performed for biological and biochemical parameters at 25, 35, 45, 55, 65 and 75 days of storage.

3. RESULTS

The LED light treatments did not affect fresh weight loss (Table 1). However, an increase in fresh weight loss was observed during storage, reaching 5.53% at the end of the storage period (75 days). Similarly, the dry matter (DM) content was not affected by the light treatments, with a tendency for an increase observed during storage (Table 1). Regarding firmness, no significant effect of the light treatments was observed, but lower firmness values were observed at harvest (20.9 N) compared to the end of the storage period (24.9 N), as shown in Table 1.

Significant interactions were observed between the light treatments and the storage period for the number of sprouts and the presence of sprouts > 2 mm (Figs. 1A and B). Potato tubers treated with blue and far-red LED lights had a lower number of sprouts, notably until day 65 when tubers from these treatments showed no sprouting (Fig. 1A). Similar behaviour was observed for the size of sprouts > 2 mm. In other words, potatoes treated with blue and far-red LED lights did not have sprouts > 2 mm until day 65 of storage and at 75 days, the sprouts > 2 mm were smaller in these

treatments (Fig. 1B). As for sprouts < 2 mm, an increase was observed throughout the storage period, with no significant effect of the light treatments.

The respiratory activity was not affected by the light treatments, but the rate of CO_2 production gradually decreased during storage (Table 2). At harvest, tubers had a higher respiratory activity (6.77 mg CO_2 kg^{-1} h^{-1}), which decreased by 53% after 25 days in storage, showing no significant differences until the end of the storage period and remaining between 3.13 and 2.69 mg CO_2 kg^{-1} h^{-1} (Table 2).

The starch content of the tubers was not affected by the light treatments (Table 2). However, there was a significant variation in the results during the storage period, with higher initial values (489 g kg^{-1}), followed by a reduction on day 35 (357 g kg^{-1}) and a tendency to increase towards the end of the storage period (Table 2). This pattern was also observed for the levels of reducing sugars (Table 2). On the other hand, the light treatments affected the total sugar content, and tubers treated with far-red LED light had a higher total sugar content (4.2 g kg^{-1}) compared to tubers kept in the dark, which had lower total sugar levels (3.2 g kg^{-1}), while the other treatments did not differ significantly (Table 2). Similarly, to the starch and reducing sugar levels, the total sugar contents varied throughout the storage, with higher concentrations at the beginning (3.8 g kg^{-1}), a decrease at 55 days (2.1 g kg^{-1}) and an increase towards the end of the storage period (6.3 g kg^{-1}), as shown in Table 2.

The Pearson correlation analysis was conducted to investigate the relationship between the number and size of sprouts, carbohydrate content (starch, reducing sugars and total sugars) and the respiratory rate during the storage period of potatoes subjected to the control and LED light treatments (Fig. 2).

Immediately after curing (25 days), a significantly positive correlation was observed between the levels of reducing sugars and total sugars ($r = 0.52$; $p < 0.05$), indicating that an increase in one variable positively contributes to the elevation of the other (Fig. 2A). At 35 days of storage, a significant positive correlation was observed between the levels of reducing sugars and starch ($r = 0.69$; $p < 0.05$) (Fig. 2B), with no sprout development up to this point. At 45 days of storage (Fig. 2C), two distinct correlations were identified. The first was a negative correlation between the size of sprouts (< 2 mm) and starch content ($r = -0.53$; $p < 0.05$), while the second showed a positive correlation between the size of sprouts (> 2 mm) and reducing sugar content,

with no correlation between the other evaluated parameters. By 55 days, there was a shift in the correlated parameters, and new correlations were established. Strong negative correlations were observed between size (> 2 mm) ($r = -0.71$; $p < 0.05$) and the number of sprouts ($r = -0.83$; $p < 0.05$) with total sugar content, as well as between the levels of reducing sugars and starch ($r = -0.71$; $p < 0.05$), indicating that these relationships occur inversely, i.e. a decrease in one parameter increases the other (Fig. 2D). A positive correlation was observed between reducing sugars and total sugars ($r = 0.52$; $p < 0.05$). At 65 days, the previously established correlations were no longer significant, and three new correlations were identified: a positive correlation between the size (> 2 mm) and the number of sprouts ($r = 0.66$; $p < 0.05$), as well as two negative correlations, one negative between the number of sprouts and reducing sugars ($r = -0.53$; $p < 0.05$) and a strong one between total sugar and starch content ($r = -0.86$; $p < 0.05$) (Fig. 2D). At the end of the storage period (75 days), the correlation that was positive at 55 days.

4. DISCUSSION

Despite the light treatments constituting a source of energy, the use of LED lights did not directly affect fresh weight loss (*FWL*), which is one of the main posharvest issues in long-term potato storage (Pringles, 2009). This is because LED lights have a lower heat emission (Agnol et al., 2009), thus not affecting storage conditions, especially temperature and relative humidity inside the boxes, and consequently, not significantly interfering with tuber transpiration. Plant tissues lose water to the environment in the form of vapour, leading to an almost constant reduction in fresh mass over time (Petrucci et al., 2023). Thus, drier environmental conditions would cause tubers to lose more water vapour to the environment (Grzesik et al., 2022).

The increase in *FWL* during storage may have affected the dry matter (*DM*) content, which also increased during this period (Table 1). The loss of water leads to a greater concentration of the solids in the tissue due to the transpiration process (Moens et al., 2021; Irungu et al., 2022). Therefore, the *FWL* might have contributed to the increase in *DM* content and consequently affected firmness. In other products

like avocados (Gamble et al., 2010) and kiwi fruit (Harker et al., 1996), higher firmness values have been related to higher *DM* levels.

Regarding sprouting, 'Asterix' potatoes have a semi-long dormancy period (60 days). In fact, the dormancy break occurred on day 65 in tubers kept in the dark (negative control) or treated with red LED light. On the other hand, the use of blue and far-red LED light affected the dormancy period and sprout development, prolonging the tubers' dormancy period and consequently delaying sprout emergence by up to 10 days compared to CIPC and conventional dark storage. Considering the need for extended storage for cultivars destined for the prefried potato industry, such as 'Asterix' (Cools et al., 2014; Jia et al., 2019), these results demonstrate the efficiency of light treatments in increasing the post-harvest shelf life of this cultivar.

Concerning sprout development, these results are in line with the studies of Withrow (1941) and Mølmann and Johansen (2020), which observed less sprout development in potato tubers treated with far-red light (735 nm). Also, McGee et al. (1987) observed reduced sprout growth in seed potatoes treated with blue LED light (450 nm — irradiance of 0.01–0.02 μmol m^{-2} s^{-1}). On the other hand, no reduction in sprout growth was observed in potatoes exposed to red LED light (660 nm irradiance of 5 μmol m^{-2} s^{-1}), contrary to what was described by Mølmann and Johansen (2020), who reported controlled sprout development in seed potatoes treated with red LED light at 0.01–0.1 μmol m^{-2} s^{-1} and a previous study with 'Asterix' potatoes treated with 1.0 μmol m^{-2} s^{-1} (Pedrosa et al., 2023). These differences might be related to the Phy A response to very low red light intensity and sensibility to higher irradiances of far-red light, and with Phy B response to low intensities (Xie et al., 2007).

The photomorphogenic responses related to bud and sprout regulation in potatoes, based on sensitivity to red, far-red and even blue light, suggest the involvement of different phytochromes, particularly Phy A and Phy B, through inactivation by red light absorption and activation in far-red light (Zhou et al., 2019; Singh et al., 2023). Thus, the active form of phytochrome when exposed to far-red light (Zhou et al., 2019) and blue light (Mølmann and Johansen, 2020; Rahman et al., 2021) may be responsible for controlling potato bud development. It is important to note that despite CIPC being used for sprout control during potato storage, showing high efficiency (Vijay et al., 2018; Shukla et al., 2019), it did not result in greater sprout

inhibition compared to blue and far-red LED light treatments (Fig. 1A). Possibly, the spray application affected the action of CIPC because it is commonly applied as a thermal fog treatment (Sliningerr et al., 2003).

Although light treatments affected sprouting, they did not result in changes in respiratory activity (Table 2). Similarly, the increased presence of sprouts and/or larger sprouts (> 2 mm) in tubers in the negative control (dark) and positive control (CIPC) treatments, as well as red LED light, did not affect the respiratory rate of the potatoes (Table 2). Physiologically mature potatoes are classified as very low perishability products, with reduced respiratory rates, which are less than 5 mL CO_2 kg^{-1} h^{-1} at 5 °C (Kader and Saltveit, 2003). The highest respiratory activities were observed at the beginning of the storage period due to field heat and harvest-related stress (6.77 mg CO_2 kg^{-1} h^{-1}). After 25 days of storage, these decreased and remained between 3.13 and 2.69 mg CO_2 kg^{-1} h^{-1} (Table 2).

Reductions in respiratory rate are commonly observed during the potato storage, which, following a nonclimacteric pattern, presents a decline in CO_2 production after harvest (Reid and Pratt, 1972). However, an increase in respiratory activity at the end of the prolonged storage period may arise due to sprouting or tuber senescence (Pringles, 2009). Higher respiration rates are associated with sprout development as this growth results in reductions of trehalose-6-phosphate (T6P) content stimulating reserves mobilization via activation of non-sucrose fermenting protein kinase (SnRK) signalling pathway (Sheikh et al., 2022).

Although the objective of this study was to identify the physiological/ biochemical changes and sprout development in ‘Asterix’ potatoes treated with LED lights, the exposure to blue and far-red LED lights, for the most part, did not promote physiological (respiration) and biochemical (carbohydrates) changes. Total soluble sugar content was the only biochemical variable affected by light treatment (Table 2). Higher total sugar concentrations (4.2 g kg−1) were observed in tubers treated with far-red LED light precisely one of the treatments with less sprouting (Tables 1 and 2). The exposure to blue (450 nm) and far-red LED light (735 nm) may be related to metabolic processes not related to carbohydrate metabolism and could still be associated with structural modifications and the induction of genes related to SnRK

and abscisic acid (ABA) catabolism, as described by Sonnewald and Sonnewald (2014).

Potato tubers usually show an increase in the sugar content in parenchymal cells with the end of dormancy and the beginning of germination until the formation of the shoots themselves, followed by a significant reduction in the sugar content from this point onwards (Viola et al., 2007). The biosynthesis and mobilization of these reserve compounds, mainly starch and sugars, depend not only on the intrinsic aspects of the tubers but also on how they respond to external factors such as light, specific wavelengths and temperature (Shukla et al., 2019). After the end of dormancy, hydrolytic enzymes, α- and β-amylases, are activated, leading to an increase in sugar concentration, which indicates the need for these components for germination and sprout development (Haider et al., 2023). In terms of quality, the accumulation of sugars directly influences the quality of the final product of processed potatoes, since reduced sugar levels are essential to meet colour standards (Morales-Fernández et al., 2015). Sugar accumulation during storage and due to environmental stimuli, such as light and temperature, can lead to the development of undesirable aspects such as darkening during processing, Maillard reaction and generation of toxic compounds, acrylamide, drastically reducing the processing capacity and commercial value of these products (Gikundi et al., 2024).

Pearson correlation analysis was performed to identify correlations between the respiratory rate of the stored tubers and the content of carbohydrates, starch, reducing sugars and total sugars over the storage period (Fig. 2) excluding the initial period covering reception (day 0) until day 15. Initially, positive correlations were identified between carbohydrates (Figs. 2A, B and D), which changed with the end of storage (Figs. 2D, E and F). With the onset of dormancy breaking of the tubers, there were positive (Fig. 2C) and negative correlations between sugar concentration and the number and size of sprouts (> 2 mm). However, at the end of the storage period, these correlations were no longer significant, with a direct positive correlation between the total soluble sugar content and CO_2 production rate, which was the only significant correlation involving the respiratory activity of the tubers. The association between carbohydrate content and subsequent responses, such as respiratory activity itself and sprout development, corroborates with Khorramifar and Rasekh

(2022) and Hu et al. (2023). These authors reported similar variations in sugar contents over the course of storage, initial reduction giving way to a new accumulation of these carbohydrates in preparation for breaking dormancy and subsequent germination.

5. CONCLUSIONS

LED light treatments, specifically blue and far-red LED light, significantly influence sprout development in ‘Asterix’ potato tubers, prolonging the dormancy period, up to 10 days, compared to CIPC and dark, and decreasing sprout formation and development. Furthermore, LED light treatments did not affect starch and reducing sugar contents, the total soluble sugar content was higher in tubers treated with far-red LED light, though.

Light responses may have relevant implications for maintaining the quality of potato tubers and the final product in the pre-fried industry, not only confirming the effectiveness of LED lights as a promising alternative for postharvest management of potatoes but also highlighting the need for further investigations on the physiological mechanisms involved, since the responses found in this study open up more study routes regarding more complex analysis of the interactions and correlations between physiological and metabolic processes involved in the synthesis and metabolism of carbohydrates, as well as the signalling and response related to potato germination, especially on the real effect of light on tubers during storage.

Despite the regulatory potential attributed to the light regime in the vegetative process, other aspects, such as the time of application and the period of exposure, should be considered and applied to obtain more insights into sprout control and carbohydrate metabolism.

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Tables

Table 1 Fresh weight loss *(FWL*), dry matter (*DM*), and firmness, of "Asterix" potato tubers stored in the dark (negative control), treated with 0.022 g L^{-1} CIPC (positive control), exposed to red LED (5 µmol m^{-2} s^{-1}), far-red LED (5 µmol m^{-2} s^{-1}) and blue LED (1 µmol m^{-2} s^{-1}) for up to 75 days at 16.7 ± 1 °C and 91.5 ± 1% RH

Main factors	*FWL* (%)	*DM* (g kg^{-1})	Firmness (*N*)
Light treatment			
Dark	3.53 a	206.3 a	23.7 a
CIPC	3.48 a	212.0 a	24.1 a
Red	3.95 a	214.0 a	23.7 a
Blue	3.91 a	211.0 a	23.8 a
Far Red	3.60 a	207.0 a	24.1 a
F	0.92 NS	1.31NS	1.17 NS
Storage			
0	0.00 e	198.1 c	20.9 d
15	2.38 d	202.1 bc	23.5 c
25	3.54 cd	211.0 abc	24.3 abc
35	4.01 bc	210.1 abc	23.9 bc
45	4.39 abc	211.4 abc	24.7 ab
55	4.70 abc	215.0 ab	24.2 abc
65	5.01 ab	219.3 a	24.4 ab
75	5.53 a	213.4 ab	24.9 a
F	37.4*	3.83*	46.9*
Interactions			
F (*L* × *D*)	0.05 NS	0.86 NS	1.11 NS
SD	1.29	1.54	0.83

Means followed by the same letter within each column do not statistically differ from each other according to the Tukey test ($p < 0.05$). Nonsignificant (*NS*), significant at $p < 0.05$ (*), and significant at $p < 0.01$ (**).

Table 2 Respiration rate, starch, reducing sugars and total soluble sugar content of "Asterix" potato tubers stored in the dark (negative control), treated with 0.022 g L−1 CIPC (positive control), exposed to red LED (5 µmol m^{-2} s^{-1}), far-red LED (5 µmol m^{-2} s^{-1}) and blue LED (1 µmol m^{-2} s^{-1}) for up to 75 days at 16.7 ± 1 °C and 91.5 ± 1% RH

Main factors	Respiration (mg CO_2 $kg^{-1}h^{-1}$)	Starch (g kg^{-1})	Reducing sugars (gkg^{-1})	Total soluble sugars (g kg^{-1})
Light treatment				
Dark	3.50 a	653.0 a	2.1 a	3.2 b
CIPC	3.43 a	575.6 a	2.1 a	3.6 ab
Red	3.67 a	587.0 a	2.2 a	3.7 ab
Blue	3.44 a	625.0 a	1.9 a	3.7 ab
Far Red	3.62 a	667.0 a	2.1 a	4.2 a
F	1.23 NS	2.90 NS	0.22 NS	3.13**
Storage				
0	6.77 a	489.3 e	2.7 ab	3.8 bc
15	4.22 b	625.5 cd	3.1 a	2.5 de
25	3.13 c	633.0 bcd	1.8 bc	3.0 cde
35	2.92 c	357.2 f	2.4 abc	4.5 b
45	2.75 c	821.0 a	1.6 bc	3.8 bc
55	2.89 c	535.7 de	1.4 c	2.1 e
65	2.85 c	752.3 abc	1.7 bc	3.4 cd
75	2.69 c	757.0 ab	2.0 abc	6.3 a
F	132.7*	27.9*	4.99*	28.7*
Interactions				
F	1.48 NS	1.20 NS	0.21 NS	1.30 NS
SD	0.37	11.41	0.10	0.09

Means followed by the same letter within each column do not statistically differ from each other according to the Tukey test ($p < 0.05$). Nonsignificant (*NS*), significant at $p < 0.05$ (*), and significant at $p < 0.01$ (**).

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Figures

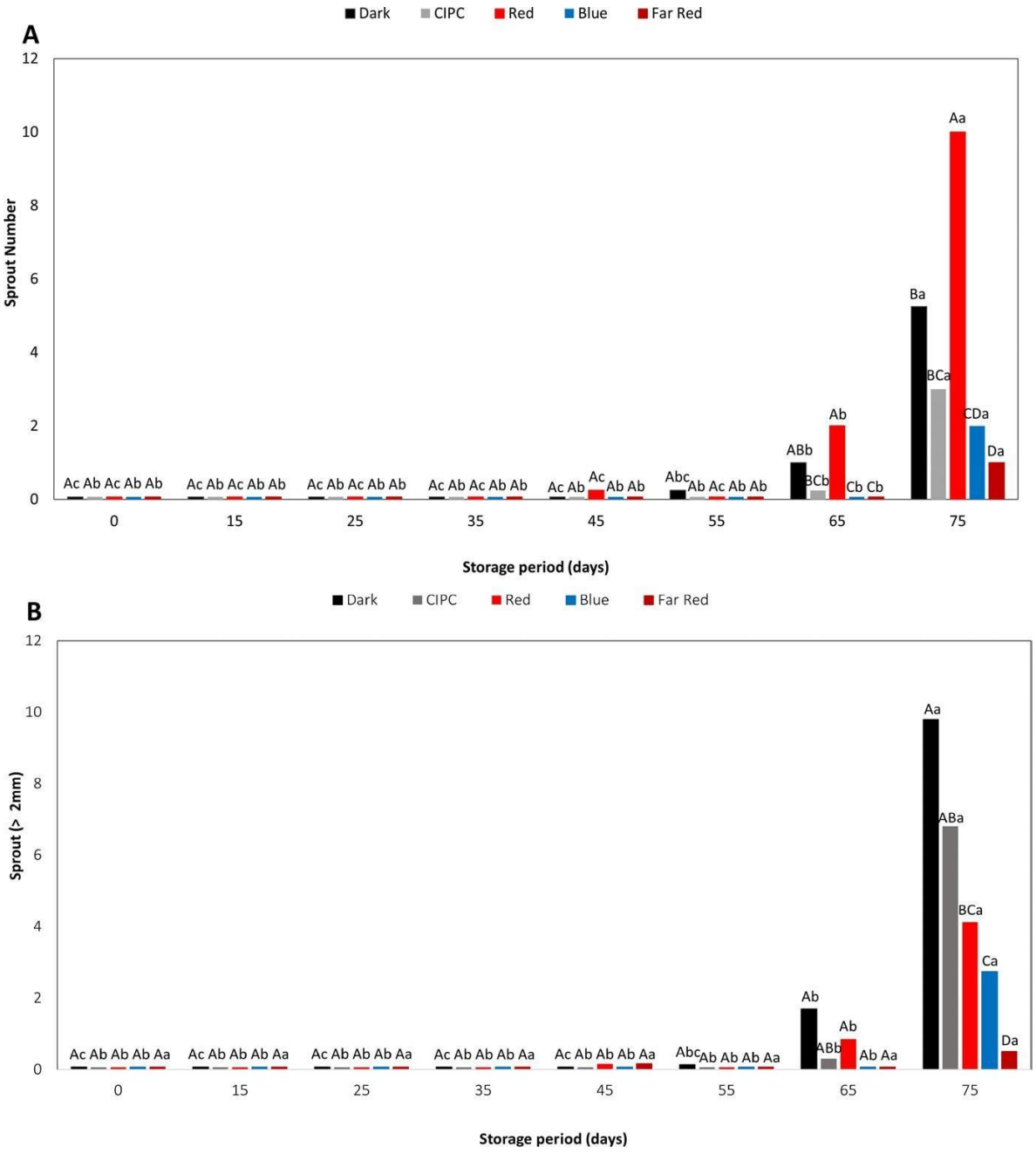

Fig. 1 Interaction between light treatments and storage period for the number of sprouts (**A**) and sprouts > 2 mm (**B**) of 'Asterix' potato tubers stored in the dark (negative control), treated with 0.022 g L^{-1} CIPC (positive control), exposed to red LED (5 µmol m^{-2} s^{-1}), far-red LED (5 µmol m^{-2} s^{-1}) and blue LED (1 µmol m^{-2} s^{-1}) for up to 75 days at 16.7 ± 1 °C and 91.5 ± 1% RH. Means followed by the same lowercase letters do not statistically differ from each other within storage periods using the Tukey test ($P < 0.05$). Means followed by the same uppercase letters do not statistically differ from each other across the storage period using the Tukey test ($p < 0.05$)

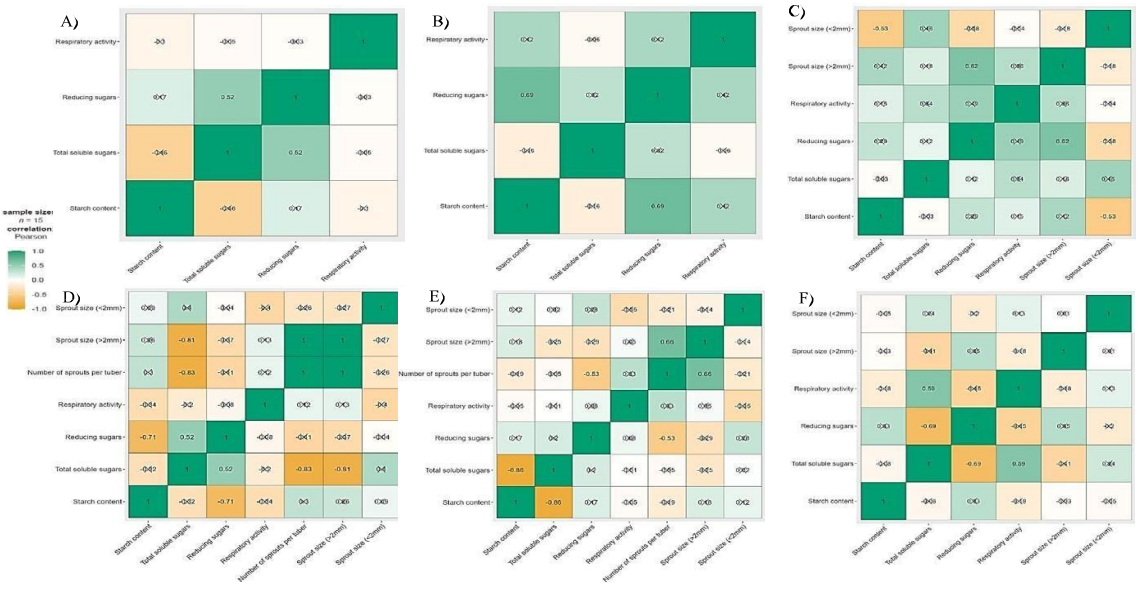

Fig. 2 Pearson coefficients (*r*) between reducing sugars, total soluble sugars, starch content, respiration rate and the presence of sprouts and sprouts > 2 mm of 'Asterix' potato tubers stored in the dark (negative control), treated with 0.022 g L^{-1} CIPC (positive control), exposed to red LED (5 µmol m^{-2} s^{-1}), far-red LED (5 µmol m^{-2} s^{-1}) and blue LED (1 µmol m^{-2} $s.^{-1}$) for day 25 (**A**), 35 (**B**), 55 (**C**), 65 (**D**) and 75 (**E**) between reducing sugars and starch levels became moderately negative ($r = -0.69$; $p < 0.05$). Additionally, a new positive correlation was established between the respiratory rate and total sugar content ($r = 0.59$; $p < 0.05$) (Fig. 2F).

CAPÍTULO 4 - Far-red LED light treatment at harvest and during storage to control sprouting in ‘Asterix’ potatoes

ABSTRACT - The application of light-emitting diode (LED) light at different wavelengths has shown promising potential in reducing sprout growth in seed potatoes. In addition, continuous exposure to high irradiance far-red LED light at 5 μmol m^{-2} s^{-1}, has been shown to be most effective in suppressing sprout development in Asterix potatoes. However, it may not be practical for sprout management, as potatoes are typically stored in bulk. Therefore, the objective of this study was to assess the feasibility of applying 5 μmol m^{-2} s^{-1} of far-red LED light prior to storage and to investigate the photomorphogenic and quality responses to these treatments throughout storage. Potato tubers of the Asterix cultivar were exposed to far-red LED light before storage (for 0, 2, or 4 min) or continuously during storage (24 h a day), and compared with untreated potatoes (control) and potatoes treated with chlorpropham (CIPC), a sprouting inhibitor. Tubers continuously exposed to far-red LED light had fewer and less developed sprouts, while the application of the pre-storage treatment for 4 min was effective for up to 55 d in storage. However, far-red LED light did not inhibit sprouting during storage. Tubers treated with far-red LED light had lower dry matter, starch, and total soluble sugar levels compared to those treated with CIPC, but showed no differences in reducing sugar levels. Although promising, the far-red LED light treatment prior to storage was not fully effective in inhibiting sprouting, necessitating further studies to elucidate the mechanisms involved in tuber responses to light during storage.

Keywords: Dormancy, ecodormancy, light-emitting diode, sprout development, starch, carbohydrates.

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1. INTRODUCTION

Sprouting is one of the primary causes of postharvest potato losses during storage (Jaiswal et al., 2023), despite the common use of various chemical sprout suppressants (Daniel-Lake et al., 2011; Visse-Mansiaux et al., 2021). Irradiation using X-rays, electron beams, or gamma rays is among physical treatments reported as effective for suppressing sprouting (Son et al., 2022). Similarly, visible light has been reported to reduce sprout development by influencing bud photomorphogenesis (Huang et al., 2018; Liu et al., 2022; Mølmann & Johansen, 2020).

Regarding visible light, a groundbreaking study on potato sprouts continuously exposed to red and far-red light showed reduced growth due to the inhibition of plumular hook formation and shortening of the hypocotyl, when present in the sprout (Withrow, 1941). McGee et al. (1987) found that 12-hour photoperiod light treatments for 23 d could inhibit sprout growth in seed potatoes of the cultivars Desiree and Maris Piper using red, far-red (707 nm), or blue (<500 nm) fluorescent lamps with low fluence (10–20 μmol m^{-2} s^{-1}). Responses to red and far-red light are mediated by phytochrome, which regulates high-irradiance inhibition, while responses to blue and ultraviolet (UV) light involve cryptochrome (Cai and Huq, 2025; Jiang, 2024; Xie et al., 2007). Low irradiance (0.01-0.1 μmol m^{-2} s^{-1}) of red light-emitting diode (LED) light inhibited sprout elongation in green-sprouting seed potatoes of the Desiree cultivar. However, a similar effect was observed using high-irradiance (1.0 μmol m^{-2} s^{-1}) far-red LED (Mølmann and Johansen, 2020). These results emphasize the photomorphogenic inhibition of sprouts in seed potatoes, which is crucial for maintaining short, robust and sprouts that remain attached during planting.

Moreover, Pedrosa et al. (2023) and Pedrosa et al. (2025) studied the effect of LED light quality on sprouting inhibition during the processing of ‘Asterix’ potatoes and reported that blue (400–500 nm), red (660–690 nm), or far-red (700–735 nm) LED light prolonged the dormancy period and reduced sprout growth, but did not completely inhibit sprouting. Regarding irradiance, low fluence (0.1 μmol m^{-2} s^{-1}) of blue light and high fluence (1.0–5.0 μmol m^{-2} s^{-1}) of red or far-red LED light were more effective, with red and far-red light showing greater efficacy. All treatments were

applied continuously during storage, but no clear biochemical response was detected (Pedrosa et al., 2025).

Although light can reduce sprout development, it may not be practical for sprout management, as potatoes are typically stored in bulk, in piles up to 5.5 m high (Pringles, 2009). In this case, the light cannot penetrate the pile, and only potatoes at the top are exposed to light treatment. To overcome this impediment, Cools et al. (2014) treated the tubers of six potato cultivars with UV-C (254 nm) before storage using a custom-built conveyor belt, applying UV-C at different doses (0 to 30 kJ m^{-2}) for 1.5 min. They found that UV-C application (5–20 kJ m^{-2}) at harvest reduced sprout growth and incidence, especially with up to 10 % of the eyes observed during storage (Cools et al., 2014).

These aspects highlight the need to evaluate the effectiveness of far-red LED light treatment for inhibiting sprout growth before potato storage. Therefore, the objective of this study was to assess the feasibility of applying 5.0 µmol m^{-2} s^{-1} of far-red LED light prior to and continuously during storage and to investigate the photomorphogenic and quality responses to these treatments throughout storage.

2. MATERIAL AND METHODS

2.1. Plant material

Physiologically mature potato tubers (*Solanum tuberosum* L.) of the Asterix cultivar, produced according to a conventional system, were harvested in late October (winter harvest) from a commercial farm in Vargem Grande do Sul, State of São Paulo, Brazil (21° 50’ 9” S, 46° 52’ 50” W, and altitude of 730 m), were used in this study. ‘Asterix’ is one of the main potato cultivars grown in Brazil for fresh and processed markets. This cultivar has a moderate dormancy period of 60 days, as reported by Abba (2021).

2.2. LED light treatments

After harvesting, the tubers underwent a superficial cleaning process to remove coarser dirt, such as clods of earth, using soft brushes on a conveyor belt, thus

allowing greater exposure of the treatments to the periderm and plant buds. They were then sorted, with only sound tubers, free of blemishes or decay, selected for the LED treatments. The tubers were exposed to far-red LED light at 5 μmol m^{-2} s^{-1} with fluence adjusted using a spectroradiometer (PSI, model SpectraPen LM 510, Madrid, Spain) for different periods prior to storage, since this fluence was identified as the most effective in reducing sprout growth (Pedrosa et al., 2023). Given the rapid loading process for potato storage, the application of far-red LED light was based on the methodology of Cools et al. (2014), with modifications. The treatments consisted of exposing the tubers to far-red LED light (Figure 1) for 0 min (control), where no light was applied, and tubers were kept in darkness; 2 min (1 min on each side) before storage; 4 min (2 min on each side) before storage; continuously (24 h a day) throughout storage; and a spray treatment with 22 mg L^{-1} of 50 % 3-chlorophenil carbamate (CIPC) and ethanol solution (v/v), (500 mL manual sprayer) after 20 d in storage.

After treatment application, the tubers were immediately stored at 15 °C and 90–93 % relative humidity for 65 d, the required period to break dormancy in 'Asterix' potatoes (Abba, 2021). This temperature was chosen to promote fast dormancy break and sprout development. Evaluations were carried out at 0, 15, 25, 35, 45, 55, and 65 d after treatment application. The experiment was conducted in a completely randomized design, using a 5×7 factorial arrangement (treatments × evaluations), with four replicates of four tubers for photomorphological evaluations and four replicates of three tubers for quality and metabolic evaluations.

2.3. Photomorphological parameters

Tubers were evaluated on day 0 and subsequently every 10 d from day 15 until the end of the storage period (65 d). Thus, the morphological parameters were evaluated on days 0, 15, 25, 35, 45, 55, and 65, including the following variables:

2.3.1. Number of sprouts: The number of sprouts per tuber was determined by counting the number of sprouts measuring at least 2 mm in length on each tuber (Benedetti et al., 2005; Pedrosa et al., 2023).

***2.3.2. Sprout size (<2 mm or >2 mm)*:** The sprout size was measured using a digital caliper (AAZV, Brazil) with a range of 0–150 mm and an accuracy of 0.02 mm. Vegetative structures “piping” larger than 2 mm were classified as sprouts (Benedetti et al., 2005).

2.4. Physiological parameters

Physiological parameters were evaluated on days 0, 15, 25, 35, 45, 55, and 65, including the following variables:

***2.4.1. Fresh weight loss*.** Fresh weight loss (FWL) was determined by weighing the tubers at the beginning of the storage period (day 0) and on each evaluation day using a semi-analytical balance (Marte, model AS 2000, São Paulo, Brazil) with a precision of 0.01 g. Fresh weight loss was calculated based on the variation in tuber weight, with results expressed as a percentage.

***2.4.2. Respiration rate*.** The tuber respiration rate was determined using gas chromatography (Thermo Scientific, model Trace 1310, USA), measuring the carbon dioxide (CO_2) concentration following the procedures described by Pedrosa et al. (2023). Tubers were sealed in a glass jar (2.4 L) and the CO_2 content was determined after 0 and 24 h. The respiration rate was expressed as mg CO_2 kg^{-1} h^{-1}, as described by Kader and Saltveit (2003).

2.5. Quality parameters

Quality parameters were evaluated on days 0, 15, 25, 35, 45, 55, and 65. Periderm and pulp samples were frozen immediately after harvesting with liquid nitrogen and stored at -20 °C until analysis of the following variables:

***2.5.1. Dry matter contente*:** Dry matter (DM) content was determined in pulp samples (without skin) dried in a forced air oven (Lucadema, model LUCA-82/27, Brazil) at 105 °C until constant weight (Zarzecka et al., 2021); the results were expressed as grams per kilogram (g kg^{-1}).

***2.5.2. Starch contente*:** Starch content was determined as described by Pedrosa et al. (2025). A frozen pulp sample (0.5 g) was homogenized with 50 mL of distilled water and 1.0 mL of 4.0 M potassium acetate buffer solution (pH 4.5); then, 100 µL of a 50 % (v/v) alpha-amylase solution was added to the homogenate. This solution was heated to 90 °C in a water bath for 2 h under constant agitation. After this period, 100 µL of amyloglucosidase (10 mg mL^{-1}) was added to the solution. Subsequently, the solution was transferred to a water bath at 55 °C for 2 h. The solution was then filtered, diluted with distilled water, and neutralized using a 4 N NaOH solution. Sugar content was determined using the methodology described by Nelson (1944) and Somogyi (1952), with starch content results expressed as g kg^{-1}.

***2.5.3. Total soluble sugars*:** Total soluble sugars were quantified by extraction from 3.5 g of frozen pulp mixed with 60 mL of a 50 % (v/v) ethanol solution. The homogenate was heated to 60–65 °C in a stirred bath for 1 hour. Subsequently, 1 mL of hydrochloric acid (HCl) was added, and the homogenate was heated for one more hour. Finally, the homogenate was cooled and neutralized with 4 N NaOH. Total soluble sugars were determined as described by Nelson (1944) and Somogyi (1952), using a UV-vis spectrophotometer (KASVI, model K-37-UVIS), with results expressed as g kg^{-1}.

***2.5.4. Reducing sugars*:** Reducing sugars were quantified in a 4.5 g sample of frozen pulp mixed with 50 mL of distilled water. The homogenate was heated to 60 °C in a stirred bath for 30 min. After cooling, the samples were diluted with 100 mL of distilled water and filtered. Reducing sugars were determined as described by Nelson (1944) and Somogyi (1952) methods, with results expressed as g kg^{-1}.

2.6. Statistical Analysis

The data were subjected to analysis of variance (ANOVA), as described by Barbosa and Maldonado Jr. (2015). Means were compared using Tukey's test at 0.05 significance level. Data related to the number of sprouts were transformed using Arcsine [sqrt (x / 100)].

Principal component analysis (PCA) was used to assess the effect of treatments on variations in quality parameters and to integrate the data across evaluation periods. This process was performed by reducing the multivariate data matrix to a two-dimensional biplot, which explained the largest proportion of variation in the data obtained during storage (Table 1).

3. RESULTS AND DISCUSSION

3.1. Photomorphological evaluations

The number of sprouts per tuber differed only when potatoes were continuously irradiated with far-red LED light (n = 0.98) compared to those treated for 2 min (n = 1.62) before storage (Table 2). The other treatments resulted in a similar number of sprouts. However, the number of sprouts > 2 mm was lower on tubers continuously irradiated with far-red LED light (n = 4.96), followed by tubers treated for 4 min (n = 11.30) before storage. The treatments did not affect the number of sprouts < 2 mm (Table 2).

Significant interactions between factors were observed for sprouts > 2 mm (Table 2). Tubers began to develop sprouts after 15 d at 15 °C in almost all treatments, except those exposed to continuous far-red LED light treatment, which only developed fully-formed sprouts on day 35 (Figure 1). This treatment also resulted in a lower number of sprouts > 2 mm compared to the other treatments throughout the storage period. Tubers exposed to far-red LED light for 4 min before storage showed fewer sprouts > 2 mm on days 35 and 55 (Figure 1A). A significant difference in the interaction between factors was also observed for sprouts < 2 mm (Figure 1B), but only on day 35.

These results did not differ from those of Pedrosa et al. (2023; 2025), who observed extended dormancy in tubers continuously exposed to far-red LED light at 5 μmol m^{-2} s^{-1}, but no sprouting inhibition. This is consistent with Wurr (1978), who reported that light treatment affects only sprout growth after the end of the dormancy period. Moreover, treating the tubers for 4 min before storage suppressed elongation of sprouts > 2 mm. This indicates a triggering of a photomorphogenic response after harvest, which persisted throughout a 65-day storage period. Although no sprouting

inhibition was observed, this treatment could be combined with existing commercial sprout suppressants, similarly to the UV-C pre-storage treatment (Cools et al., 2014).

3.2. Physiological evaluations

Weight loss increased during storage, reaching 6.96 % at the end of the storage period (Table 2). Control tubers showed the lowest weight loss (2.73 %), followed by tubers treated with CIPC (3.13 %), far-red LED light treatment for 4 min before storage (3.64 %), far-red LED light treatment for 2 min before storage (4.19 %), and continuous far-red LED light treatment throughout storage (4.07 %), with no significant difference. The highest weight loss was observed in the far-red LED light treatment for 2 min (4.19 %) and in the continuous far-red LED light treatment (4.07 %) (Table 2). Although increased weight loss has been associated with germination in potato tubers (Paul et al., 2016), the weight loss results did not reflect the sprout development (Table 2). Thus, the treatments may have affected the wound healing process, which has been reported as an important storage procedure to reduce weight loss and spoilage in potatoes (Ge et al., 2021; Lulai et al., 2008; Pringles, 2009).

The respiratory activity decreased from 4.40 mg CO_2 kg^{-1} h^{-1} at harvest to 2.45 mg CO_2 kg^{-1} h^{-1} at the end of the storage period (Table 2). The highest respiration rate was observed in tubers continuously exposed to far-red LED light (3.66 mg CO_2 kg^{-1} h^{-1}). This result is quite contradictory, as tubers continuously irradiated with far-red LED light had the fewest sprouts and less developed sprouts (Table 2). In a similar study, Pedrosa et al. (2025) did not observe differences in the respiration rate of Asterix potatoes irradiated with red (5 µmol m^{-2} s^{-1}), far-red (5 µmol m^{-2} s^{-1}), or blue (1.0 µmol m^{-2} s^{-1}) LED light for up to 75 d at 16.7 ± 1 °C and 91.5 ± 1 % RH. Thus, no relationship between respiration rate and sprout development was observed; however, far-red LED light accelerated the energy metabolism in tubers. Zhou et al. (2023) reported increased respiratory activity in bananas irradiated with red light, attributing this to the activation of energy metabolism-related enzymes, including H^+ adenosine triphosphatase (H^+-ATPase), Ca^{2+} adenosine triphosphatase (Ca^{2+}-ATPase), succinate dehydrogenase (SDH), cytochrome C oxidase, and malic enzyme (ME).

3.3. Quality parameter evaluations

Dry matter content did not change during storage, and tubers in the control treatment (239.01 g kg^{-1}) had higher dry matter content than those treated with CIPC (206.28 g kg^{-1}) and irradiated with far-red LED for 2 mins before storage (208.90 g kg^{-1}). Contrastingly, Pedrosa et al. (2025) observed no difference in the dry matter content of Asterix potatoes irradiated with red, far-red, or blue LED light. Control tubers lost more weight during storage (Table 2), this may have caused an increase in dry matter, as reported by Moens et al. (2021) and Irungu et al. (2022). Dry matter content was constant during storage, and no differences were observed from day 0 to day 65 (Figure 2). Dry matter content in potatoes ranges from 160 to 261 g kg^{-1} (Pringles, 2009), and a large part of it is composed of starch, whose mobilization has been associated with sprout growth and development (Pringles, 2009; Sonnewald and Sonnewald, 2014). However, the far-red LED treatments had little effect on starch content (Table 3).

The interaction between treatments and storage periods was significant for starch content (Figure 2). Peng et al. (2024) reported a 30 % reduction in starch content in Zihuabai potatoes stored for 200 d at 8±1 °C, and attributed this reduction to starch hydrolysis, soluble sugar accumulation, and the higher respiratory activity prior to sprouting (Ierna et al., 2017; Dite Hunjek et al., 2020). Mobilization of carbohydrates, which has been associated with the increase of trehalose-6-phosphate (T6P), starch hydrolysis, and soluble sugars, is expected for the sprouts to develop (Shukla et al., 2019; Sonnewald and Sonnewald, 2014). These metabolic changes can ultimately result in more energy for sprout growth.

The total sugar content of tubers continuously irradiated with far-red LED light was less (3.32 g kg^{-1}) than in tubers treated with CIPC (4.64 g kg^{-1}) (Table 3). The other treatments had similar total sugar content, with considerable variability during storage (Table 3). Similar variability was observed for reducing sugars; however, the treatments showed no significant effect (Table 3). Pedrosa et al. (2025) also reported no differences in reducing sugars of Asterix potatoes irradiated with red, far-red, or blue LED light but observed lower total soluble sugar content in tubers stored in darkness (control) compared to those continuously treated with 5 µmol m^{-2} s^{-1} far-red

LED (Table 3). Sonnewald and Sonnewald (2014) reported decreases in total sugar content with sprout development; however, starch mobilization and soluble sugar accumulation were observed at the end of sprout growth. Thus, extending the dormancy period using continuous far-red LED light treatment may keep the tubers in a metabolic stage prior to starch mobilization and soluble sugar accumulation. These findings are corroborated by the significant interaction effect on starch content (Figure 2).

3.4. Principal Component Analysis (PCA)

The horizontal axis, representing Principal Component 1 (PC1), explained 47.7 % of the total variance in the data. This component captured most of the variations that produced the most relevant responses and mainly influenced the observed group formation. Principal Component 2 (PC2) accounted for 17.5 % of the total variance, resulting in a cumulative explained variance of 65.2 % (Figure 3A).

At the beginning of the storage (day 0), the samples formed a distinct group on the left-hand side of the PC1 (Figure 3A), which was associated with higher respiratory activity and starch content (Figure 3B). Consistently with the previous results (Tables 2 and 4), tubers continuously exposed to far-red LED light for up to 35 d grouped with the tubers subjected to the other treatments for 15 and 25 d (Group 2), indicating a delay in sprout development (Figure 3A). The loading plot indicated that this group was associated with the variables total sugar (TSS) and reducing sugar (RS) contents (Figure 3B). Interestingly, the dry matter (DM) content was negatively correlated with soluble sugar (TSS and RS). This result agrees with Artés-Hernández et al. (2022) and Di et al. (2024), who associated the modulation of physiological parameters, such as hormonal activity and carbohydrate metabolism with the use of LED light.

As sprouts developed during storage, the samples dislocated from the left-hand side of the PC plot to the right-hand side, indicating a negative correlation between higher weight loss (FWL), sprout number (SN), and sprouts > 2 mm with respiration rate and starch content (Figures 3A and 3B). Therefore, higher FWL, SN, and sprouts > 2 mm were the variables associated with the formation of groups 3 and 5 (Figure 3), indicating a greater relevance of the FWL and shoot size variables for these samples

cluster together. The continuous exposure of tubers to far-red LED light for 45 and 55 d and the pre-loading treatments for 2 and 4 min for 35 d formed a group (Group 4) in the center of the PC plot (Figure 3A). This cluster indicates the effectiveness of continuous far-red LED lights to germination and sprout development, and that a pre-loading treatment for 2 and 4 min also had a photomorphogenic effect on sprouting. Thus, environmental parameters such as light significantly influence the physiological and biochemical characteristics of the tubers, particularly respiratory activity, mass loss, and carbohydrate content (Gumbo et al.,2021; Hu et al., 2023 and Lulu et al., 2023).

4. CONCLUSIONS

Continuous exposure to far-red LED has proven to be a promising alternative for controlling the development of potato tuber sprouts, reducing the number and development of sprouts, and prolonging the dormancy period without negatively affecting tuber quality.

Exposing tubers to far-red LED light for 4 min before storage also demonstrated potential photomorphogenic action, reducing sprout development.

Despite its promise, the use of far-red LED light before and during storage did not inhibit sprouting. Therefore, further studies are needed to improve the use of this technology.

5. ACKNOWLEDGMENTS

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Tables

Table 1. Variable codes used for the principal component analysis.

Variables	Code	Variables	Code
Sprout number	SN	CIPC - Day 45	CIPC-45
Sprout Size	> 2 mm	CIPC - Day 55	CIPC-55
Fresh weight loss	FWL	CIPC - Day 65	CIPC-65
Respiration rate	Resp	2 min - Day 0	2 min -0
Dry matter	DM	2 min - Day 15	2 min -15
Starch	Starch	2 min - Day 25	2 min -25
Total soluble sugars	TSS	2 min - Day 35	2 min -35
Reducing sugars	RS	2 min - Day 45	2 min -45
Control (Dark)	Control	2 min - Day 55	2 min -55
3-chlorophenil carbamate (CIPC)	CIPC	2 min - Day 65	2 min -65
Expose to far-red for 2 min	2 min	4 min - Day 0	4 min -0
Expose to far-red for 4 min	4 min	4 min - Day 15	4 min -15
Expose to far-red for 24 h /d	Continuously	4 min - Day 25	4 min -25
Control - Day 0	Dark-0	4 min - Day 35	4 min -35
Control - Day 15	Dark-15	4 min - Day 45	4 min -45
Control - Day 25	Dark-25	4 min - Day 45	4 min -55
Control - Day 35	Dark-35	4 min - Day 65	4 min -65
Control - Day 45	Dark-45	Continuously - Day 0	Cont.-0
Control - Day 55	Dark-55	Continuously - Day 15	Cont.-15
Control - Day 65	Dark-65	Continuously - Day 25	Cont.-25
CIPC - Day 0	CIPC-0	Continuously - Day 35	Cont.-35
CIPC - Day 15	CIPC-15	Continuously - Day 45	Cont.-45
CIPC - Day 25	CIPC-25	Continuously - Day 55	Cont.-55
CIPC - Day 35	CIPC-35	Continuously - Day 65	Cont.-65

Table 2. Photomorphological, physiological, and quality parameters of 'Asterix' potatoes under different treatments for sprouting inhibition during storage at 15 °C and 90–93 % relative humidity (RH) for 65 d.

Factors	Number of sprouts	Sprout size		Fresh weight loss	Respiration Rate	Dry matter
		(>2 mm)	(<2 mm)	(%)	(mg CO_2 kg^{-1} h^{-1})	(g kg^{-1})
Treatments (T)						
Control	1.35 ab	12.78 ab	2.26 a	2.73 c	3.04 b	239.01 a
CIPC	1.50 ab	11.95 ab	2.41 a	3.13 bc	2.97 b	206.28 b
2 minutes	1.62 a	13.83 a	2.27 a	4.19 a	2.90 b	208.90 b
Continuous	0.98 b	4.96 c	2.59 a	4.07 a	3.66 a	214.86 ab
4 minutes	1.41 ab	11.30 b	2.62 a	3.68 ab	2.85 b	213.64 ab
Period (P)						
0 d	0.00 d	0.00 e	0.00 d	0.00 g	4.40 a	214.56 a
15 d	0.75 d	1.43 e	0.95 cd	0.96 f	3.41 b	205.15 a
25 d	0.45 d	7.58 d	1.70 c	2.53 e	3.10 bc	210.98 a
35 d	0.71 cd	11.66 c	1.91 c	3.66 d	2.92 bcd	215.61 a
45 d	1.35 c	15.51 b	2.38 c	4.87 c	2.71 cd	225.36 a
55 d	2.32 b	20.0 a	4.10 b	5.93 b	2.60 cd	236.22 a
65 d	4.72 a	20.47 a	6.10 a	6.97 a	2.45 d	207.82 a
F (Treatments)	ns	40.80**	ns	16.20 **	10.65**	3.53**
F (Period)	76.73**	166.86**	32.39**	197.81 **	30.51**	2.32**
F (T × P)	ns	3.91**	1.65*	ns	ns	ns
C V (%)	62.41	26.32	65.73	22.88	15.11	16.97

Means followed by different letters are significantly different from each other by the Tukey's test at a 5 % significance level. ** = significant at a 1% level and ns = not significant at a 5 % level by the F-test; CV = coefficient of variation. Sprout size data were transformed using Arcsine [sqrt (x / 100)]. Control = no far-red LED light, with tubers stored in darkness; 2 min = far-red LED light for 1 min on each side before storage; 4 min = far-red LED light for 2 min on each side before storage; Continuous = continuous far-red LED light (24 h a d) throughout storage; CIPC = treatment with 22 mg L^{-1} of 50 % 3-chlorophenil carbamate () and ethanol solution (v/v), applied after 20 d of storage.

Table 3. Starch, total soluble sugars, and reducing sugars in 'Asterix' potatoes under different treatments for sprouting inhibition during storage at 15 °C and 90–93 % relative humidity (RH) for 65 d.

Factors	Starch	Total soluble sugars	Reducing sugars
	(g kg^{-1})	(g kg^{-1})	(g kg^{-1})
Treatments (T)			
Control	534.15 b	3.66 ab	3.57 a
CIPC	641.47 a	4.64 a	3.33 a
2 min	548.97 ab	3.92 ab	3.27 a
Continuous	543.86 ab	3.32 b	3.89 a
4 min	559.04 ab	4.04 ab	3.57 a
Period (P)			
0 d	770.52 a	3.36 cd	2.59 c
15 d	545.97 b	5.74 a	5.05 a
25 d	544.73 b	4.87 ab	4.77 ab
35 d	574.80 b	4.46 abc	3.11 bc
45 d	559.99 b	3.69 bc	3.08 bc
55 d	462.82 b	3.17 cd	2.32 c
65 d	491.64 b	2.13 d	3.75 abc
F (Treatments)	3.08*	3.70**	ns
F (Period)	12.14**	15.89 **	5.53**
F (T × P)	1.95*	ns	ns
C V (%)	20.03	29.77	49.02

Means followed by different letters are significantly different from each other by the Tukey's test at a 5 % significance level. ** = significant at 1 % level and ns = not significant at a 5 % level by the F-test. CV = coefficient of variation. Control = no far-red LED light. with tubers stored in darkness; 2 min = far-red LED light for 1 min on each side before storage; 4 min = far-red LED light for 2 min on each side before storage; Continuous = continuous far-red LED light (24 h/ d) throughout storage; CIPC = treatment with 22 mg L^{-1} of 50 % 3-chlorophenil carbamate and ethanol solution (v/v) applied after 20 d of storage.

Figures

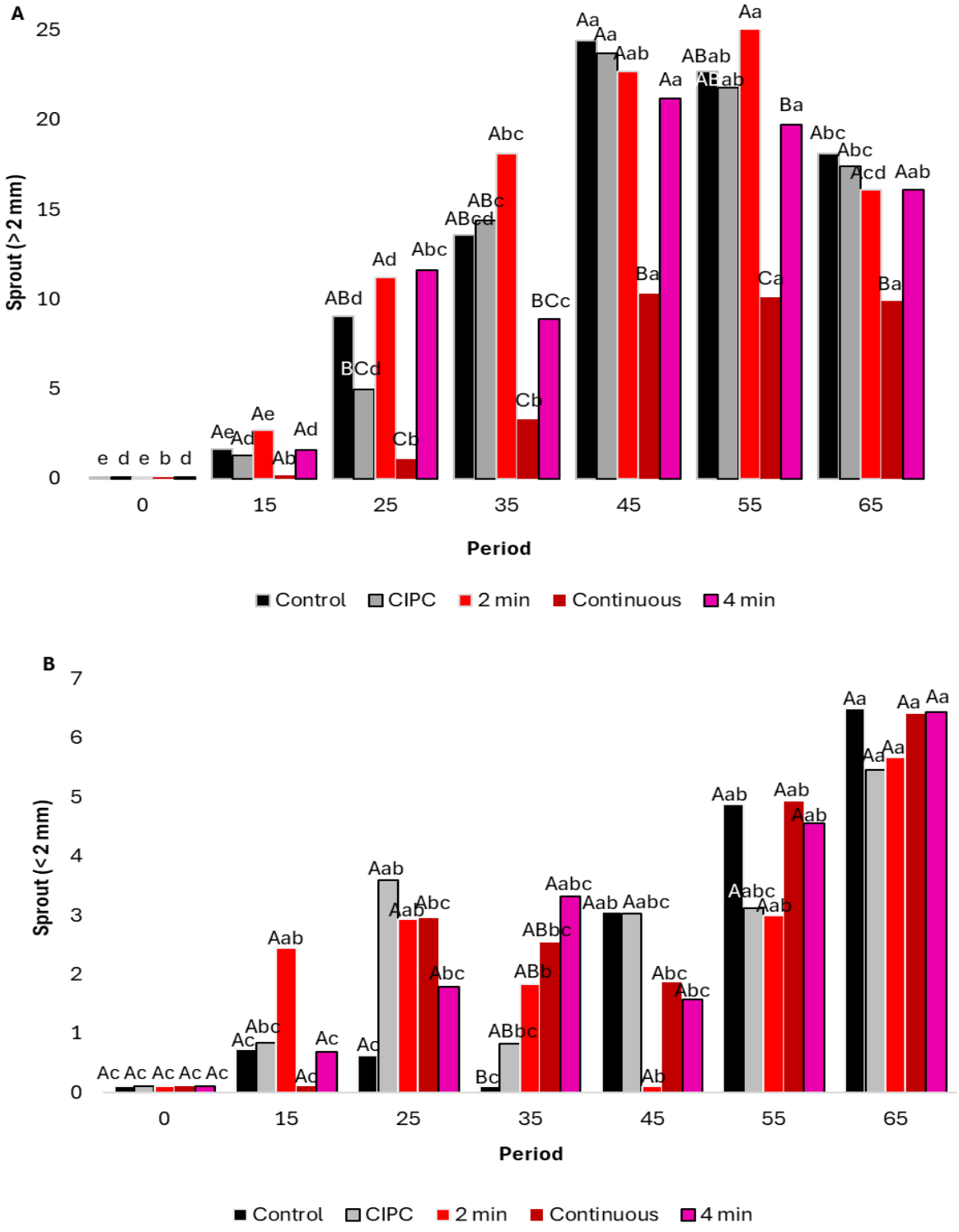

Figure 1. Effect of the interaction between factors (Treatments × Periods) on sprout size (> 2 mm (A) or < 2 mm (B)) in Asterix potatoes under different treatments for sprouting inhibition during storage at 15 °C and 90–93 % relative humidity (RH) for 65 d.

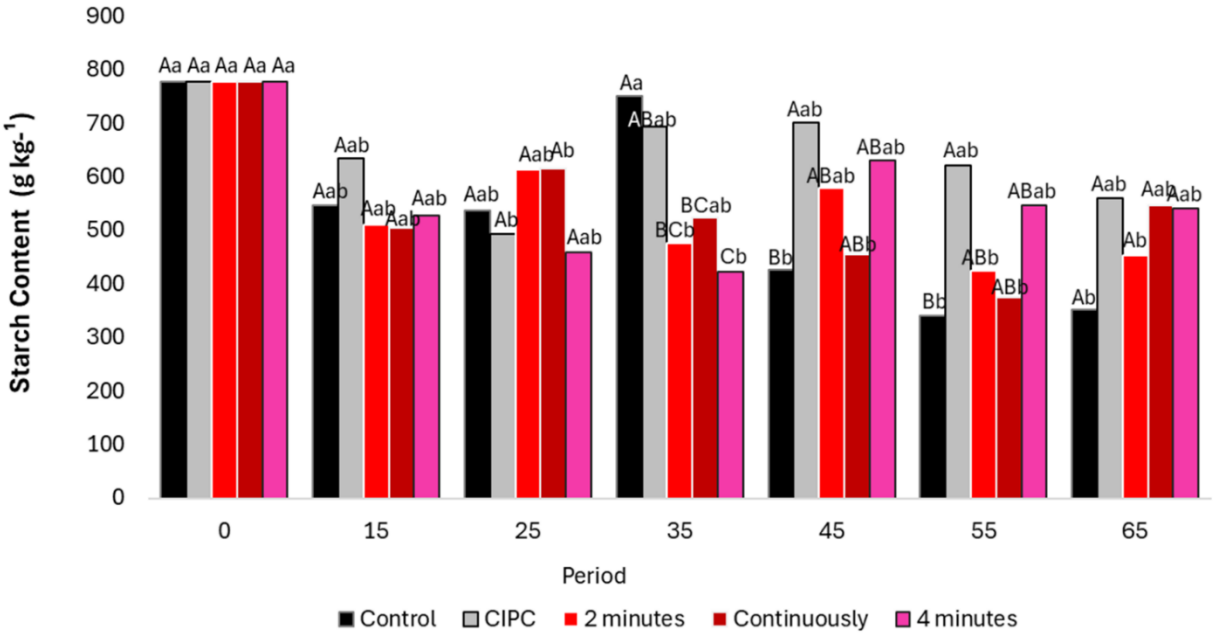

Figure 2. Effect of the interaction between factors (Treatments × Periods) on starch content (g kg^{-1}) in Asterix potatoes under different treatments for sprouting inhibition during storage at 15 °C and 90–93 % relative humidity (RH) for 65 d.

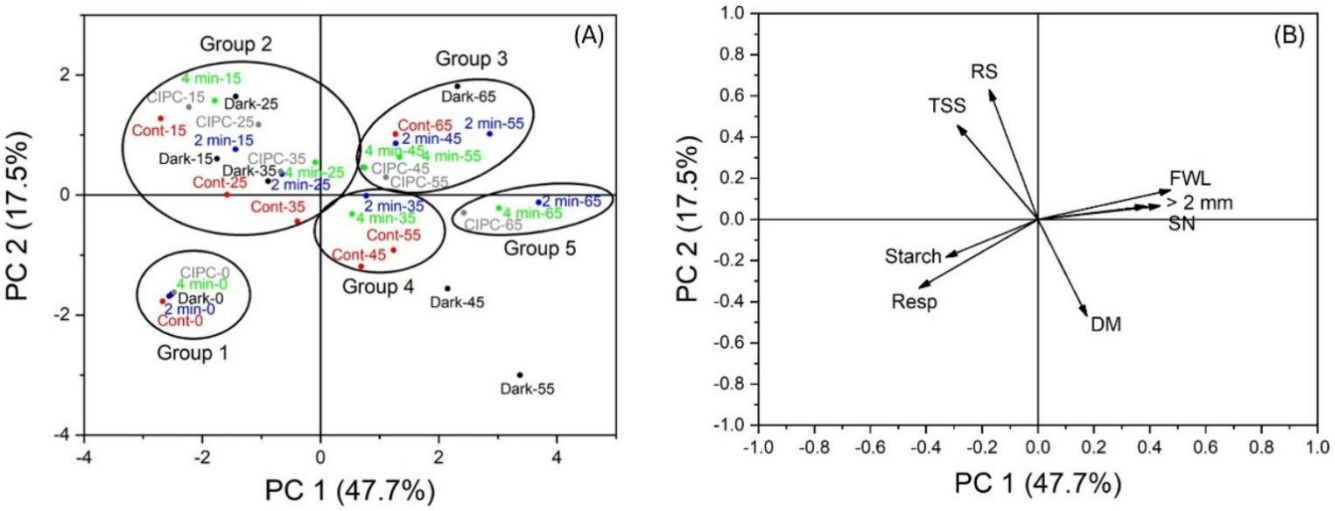

Figure 3. Score plot (A) and loading plot (B) of PC1 versus PC2 from selected data PCA of 'Asterix' potatoes under different LED light regimes stored at 15 °C and 90–93 % relative humidity (RH) for 65 d. Samples were labeled using the code defined in Table 1.

CAPÍTULO 5 - Considerações finais

Tendo em vista a problemática abordada no presente estudo a respeito do desenvolvimento de brotações durante o armazenamento de tubérculos e as atuais políticas adotadas por países que buscam tecnologias de menor impacto ambiental e de menor risco à saúde dos consumidores, há uma demanda crescente por parte das indústrias de processamento por métodos mais eficientes e menos problemáticos do ponto de vista da segurança, que assegurem a manutenção dos parâmetros de qualidade dos tubérculos de batata. Isso se torna especialmente relevante em países onde ocorre apenas uma safra anual e o período de armazenamento refrigerado dos tubérculos colhidos pode se estender por até doze meses.

Atualmente, o controle da brotação durante o armazenamento depende do uso decompostos químicos sintéticos como o clorprofam (*isopropyl N-(3-chlorophenyl) carbamate* – CIPC) e o 1,4-dimetilnaftaleno (1,4-DMN). Apesar de eficazes, esses produtos apresentam toxicidade e potencial carcinogênico, representando riscos à saúde humana e ao meio ambiente.

A radiação luminosa surge como alternativa promissora, já reconhecida por sua capacidade de modular processos fisiológicos em tecidos vegetais, atuando principalmente na inativação ou regulação de processos metabólicos. No entanto, seu uso exige a definição precisa de comprimentos de onda, métodos de aplicação e tempo de exposição, fatores que variam conforme o tipo de vegetal e sua variedade, sendo assim necessário que o estudo seja continuado e replicado em outras variedades de batatas, ampliando o entendimento das variações fisiológicas que podem ocorrer mediante a utilização da luz como regulador na pós-colheita dos tubérculos de batata.

Neste estudo, o espectro de vermelho distante, apresentou os resultados mais promissores, especialmente em relação ao conteúdo de carboidratos e ao controle do tamanho das brotações. No entanto, não foi possível estabelecer um regime luminoso ou método de aplicação que inibisse de forma eficaz a brotação em batatas da cultivar Asterix.

Os dados obtidos indicam o potencial do vermelho distante na regulação da dormência ou da germinação. Investigações futuras devem explorar diferentes formas

e regimes de aplicação de aplicação dos tratamentos luminosos (luz pulsada, exposição intermitente, composição luminosa), identificar o momento ideal para a aplicação dos tratamentos (pré-armazenamento, pós-armazenamento, dentro da indústria, gondolas de mercados) e avaliar estratégias que permitam integrar essa tecnologia à linha de beneficiamento dos tubérculos (capacidade de adaptação estrutural), considerando a resolução de desafios a implementação dessas técnicas na indústria, como as limitações impostas pelo armazenamento, onde se emprega o uso de bins ou a amontoa, formação de pilhas, de batatas em um armazém fechado.

APÊNDICES

Supplementary material

S1. Setting up of plastic box containers equipped with an air circulation system and LED lights to apply the light treatments to ‘Asterix’ potatoes, constituting the experimental units.