UNIVERSIDADE FEDERAL DE ALFENAS

ÁLISSON NEVES SANTOS

O ÓXIDO NÍTRICO MITIGA O DÉFICIT HÍDRICO NO MILHO? REVISÃO SISTEMÁTICA E METANÁLISE.

ALFENAS/MG

2023

ÁLISSON NEVES SANTOS

O ÓXIDO NÍTRICO MITIGA O DÉFICIT HÍDRICO NO MILHO? REVISÃO SISTEMÁTICA E METANÁLISE.

Dissertação apresentada como parte dos requisitos para obtenção do título de Mestre em Biotecnologia, pela Universidade Federal de Alfenas. Área de concentração: Biomoléculas

Orientador: Prof. Dr. Plínio Rodrigues dos Santos Filho

ALFENAS/MG

2023

Sistema de Bibliotecas da Universidade Federal de Alfenas
Biblioteca Central

Santos, Álisson Neves.
O Óxido Nítrico mitiga o déficit hídrico no milho? Revisão sistemática e metanálise. / Álisson Neves Santos. - Alfenas, MG, 2023.
52 f. : il. -

Orientador(a): Plinio Rodrigues dos Santos Filho.
Dissertação (Mestrado em Biotecnologia) - Universidade Federal de Alfenas, Alfenas, MG, 2023.
Bibliografia.

1. Bioestimulante Vegetal. 2. Peroxidação Lipídica. 3. Zea Mays. I. Santos Filho, Plinio Rodrigues dos , orient. II. Título.

Ficha gerada automaticamente com dados fornecidos pelo autor.

ÁLISSON NEVES SANTOS

O ÓXIDO NÍTRICO MITIGA O DÉFICIT HÍDRICO NO MILHO? REVISÃO SISTEMÁTICA E METANÁLISE.

O Presidente da banca examinadora abaixo assina a aprovação da Dissertação apresentada como parte dos requisitos para a obtenção do título de Mestre em Biotecnologia pela Universidade Federal de Alfenas. Área de concentração: Biomoléculas.

Aprovado em: 13 de julho de 2023.

Prof. Dr. Plinio Rodrigues dos Santos Filho

Presidente da Banca Examinadora

Instituição: Universidade Federal de Alfenas (UNIFAL)

Prof. Dr. Adriano Bortolotti da Silva

Instituição: Universidade Prof. Edson Antônio Velano (UNIFENAS)

Prof. Dr. Breno Régis Santos

Instituição: Universidade Federal de Alfenas (UNIFAL)

AGRADECIMENTOS

Primeiramente, agradeço a Deus por toda capacitação, força, coragem e vontade de me fazer chegar até aqui.

Aos meus pais José Luz e Marlucia Neves, juntamente com meu irmão Guilherme por estarem sempre presentes comigo, me apoiando, incentivando e por serem o meu ponto de refúgio. Obrigado por todo amor e carinho, em vocês encontro o verdadeiro significado da palavra família.

Aos meus amigos por todas palavras de incentivo.

Ao meu orientador, Prof. Dr. Plínio Rodrigues dos Santos Filho pelo constante ensinamento, considerações e principalmente por sua confiança.

Ao Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) e à Fundação de Amparo à Pesquisa do Estado de Minas Gerais (FAPEMIG- APQ-01671-17) pelo apoio financeiro.

À Universidade Federal de Alfenas por ter me oportunizado a realização desse trabalho.

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

RESUMO

A cultura do milho é uma das mais importantes do cenário agrícola mundial e possui papel fundamental no que se refere a economia de muitos países, entretanto alguns fatores bióticos e abióticos podem impactar em resultados negativos sobre esta cultura. Um fator abiótico que se destaca entre os outros, é o déficit hídrico. Nessas condições, pesquisas vêm sendo realizadas com o intuito de identificar maneiras de tornar a planta mais tolerante a esse tido de estresse. O Óxido Nítrico é uma molécula que desempenha diversos efeitos fisiológicos nas plantas, e um desses podem está envolvidos no aumenta da tolerância ao estresse hídrico, assim o objetivo do presente estudo foi realizar uma revisão sistemática com metanálise para verificar se o Óxido Nítrico pode atuar como molécula sinalizadora na tolerância ao estresse hídrico em plantas de milho. O estudo, se trata de uma revisão sistemática com metanálise desenvolvida de acordo com as orientações da recomendação PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-analyses), sob o registro no International Prospective Register of Ongoing Systematic Reviews (PROSPERO) de número CRD42022335324. Ao todo foram identificados 1.843 registros, no qual destes, 67 foram destinados à analise bibliométrica e 6 à Metanálise. A tendência no número de publicações apresentou-se crescente entre os anos de 2002 a 2021, com b1 de 0,1584, as pesquisas foram realizadas em 18 países diferentes e a China foi o país com maior número de investigações. Para a metanálise foram utilizados as seguintes variáveis: peroxidação lilipidica (MDA), atividade da Superóxido Dismutase (SOD) e a presença do NO. Após a aplicação de NO houve diminuição nos teores de MDA e aumento da atividade SOD. O tamanho do efeito foi calculado e através dos seus resultados pode se dizer que o NO atua como molécula sinalizadora na tolerância ao estresse hídrico em plantas de milho.

Palavras-chave: bioestimulante vegetal; peroxidação lipídica; Zea Mays

ABSTRACT

The corn crop is one of the most important in the world agricultural scenario and plays a fundamental role in the economy of many countries, however some biotic and abiotic factors can impact negative results on this crop. An abiotic factor that stands out among the others is the water deficit. Under these conditions, research has been carried out with the aim of identifying ways to make the plant more tolerant to this type of stress. Nitric Oxide is a molecule that performs several physiological effects in plants, and one of these may be involved in increasing tolerance to water stress, so the objective of the present study was to carry out a systematic review with meta-analysis to verify if Nitric Oxide can act as a Signaling molecule on water stress tolerance in maize plants. The study is a systematic review with meta-analysis developed in accordance with the guidelines of the PRISMA recommendation (Preferred Reporting Items for Systematic Reviews and Meta-analyses), under registration in the International Prospective Register of Ongoing Systematic Reviews (PROSPERO) number CRD 42022335324. In all, 1,843 records were identified, of which 67 were destined for bibliometric analysis and 6 for meta-analysis. The trend in the number of publications showed an increase between the years 2002 to 2021, with b1 of 0.1584, the surveys were carried out in 18 different countries and China was the country with the highest number of investigations. For the meta-analysis, the following variables were used: lipid peroxidation (MDA), Superoxide Dismutase (SOD) activity and the presence of NO. After NO application, there was a decrease in MDA levels and an increase in SOD activity. The effect size was calculated and through its results it can be said that NO acts as a signaling molecule in tolerance to water stress in maize plants.

Keywords: vegetable biostimulant; lipid peroxidation; Zea Mays.

LISTA DE FIGURAS

LISTA DE ABREVIATURAS E SIGLAS

NO	Óxido Nítrico
NOS	Óxido Nítrico Sintase
NR	Nitrato redutase
NADPH	Fosfato de dinucleótido de nicotinamida e adenina
NADH	Dinucleótido de nicotinamida e adenina
NO^{2-}	Dióxido de nitrogênio
PRISMA	Principais itens para produção de uma Revisão Sistemática e Metanálise
PROSPERO	Registro prospectivo de revisões sistemáticas contínuas
UV	Ultravioleta
SNP	Nitroprussiato de sódio
SNAP	S-nitroso-N-acetilpenicillamina
GSNO	S-nitrosoglutathione
L-NMMA	N^{G}-monometil-L-arginina
L-NAME	N^{G}-nitro-L-arginina metil ester
cPTIO	2-4-carboxifenil-4,4,5,5-tetrametilimidazol1-oxil-3-oxido
H2S	Sulfeto de hidrogênio
ABA	Ácido abscísico
DETA NO	2,2'-(Hydroxy-nitrosohydrazano)bis-ethane
SOD	Superóxido Dismutase
MDA	Malondialdeído

SUMÁRIO

1 INTRODUÇÃO GERAL

O cenário agrícola vem mostrando que as culturas estão continuamente submetidas à diferentes condições de estresses abióticos (TEIXEIRA *et al*., 2020), que ocorrem quando fatores ambientais prejudicam as condições fisiológicas das plantas, sendo denominados de fatores de estresse ou apenas estresse (WARSI; HOWLADAR; ALSHARIF, 2023). De todos os fatores de estresse envolvidos no cultivo de cereais, a disponibilidade hídrica é considerado o grupo com maior destaque a ser estudado, uma vez que há, uma grande necessidade de alternativas que visam diminuir os impactos causados pela falta de água. Além da seca, o desenvolvimento de possibilidades que ajudam a mitigar os efeitos negativos dos mais diferentes tipos de estresses é indispensável para a evolução das culturas agrícolas (AMARO *et al*., 2023).

Na cultura do milho os fatores que estão mais ligados à redução da produtividade são abióticos relacionados ao clima (disponibilidade hídrica, temperatura do ar, umidade relativa do ar e irradiação solar), e o fator com maior frequência e intensidade é a disponibilidade de água, gerando consequentemente perdas no rendimento da cultura (SANTOS *et al*., 2022).

Sendo considerado a mais antiga e importante cultivar comercial do mundo, plantado em escala global, o cultivo do milho teve sua origem nas américas e permanece até os dias de hoje. Atualmente, os maiores produtores mundias da cultura são: Argentina, Brasil, China e Estados Unidos (UNITED STATES DEPARTMENT OF AGRICULTURE, 2021).

Para que novos métodos possam ser idealizados a fim de reverter danos causados por algum tipo de estresse em plantas, é imprescidível um entendimento detalhado (fisiológico e bioquímico) das consequências causadas pelo mesmo. Pois, é a patir de então que experimentos de várias formas podem ser realizados, com o propósito de gerar resultados que contribuam para culturas em condições de estresse (SILVA *et al*., 2021).

O Óxido Nítrico (NO) por exemplo, é uma molécula que pode desempenhar vários papéis na fisiologia das plantas, pois não necessita de um transportador para atravessar membranas, e é considerado como lipofílico, diatômico e incolor (KHAN *et al*., 2023).

O NO pode ser chamado também de monóxido de hidrogênio, e pertence às moléculas do tipo radical livre por possuir um elétron não emparelhado em um de seus orbitais. Outro aspecto do NO e derivados da molécula é que, direta ou indiretamente, eles podem estar envolvidos em modificações pós-traducionais, incluindo ligação a centros metálicos, a S-nitrosilação de grupos tiol e a nitração da tirosina, a qual pode estar envolvida na sinalização celular em situações de estresse (CORPAS *et al*., 2011).

O óxido nítrico endogenamente nas plantas pode ser gerado tanto por mecanismos enzimáticos quanto não enzimáticos (NEILL; DESIKAN; HANCOCK, 2003). Os mecanismos enzimáticos foram descritos a partir do uso e eficácia de uma série de inibidores de NOS, dos quais a aminoguanidina foi considerada a mais eficaz, essas moléculas catalisam a formação de NO a partir da L-arginina, que sofre uma oxidação de cinco elétrons, sendo indispensáveis para a reação NADPH e oxigênio molecular. Já a nitrato redutase gera NO usando como substratos o NO^{2-} e NADH (YAMASAKI; SAKIHAMA; TAKAHASHI, 1999).

As revisões sistemáticas são evidências de alta qualidade, que resumem em um único estudo os resultados de pesquisas originais desenvolvidas em uma determinada área, no qual são construídas de forma metódica, transparente e replicavél (DONATO; DONATO, 2019). Em alguns casos, a metanálise, que consiste em um método estatístico empregado através da combinação dos resultados originais com intuito de elucidar questões sobre o tema proposto, pode ser realizada junto com a revisão sistemática (BALDUZZI; RUCKER; SCHWARZER, 2019).

Considerando a relevância da cultura do milho no âmbito mundial e a potencialidade do óxido nítrico enquanto sinalisador, o objetivo do presente estudo foi conduzir uma revisão sistemática com metanálise para verificar se o Óxido Nítrico pode atuar como molécula sinalizadora na tolerância ao estresse hídrico em plantas de milho.

2 REVISÃO LITERATURA / DESENVOLVIMENTO

2. 1 A CULTURA DO MILHO

O Brasil é atualmente o terceiro maior produtor de milho do mundo e essa produção deve crescer na comparação entre as safras 2021/2022 e 2022/2023, o CONAB prevê um aumento de 10,4% na produção total entre as safras, presumindo um total de 124,8 milhões de toneladas para a safra 2022/2023 (CONAB, 2023). A China, na segunda posição, foi responsável por 268 milhões de toneladas na safra 2021/2022, e os Estados Unidos lideram a produção, com 380,8 milhões de toneladas também na mesma safra (USDA, 2021).

A cadeia produtiva do milho é uma das mais importantes do agronegócio brasileiro, considerando que apenas a produção primária corresponde à aproximadamente 37% da produção nacional de grãos. O milho é cultivado em praticamente todo o território brasileiro, e 90% da produção se concentra nas regiões sul, sudeste e centro-oeste (CONAB, 2021).

Sendo considerado o principal cereal produzido no país, a cultura do milho é capaz de impulsionar os mais diversos setores da agricultura, exercendo relevante papel socioeconômico. Nas últimas sete décadas, a produção brasileira de milho aumentou significativamente, sendo este aumento reflexo da constante adoção de novas tecnologias na cadeia produtiva da cultura. A produção deve seguir crescente, podendo atingir entre 9,6 e 12,3 bilhões de pessoas até 2100 (GERLAND *et al*., 2014).

Por possuir metabolismo C4, o milho tem alta eficiência fotossintética o que possibilita à cultura atingir patamares de produtividade superiores a 10 Mg ha^{-1} (BERGAMASCHI *et al*, 2004). Devido à ausência de fotorrespiração, o ponto de compensação luminosa das plantas C4 é próximo de zero, o que favorece o processo fotossintético (TAIZ; ZEIGER, 2017). As variáveis climáticas que mais afetam o crescimento da cultura do milho são a temperatura, a radiação solar e a precipitação pluviométrica, que irão definir o seu potencial produtivo. A necessidade hídrica do milho varia de acordo com a época e local da semeadura e, também, com a área foliar e os genótipos utilizados, oscilando entre 500 e 800 mm durante seu ciclo, podendo ultrapassar 900 mm em locais onde a evapotranspiração da cultura é muito elevada (ABDRABOO *et al*., 2016).

2. 2 ESTRESSE ABIÓTICO E SEUS EFEITOS

Condições ambientais como: umidade, luminosidade, velocidade do vento e temperatura são exemplos que se encaixam como fatores abióticos relacionados ao desenvolvimento vegetal. Geralmente os efeitos negativos desses fatores são mais intensos na fase reprodutiva das culturas, principalmente no florescimento. Todas espécies possuem exigências especificas que influenciam no seu crescimento, tornando deste modo certas regiões mais tendenciosas a determinados tipos de culturas (SILVA *et al*., 2021).

Quando os fatores ambientais prejudicam as condições fisiológicas das plantas eles são denominados de fatores de estresse ou apenas estresse (ZHU, 2016). Segundo Silva *et al*. (2021), ainda há uma potencialização nos efeitos negativos quando simultaneamente ocorrem dois ou mais fatores.

A planta no momento em que se encontra sobe algum tipo de estresse aciona diversos mecanismos de defesa e alterna seu metabolismo celular induzindo a produção de espécies reativas de oxigênio que, tem por objetivo fazer com que as células tentem retornar às suas funcionalidades normais (MILLER *et al*., 2010).

Dentre os principais tipos de estresses abióticos tem-se o excesso de metais pesados. A presença desses metais no ambiente é comum, sendo resultante tanto de processos naturais quanto antrópicos, entretanto ocorre uma interferência direta na fisiologia das plantas quando há alta concentração desses metais no solo. O uso excessivo ou incorreto de agroquímicos e dejetos liberados pelas industrias são alguns exemplos de contaminação por metais pesados (MÂNCIO *et al*., 2022).

Outro tipo de estresse abiótico é a salinização dos solos. Nessas condições ocorre um desequilíbrio osmótico nas células e na homeostase iônica (MUCHATE, 2016). Esses processos implicam na retenção de água e diminuição do potencial hídrico, provocando deficiência na absorção de nutrientes devido ao acúmulo de íons tóxicos intracelular. Os processos metabólicos são impactados drasticamente nessas condições, inferindo perda da absorção de água e promovendo o fechamento dos estômatos (MÂNCIO *et al*., 2022).

2. 3 ESTRESSE HÍDRICO

O estresse hídrico destaca-se diante dos outros tipos de estresse por ser um dos mais comuns presentes nos ecossistemas. A falta de água nas células vegetais pode ocasionar variados tipos de desordens fisiológicas, morfológicas e bioquímicas. A depender da espécie cultivada e da intensidade do estresse, determinadas plantas conseguem se adaptar e até mesmo desenvolver mecanismos de tolerância, no entanto nem sempre isso ocorre, levando a grandes perdas de culturas (ARAUJO JÚNIOR *et al*., 2019).

Durante condições de estresse abiótico, as plantas induzem a síntese de osmólitos, como açúcares solúveis e aminoácidos, que contribuem para a manutenção do turgor por ajuste osmótico. Entre os aminoácidos, a prolina é o principal agente nesta resposta (além das hexoses), contribuindo para cerca de 50% do ajuste osmótico nas pontas das raízes do milho (NISHIZAWA *et al*, 2008).

2. 4 ÓXIDO NÍTRICO

Lipofílico, diatômico e incolor, o gás óxido nítrico, ou monóxido de nitrogênio (NO), pertence às moléculas do tipo radical livre devido possuir um elétron não emparelhado em um de seus orbitais (CORPAS *et al*., 2011; LAMATTINA *et al*., 2003; NEILL; DESIKAN; HANCOCK, 2003). O NO não necessita de transportador para atravessar membranas, se difundindo muito rapidamente por causa de sua natureza gasosa, além de poder reagir com certa quantidade de macromoléculas, como as proteínas, os lipídeos, os ácidos nucléicos, entre outras (CORPAS *et al*., 2011; DOMINGOS *et al*., 2015). Outro aspecto do óxido nítrico e derivados da molécula é que, direta ou indiretamente, eles podem estar envolvidas em modificações pós-traducionais, incluindo ligação a centros metálicos, a S-nitrosilação de grupos tiol e a nitração da tirosina, a qual pode estar envolvida na sinalização celular sob as condições fisiológicas e de estresse (CORPAS *et al*., 2011).

O óxido nítrico endogenamente pode ser gerado por mecanismos enzimáticos, os quais incluem as óxido nítrico sintases (NOS) e a nitrato redutase (NR), e não enzimáticos (NEILL; DESIKAN; HANCOCK, 2003). Os mesmos autores mencionam que a presença desses primeiros em plantas foi sumarizada pelo uso e eficácia de uma série de inibidores de NOS, dos quais a aminoguanidina foi considerada a mais eficaz; essas moléculas catalisam a formação de NO a partir da L-arginina, que sofre uma oxidação de cinco elétrons à L-citrulina, sendo indispensáveis para a reação NADPH e oxigênio molecular. Já a nitrato redutase gera NO usando como substratos o NO_2– e NADH (YAMASAKI; SAKIHAMA; TAKAHASHI, 1999).

Em relação aos não enzimáticos, sabe-se que os ciclos de nitrificação e de desnitrificação fornecem o NO como um subproduto da oxidação do N_2O para a atmosfera; ademais, a redução não enzimática do nitrito pode levar à formação de NO, e essa reação é favorecida por pH ácido quando o nitrito pode desmutar em NO e nitrato, assim como o nitrito pode também ser reduzido quimicamente pelo ácido ascórbico em pH de 3 a 6 produzindo o NO e ácido dehidroascórbico (CORPAS *et al*., 2007). Além disso, Cooney *et al*.

(1994), sugerem a formação de óxido nítrico através da redução mediada por luz de N_2O por carotenoides.

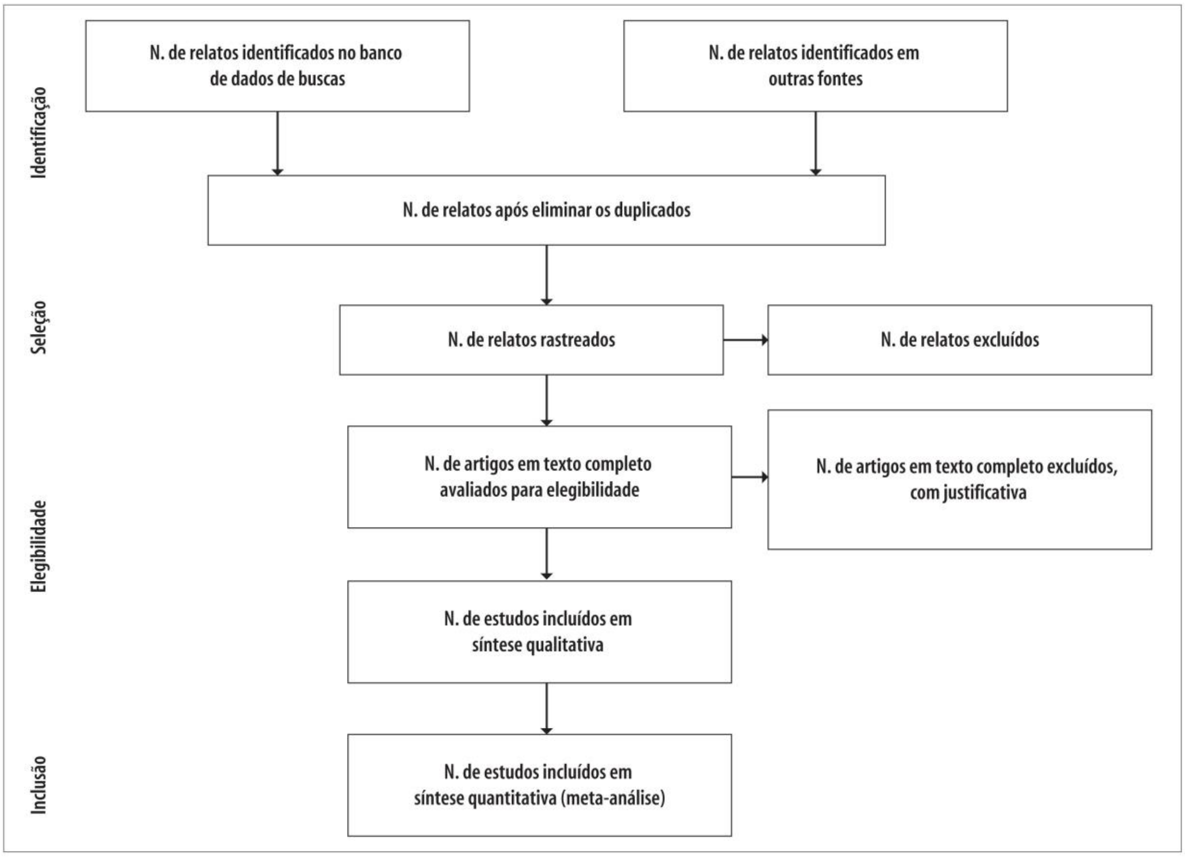
Em relação aos estresses abióticos, os papeis do óxido nítrico estão associados às respostas que induzem alterações fitormonais e fisiológicas, com destaque para os movimentos estomatais, bem como bioquímicas e nas rotas de sinalização, desencadeando a diminuição das injúrias celulares (GARCÍA-MATA; LAMATTINA, 2001; SHAPIRO, 2005; XIONG *et al*., 2012). Sendo assim, Neill *et al*. (2008) reiteram que o NO é um fator chave na tolerância celular ao estresse oxidativo induzido por inúmeras condições desfavoráveis, por atuar de forma efetiva no controle das EROs.

2. 5 REVISÃO SISTEMÁTICA E METANÁLISE

Sendo considerada como uma evidência de alta qualidade, a revisão sistemática resume em um único estudo os resultados de todas as pesquisas originais desenvolvidas em uma determinada área (DONATO; DONATO, 2019). A Metanálise por sua vez, consiste em um método estatístico empregado através da combinação dos resultados originais no intuito de elucidar questões abordadas sobre um tema (BALDUZZI; RUCKER; SCHWARZER, 2019).

O método PRISMA (Principais Itens para Relatar Revisões Sistemáticas e Meta-análises), é um dos mais creditáveis e importantes guias para a realização de uma revisão sistemática, o mesmo instrui detalhadamente as formas de identificação e seleção de estudos que devem ser inclusos em uma pesquisa. Esse sistema tem por objetivo ajudar os autores a executarem estudos de alta qualidade, para isso fornece um fluxograma de quatro etapas, classificando as fases no qual os pesquisadores devem seguir para que a revisão possa ser considerada sistemática, (Figura 1) (MOHER *et al*., 2015).

Figura 1 – Fluxograma de uma revisão sistemática com Metanálise.



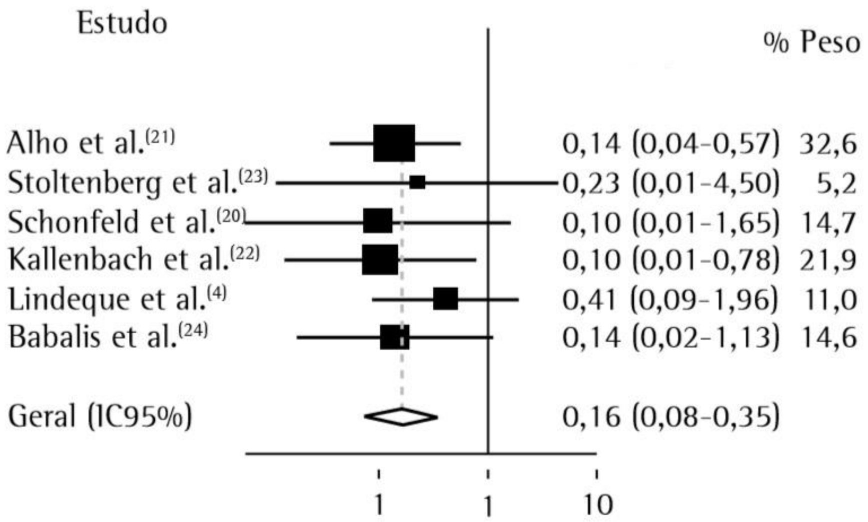
Fonte: MOHER *et al*., 2015.

Além do fluxograma o guia apresenta também um *checklist* com 27 itens descrevendo o que deve ser contido em uma revisão sistemática com meta-análise de qualidade (1- Título, 2- Resumo estruturado, na introdução: 3- Justificativa, 4- Objetivos, nos métodos: 5- Protocolo e registro, 6- Critérios de elegibilidade, 7- Fontes da informação, 8- Busca, 9- Seleção dos estudos, 10- Processo de coleta dos dados, 11- Lista dos dados, 12- Risco de viés em cada estudo, 13- Medidas de sumarização, 14- Síntese dos resultados, 15- Risco de viés entre estudos, 16- Análises adicionais, nos resultados: 17- Seleção de estudos, 18- Características dos estudos, 19- Risco de Viés em cada estudo, 20- Resultados dos estudos individuais, 21- Síntese dos resultados, 22- Risco de viés entre estudos, 23- Análises adicionais, na discussão: 24- Sumário de evidência, 25- Limitações, 26- Conclusões e 27- Financiamento) (MOHER *et al*., 2015).

A Metanálise é um recurso que pode ser em alguns casos incluso junto com a revisão sistemática. O gráfico de Forest Plot é um esquema onde é apresentado os resultados de uma meta-análise, e onde pode ser identificado a resposta da pergunta, neste, encontra-se o intervalo de confiança, valor do tamanho do efeito e o peso de cada estudo (RÜCKER;

SCHWARZER, 2020). Sua interpretação está diretamente ligada à linha vertical localizada no centro do gráfico, posto que a mesma representa o efeito nulo do estudo. O intervalo de confiança é expresso através das linhas horizontas do lado do quadrado de cada estudo, quando o intervalo de confiança se apresenta distante ou não ultrapassa essa linha do eixo vertical o próprio é dado com nível de significância menor que 0,05. No gráfico, é fornecido também o valor do tamanho do efeito global médio, simbolizado em forma de diamante, e seu intervalo de confiança médio. O peso de cada estudo é demostrado pelo tamanho do quadro central de cada análise (Figura 2) (MARQUES JUNIOR, 2014). Existem diferentes cálculos para confecção do gráfico Forest Plot (SANTOS; CUNHA, 2013).

Figura 2 - Modelo de gráfico Forest Plot



Fonte: adaptado de CAVALLAZZI; CAVALLAZZI, 2008.

3 ARTIGO 1 – DOES NITRIC OXIDE MITIGATE WATER DÉFICIT IN MAIZE? SYSTEMATIC REVIEW AND META-ANALYSIS

Álisson Neves Santos; Thiago Corrêa de Souza; Plinio Rodrigues dos Santos Filho

ABSTRACT

The objective of the present study was to conduct a systematic review with meta-analysis to determine if Nitric Oxide can act as a signaling molecule in water stress tolerance in maize plants. The study consisted of a systematic review with meta-analysis, and a total of 1,843 records were identified. Out of these, 67 were allocated for bibliometric analysis and 6 for meta-analysis. The number of publications showed an increasing trend between the years 2002 and 2021. The research was conducted in 18 different countries, with China being the most prominent. The variables considered for the meta-analysis were lipid peroxidation (MDA), Superoxide Dismutase (SOD) activity, and the presence of NO. After the application of NO, there was a decrease in MDA levels and an increase in SOD activity. The results of the meta-analysis indicate that NO acts as a signaling molecule in water stress tolerance in maize plants.

Keywords: Vegetable biostimulant, lipid peroxidation, Zea Mays.

INTRODUCTION

Systematic review and meta-analysis are a high-quality strategy for summarizing in a single study the results of original research carried out in a given area (Donato and Donato 2019). For its implementation, the PRISMA method (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) is one of the most credible and important guide. It instructs in detail the forms of identification and selection of studies that should be included in a search. The systematic review according to the PRISMA method is divided into well-defined steps in order to produce a good selection of studies. In the application of the PRISMA method, meta-Analyses is the final step after classifying and organizing the studies. Usually, the number of studies included in the meta-analysis small, once it should only include studies fully associated with the search terms initially employed. (Balduzzi et al. 2019, Donato and Donato 2019, Moher et al. 2015).

The agricultural scenario has shown that crops are continuously subjected to different abiotic stress conditions (Teixeira et al. 2020), which occur when adverse environmental factors impair the physiological conditions of plants (Warsi et al. 2023). In the case of maize, abiotic factors related to climate (water availability, air temperature, relative humidity, and solar radiation) are most closely associated with yield reduction. Among these abiotic factors drought is the most frequent and intense factor, resulting in crop yield losses (Santos et al. 2022). Therefore, the development of strategy to mitigate the negative effects of stress factors, specially water déficit, is essential for the evolution of maize crops (Amaro et al. 2023).

NO belongs to the group of free radical molecules due to having an unpaired electron in one of its orbitals. Another aspect of NO and its molecule derivatives is that they can be directly or indirectly involved in post-translational modifications, including binding to metal centers, S-nitrosylation of thiol groups, and tyrosine nitration, which may be involved in cellular signaling under stress conditions (Corpas et al. 2011).

Endogenously, nitric oxide in plants can be generated by both enzymatic and non-enzymatic mechanisms (Neill et al. 2003). Enzymatic mechanisms have been described based on the use and effectiveness of a series of Nitric oxide Synthase (NOS) inhibitors. NOS catalyze the formation of NO from L-arginine, which undergoes a five-electron oxidation and requires NADPH and molecular oxygen for the reaction. On the other hand, nitrate reductase generates NO using NO^{2-} and NADH as substrates (Yamasaki et al. 1999). In order to maintain sustainable agriculture, it is necessary to protect plants from climate variations and thus meet the world demand for food. Nitric oxide provides tolerance to different types of stress and is related to developmental processes, thus is a promising strategy for improve the abiotic stress tolerance in plants.

Considering the global relevance of maize cultivation and the potential of nitric oxide as a signaling molecule, the objective of this study was to conduct a systematic review with meta-analysis to investigate whether Nitric Oxide can act as a signaling molecule in water stress tolerance in maize plants.

MATERIAL AND METHODS

Search strategy

The systematic review was conducted following the guidelines of the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-analyses) recommendation (Moher et al. 2015), registered under the International Prospective Register of Ongoing Systematic Reviews (PROSPERO) with the number CRD42022335324. The search was performed using the terms: nitric oxide, maize, Zea mays, drought, water stress in the PubMed, Scielo, and ScienceDirect databases. Searches were conducted with and without Boolean operators. In PubMed and Scielo, more documents were found using Boolean operators, probably because an alternate search was conducted between documents that use one term or the other with the same meaning. The searches were conducted with a time frame from January, 2002, to May 13, 2022.

Study selection criteria and data extraction

The selection of studies was performed by two reviewers separately, and in the case of articles that presented conflicts a third reviewer was involved. Initially, the titles and abstracts of each study were evaluated. Microsoft Excel 2019 was used for organizing the extracted data from each study. Initially, basic information was extracted from all articles: year of publication, origin of the research, title, journal, impact factor, number of document citations, and authors. As an inclusion criterion for bibliometric review, manuscripts had to necessarily use maize plants subjected to some type of abiotic stress, and the responses had to be related to nitric oxide. After separating the works by type of abiotic stress, the articles that specifically studied water deficit were selected, and these studies were used for meta-analysis. Three parameters were common to more than one article and could be used in the meta-analysis: malondialdehyde (MDA) content, quantification of superoxide dismutase (SOD) activity, and NO concentration.

Data treatment and analysis

Data tabulation, graph, and table production were performed using Microsoft Excel 2019. Statistical analysis, as well as the creation of Forest Plots, was conducted using the Review Manager 5.4 software. Data extraction regarding results presented in the form of graphs by the authors was performed using GetData Graph Digitizer. As the data were continuous, the method of combining the random effects of the mean of the studies was used, as described by Rodrigues and Ziegelmann (2010). The statistical analysis of the bibliographic review was conducted using BioEstat 5.0, in which the trend of the number of publications per year, both overall and for China, was classified using the method proposed by Antunes and Waldman (2015). In the analysis, the formula y = b0 + b1X was used, where y corresponds to the value of the time series, x to the year, b0 to the intercept of the line with the vertical axis, and b1 to the slope of the line. The trend line, as well as the value of b1 and the decrease in heterogeneity of the residual variance, were executed using statistical software. According to Antunes and Waldman (2015), the trend is considered increasing when the value of b1 is positive and the significance level is <0.05, decreasing when negative with significance <0.05, and stationary when p is greater than 0.05. As it is a value obtained through linear regression, the confidence interval given by the formula 95% CI = [–1+10b1min] * 100%; [–1+10b1max.] * 100% (Antunes and Waldman 2015) is also verified.

Risk of bias assessment

For the bibliographic analysis, records developed without abiotic stress, classified as "others," were removed, and articles that did not present any type of donor or NO quantification were also excluded. Additionally, it was carefully verified whether each document reported consistent and adequately referenced methodologies, including at least the description of the experimental design, plant material used, and experimental conditions of each analysis performed. The criteria for assessing the risk of bias were evaluated according to the guidelines of Sterne et al. (2019).

RESULTS AND DISCUSSION

Following the PRISMA system guidelines, the flowchart below (Figure 1) was constructed, divided into different stages (search and identification, study selection, eligibility, inclusion, and meta-analysis). In the search stage, 1.843 titles were found. As expected, most of the articles were found on ScienceDirect (1.457), followed by PubMed (340) and Scielo (31). At this point, it is important to clarify the choice of these three databases. The objective of this research was to search for only full-text scientific articles with original data from experimentation. Abstracts, Thesis, citations, books, and book chapters would not be considered. Gebre et al. (2021) point out some characteristics of the Web of Science, Scopus, Google Scholar, and ScienceDirect databases that guided our choices. Considering these four databases, ScienceDirect is the most restrictive. Consequently, searches in Web of Science, Scopus, and Scholar tend to generate a greater number of results because they search, among other things, abstracts. The objective of this systematic review was to present a review scenario and conduct the work for the meta-analysis, which depends on the existence of consistent data and information about the experimental design. For this reason, ScienceDirect, which contains works from different areas with full text in high-quality journals, was used, and searches resulted in few discards in the selection process. The use of PubMed was due to the presence of robust works usually found on this platform, even though it is a database more associated with the medical field. Scielo, on the other hand, covers many research studies from Latin America, and maize is an important crop for the continent. The criteria for the temporal cut were based on the trajectory of nitric oxide research in plants. In 1992, NO was considered the molecule of the year by Science Magazine (Koshland Jr 1992). From that point on, studies also intensified in plants since there were indications that NO also acted in plants. At the end of that decade, different studies demonstrated that NO is indeed an important signaling molecule in plants. Since then, studies associating NO with plants have only increased. Thus, the temporal cut employed in this work excludes the final decade of the 20th century, assuming that this period was a consolidation period for NO as a signaling molecule in plants. Although there were still many controversies, mainly regarding the synthesis mechanisms of NO in plants, from the 2000s onwards, there was no doubt that NO is an important signaling molecule in plants. Following the identification of studies, the selection and eligibility stages were carried out. Duplicate studies and those that did not meet the inclusion criteria were excluded. Thus, 67 articles were selected for the bibliometric review. The inclusion criteria were a description of the methodology, experimental design, and experimentation involving nitric oxide, maize, and abiotic stresses. Therefore, in the inclusion stage, 32 articles remained, which were divided into 6 groups considering the type of stress studied (Figure 1).

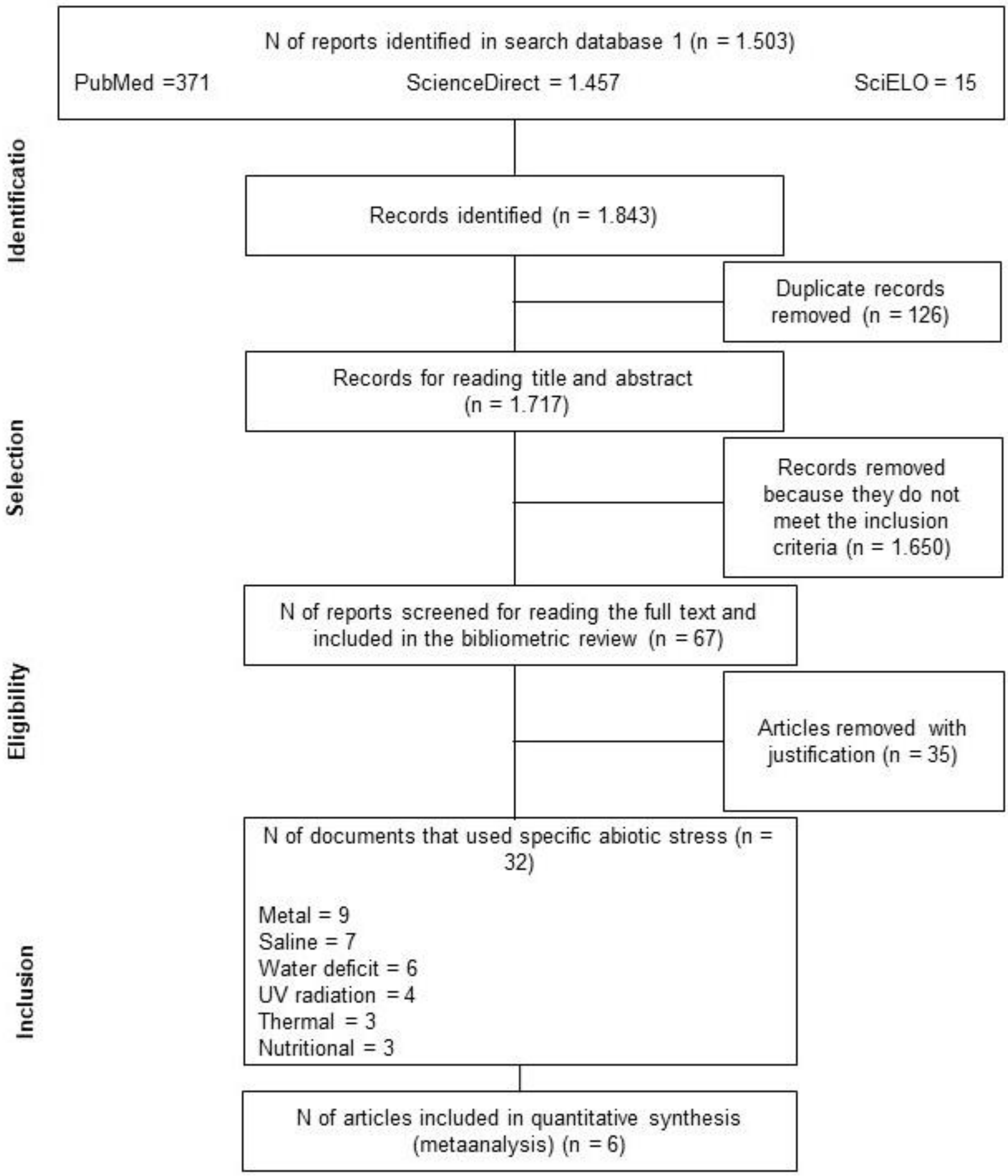


Figure 1 - Organizational chart of the stages of Systematic Review with Meta-analysis.

Source: (Adapted from MOHER et al., 2015)

As can be observed in Figure 2, the trend in the number of publications regarding Nitric Oxide and maize plant under some type of abiotic stress or as a study model showed an increasing pattern between the years 2002 and 2021 (complete years used for this study), with a b1 of 0.1584

(95% CI 0.049; 0.0068) (p = 0.0068). A total of 67 articles were selected for publication analysis, with the year 2020 standing out with 7 publications. No publications were identified in 2005.

Nitric oxide is a multifaceted molecule, and the first demonstration of its production in living organisms occurred 68 years ago (Baalsrud and Baalsrud 1954). With the discovery that NO was responsible for the vasodilation of smooth muscle in blood vessels, extensive research on the topic was conducted at that time, and NO was designated as the molecule of the year in 1992 by Science magazine (Furchgott and Zawadzki 1980, Ignarro et al. 1987). A little earlier, in 1979, evidence of NO production in soybean leaves treated with herbicide emerged (klepper 1979).

In maize, one of the pioneering studies on nitric oxide was conducted by Gouvêa and colleagues in 1997, demonstrating a dose-dependent effect of NO on the growth of root segments. This effect was also related to signaling pathways common to auxin. Considering the importance of maize as a food source, biofuel, and study model (Li 2017), it is not surprising that the number of studies linking this crop to nitric oxide is increasing. On the contrary, this number may even be considered modest.

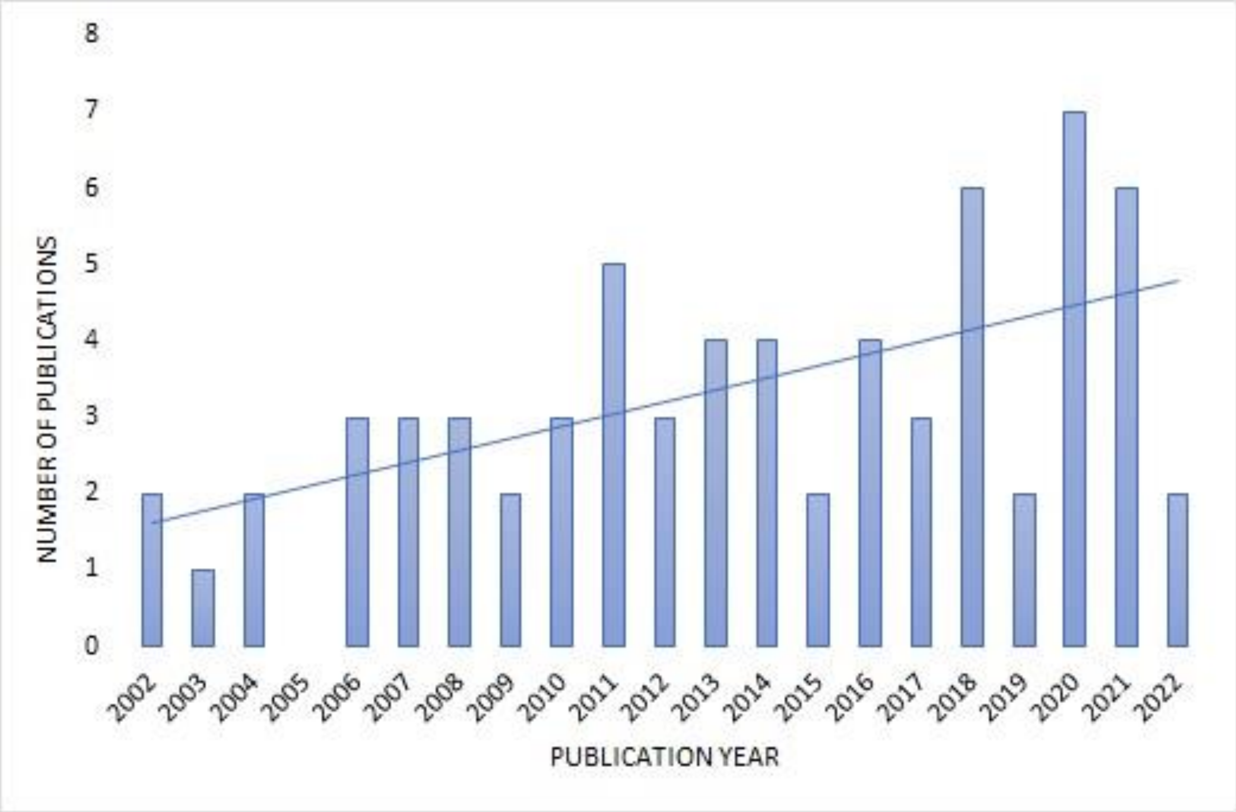


Figure 2 - Number of publications per year related to Nitric Oxide and maize plants under some type of stress or as a study model.

As for the study locations, the selected documents resulted from research conducted in 18 different countries, with China being the standout country in terms of the highest number of investigations. China only did not publish studies in the years 2002, 2005, 2009, and 2014, showing a consistent research activity in the country. However, when analyzed independently, China does not show a growing trend in terms of the number of publications, but rather a stationary trend with a b1 of -0.0351 (95% CI -0.110; 0.040) ($p = 0.3410$). This suggests that the increase in the number of publications per year is due to the involvement of new countries in research on Nitric Oxide/maize plant (Figure 3).

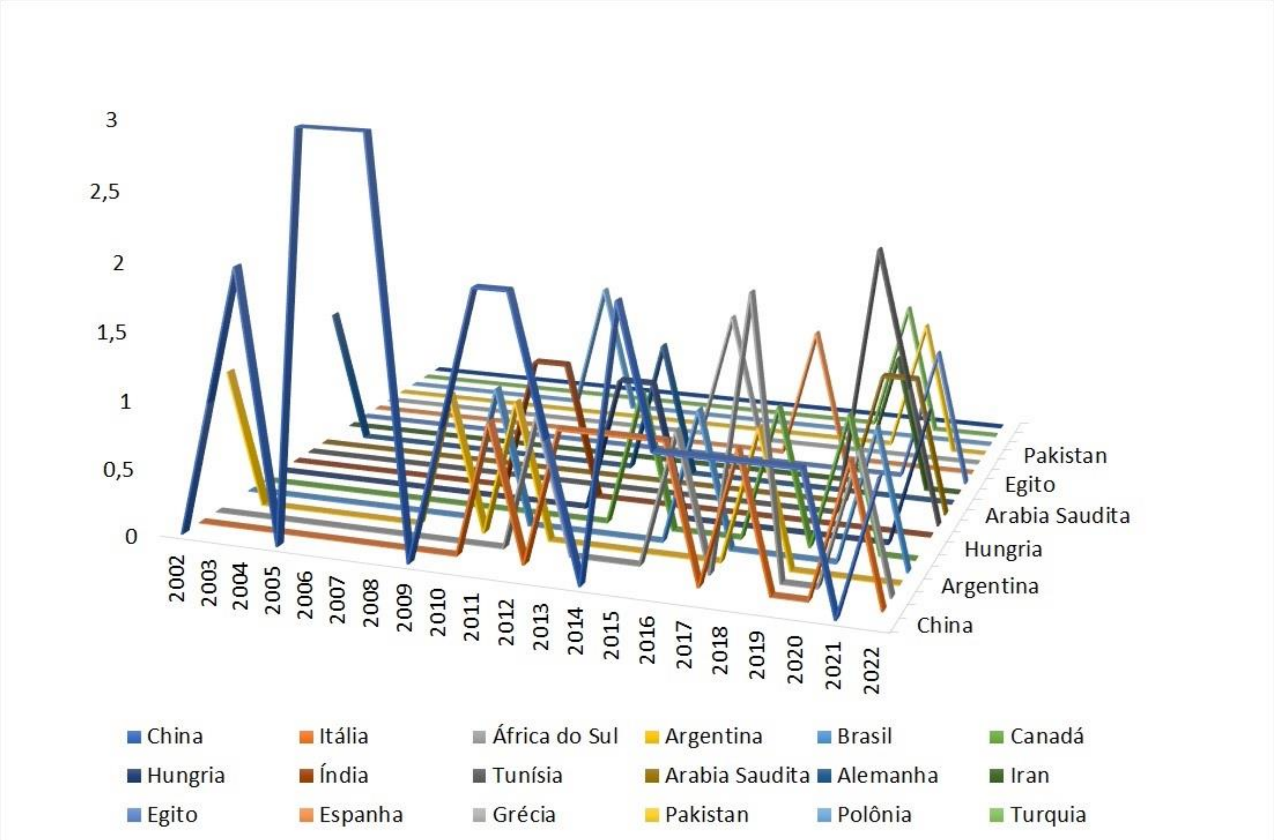


Figure 3 - Number of publications according to the year and country of research development from the tracked records.

Leading the ranking of the number of publications (Table 1), China accounted for 38.81% of the total selected documents, followed by Italy (8.96%), South Africa (7.46%), Argentina (5.97%), and Brazil with 4.48% of the publications. A significant portion of the studies were conducted using maize as a model to investigate Nitric Oxide interactions, without any specific type of stress on the maize plants or production inferences. These manuscripts corresponded to 38.81% of the selected ones.

Among the maize top global producers, only the United States (the world leader in maize production) and Ukraine (the 6th largest producer) did not produce scientific papers relating NO and maize. The other major global producers (China, Brazil, European Union, and Argentina) are represented. Regarding the investigation models used in the studies, abiotic stresses caused by metals, salt, water deficit, UV radiation, thermal stress, and nutritional stress were predominantly observed. In addition to investigating Nitric Oxide using maize as a model and different types of stress, one article analyzing the plant-pathogen interaction was also included. Among the types of stress, those with the highest percentages were metal stress, salt stress, and water deficit stress (Table 1).

China, which had the highest number of publications, was responsible for two research studies on metal stress, three on salt stress, and five on water deficit stress. Abiotic stresses are an important factor that negatively affects the growth, development, and yield of crops (Arora 2019, Usman et al. 2020).

Table 1 - Country of Research Development and Type of Tracked Stress Records

Classification	**Country of research development**	**N**	**%**
1	China	26	38.81
2	Italy	6	8.96
3	South Africa	5	7.46
4	Argentina	4	5.97
5	Brazil	3	4.48
6	Canada	3	4.48
7	Hungary	3	4.48
8	India	3	4.48
9	Tunisia	3	4.48
10	Saudi Arabia	2	2.99
11	Germany	2	2.99
12	Iran	1	1.49
13	Egypt	1	1.49
14	Spain	1	1.49
15	grace	1	1.49
16	Pakistan	1	1.49
17	Poland	1	1.49
18	Türkiye	1	1.49
	type of stress		
1	Metal	11	16.42
2	Saline	9	13.43
3	Water Deficit	8	11.94
4	UV radiation	4	5.97
5	Thermal	4	5.97
6	nutritional	3	4.48
	Others		
7	No Stress - Corn as a Fungus	26	38.81
8	Model	1	1.49
9	hypoxia	1	1.49
10	Plant pathogen interaction	1	1.49

In relation to the journals (Table 2), a total of 36 different journals were found with records, with the majority having only one document relating Nitric Oxide to maize plants under some type of stress or as a study model. Some journals had two or even more documents on the subject, such as the Journal of Plant Physiology and the Plant Physiology and Biochemistry, which stood out with 6 articles each. The impact factors ranged from 0.175 to 25.617.

Table 2 - Number of articles published by journals.

Journal	Impact Factor	Number of Documents
Journal of plant physiology	3,549	6
Plant physiology and biochemistry	5,437	6
Journal of experimental botany	6,992	5
Plant signaling and behavior	2.53	4
The New phytologist	10,323	4
Physiologia plantarum	5,081	3
Planta	4,540	3
International journal of molecular sciences	5,542	2
Journal of Hazardous Materials	10,588	2
Journal of integrative plant biology	9,106	2
Journal of Plant Physiology and Molecular Biology	0.175	2
Plant, cell & environment	7,228	2
Protoplasma	3,186	2
South African Journal of Botany	2,315	2
Journal of plant physiology and molecular biology	0.175	1
Annals of botany	4,357	1
AoB PLANTS	3,138	1
Bragantia	1.5	1
Cell Research	25,617	1
Chinese Journal of Applied Ecology	3,593	1
Ecotoxicology and environmental safety	6.68	1
Environmental Pollution	8,071	1
Environmental science and pollution research international	5,190	1
Frontiers in plant science	6,627	1
Fungal biology	2.83	1
Journal of Applied Genetics	2,653	1
Journal of proteome research	4,466	1
Nitric Oxide	4,898	1
Nitric oxide: biology and chemistry	4.68	1
Photochemistry and photobiology	3,521	1
Plant and Cell Physiology	4,927	1
Plant biology	3,877	1
Plant cell reports	3,825	1
Plant physiology	8,340	1
Scientific Reports	4,996	1
The Journal of Hazardous Materials	14,224	1
Viruses	5,048	1

The most cited authors in each stress category, as presented in Table 3, were: Kaya et al. (2020) with 84 citations in metal stress, Zhang et al. (2006) with 418 citations in saline stress, Zhang et al. (2011) with 186 citations in water deficit, Tossi, Lamattina, and Cassia (2009) with 186 citations in UV radiation stress, Li et al. (2013) with 212 citations in thermal stress, and Sun et al. (2007) in nutritional stress.

Table 3 - Ranking of most cited authors in articles with specific abiotic stress.

Authors	Number of citations
Metal stress	
Kaya et al. (2020)	84
Kharbech et al. (2017)	66
Okant e Kaya (2019)	43
Liu et al. (2020)	31
Kharbech et al. (2020)a	30
Kharbech et al. (2020)b	18
Zanganeh, Jamei e Rahmani (2020)	7
Kharbech et al. (2022)	5
Díaz et al. (2021)	2
Kaya et al. (2021)	2
Shao et al. (2022)	0
Saline	
Zhang et al. (2006)	418
Bai et al. (2011)	115
Oliveira et al. (2016)	100
Keyster e Ludidi (2012)	50
Zhang e Liu (2004)	47
Klein et al. (2018)	34
Boldizsár et al. (2013)	23
Simon-Sarkadi, Ludidi e Kocsy (2014)	7
Chen et al. (2006)	6
Water deficit	
Zhang et al. (2011)	174
Sang et al. (2008)	135
Hao, Xing e Zhang (2008)	101
Majeed et al. (2020)	18
Shao et al. (2018)	5
Hammond et al. (2018)	2
UV radiation	
Tossi, Lamattina e Cassia (2009)	186
An et al. (2005)	128
Zhang et al. (2003)	112
Tossi et al. (2011)	90
Thermal	
Li et al. (2013)	212
Ma et al. (2015)	9
Majláth et al. (2022)	1
Mira et al. (2021)	1
Nutritional	
Sun et al. 2007	208
Kumar, Tewari e Sharma (2010)	61
Ramos-Artuso et al. (2018)	18

With confirmation of NO as an important signaling molecule in plants, the major challenge for the scientific community became unraveling the various mechanisms of its production and homeostasis. In animals, it is well established that there is an enzyme responsible for NO synthesis from the amino acid arginine. This enzyme, called nitric oxide synthase (NOS), has been thoroughly characterized in both its constitutive and inducible isoforms.

It was expected that there would be an intense search for a similar enzyme in plants. However, it was observed that the NO generating mechanisms in plants are much more diverse (Brouquisse 2019). In fact, although many studies demonstrate the influence of nitric oxide synthase inhibitors on NO production and/or effects, no NOS homologous enzyme has been characterized in plants so far. The mutant Arabidopsis AtNOS1 was even considered a plant deficient in NO synthase, but it was later renamed ATNOA1 (associated with NO) due to the inability to characterize the enzyme (Guo et al. 2003, CRAWFORD et al. 2006).

Currently, at least seven sources of NO are known in plants, contributing to the pleiotropic effects exhibited by this molecule. Given this diversity of effects and sources, many studies use NO donors and/or competitive inhibitors of nitric oxide synthase (Praveen 2022). The use of donors is particularly relevant since working with pure gas presents significant challenges in terms of cost and toxicity. Therefore, studies involving NO mainly rely on donors, NO synthase inhibitors, and measurements of nitric oxide levels. Thereafter, the articles were classified based on the use or non-use of NO donors and/or substances related to their effects (Figure 4).

In figure 4, it can be observed that, among the studies analyzed, only one (Majláth et al. 2022) did not use a donor or a substance related to the effects of NO. The most commonly used donor was sodium nitroprusside (SNP), which is understandable considering its low cost. However, there are certain drawbacks to its use, mainly related to its byproduct potassium ferricyanide, as mentioned by Bethke et al. (2006). This does not render the use of SNP unfeasible, but it requires some caution regarding its signaling effects and, more importantly, its toxicity. Other donors such as NONOates (spermidine or diethylenetriamine-NONOate), S-nitroso-N-acetylpenicillamine (SNAP), and S-nitrosoglutathione (GSNO) are more efficient and "clean". As mentioned earlier, although there is no known nitric oxide synthase among plants, inhibitors of this enzyme are still widely used. Table 4 shows the use of L-NMMA (NG-monomethyl-L-arginine) and L-NAME (NG-nitro-L-arginine methyl ester) as inhibitors. These are inhibitors of mammalian nitric oxide synthase (Alderton et al. 2001). However, they continue to be applied in plants, and many effects are observed as a result of their use.

In addition to donors and NOS inhibitors, cPTIO (2-4-carboxyphenyl-4,4,5,5-tetramethylimidazoline 1-oxyl-3-oxide) and, more recently, H_2S are commonly used. cPTIO is a NO-chelating molecule permeable to cells and, therefore, widely employed in various studies (D'Alessandro et al. 2013). Hydrogen sulfide (H_2S), like nitric oxide, has different sources in plants (Gotor et al. 2015, Scuffi et al. 2014, Corpas et al. 2019). Many articles explore the interplay between NO and H_2S due to their pleiotropic actions, especially their reactivities with thiol groups.

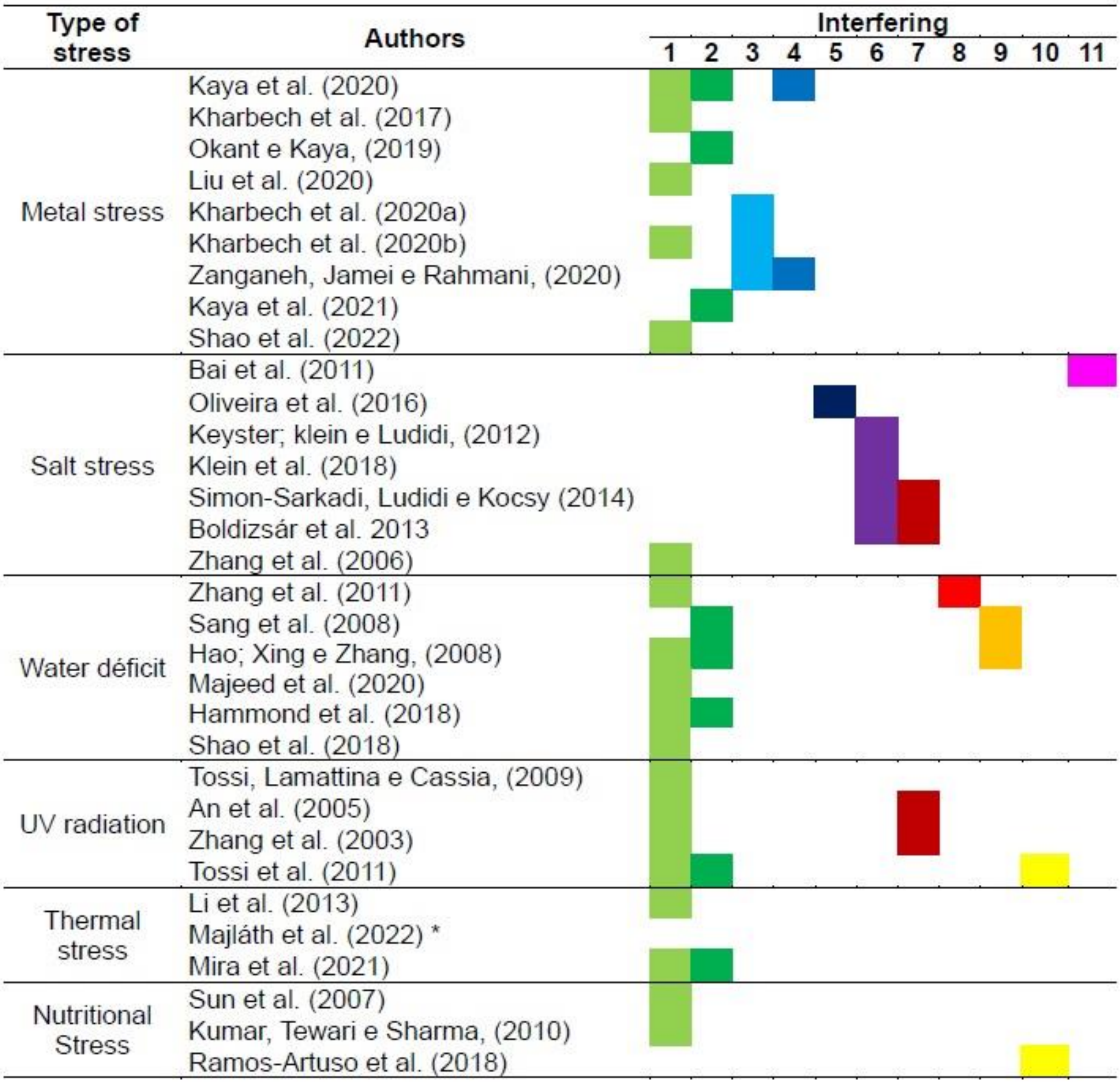


Figure 4 - Relationship of NO interferences by type of stress and author.

* Did not use donor, only measured NO.

Following the PRISMA method, the articles included in Meta-analysis are show in the table 4. The journals in which the manuscripts were published have impact factors ranging from 3.686 to 9.106, demonstrating that they are prestigious journals in the scientific field.

Table 4 - Bibliometric analysis of the articles included in the Meta-analysis.

Authors	**Journal**	**Impact factor**	**Year of publication**	**Development country**	**N of citations**
Hammond et al., 2018	Plant Physiology and Biochemistry	5.437	2020	Canadá	2
Hao; Xing e Zhang, 2008	Journal of Integrative Plant Biology	9.106	2008	China	101
Majeed et al., 2020	Plant Physiology and Biochemistry	5.437	2020	Paquistão	18
Sang et al., 2008	Journal of Integrative Plant Biology	9.106	2008	China	135
Shao et al., 2018	Nitric Oxide	4.898	2010	China	5
Zhang et al., 2011	Plant and Cell Physiology	4.937	2011	China	174

Through data extraction from each study and performing the Meta-analysis, we can obtain new results by combining two or more research studies.

When a plant is under water stress conditions, one of the damages that occur is lipid peroxidation, which is caused by uncontrolled production of reactive oxygen species (ROS) (Zhang et al. 2011). Malondialdehyde (MDA) is one of the markers for ROS production.

Hammond et al. (2018), Majeed et al. (2020), and Zhang et al. (2011) analyzed the MDA content between control samples and samples under stress conditions to assess lipid peroxidation caused by ROS. Figure 5A represents the cross-analysis of these data, where the effect size (diamond) is on the left side of the graph, and the confidence interval, represented by the tips of the diamond, does not touch the null effect line (central line). Thus, we can say that there is a significant difference between the analyzed results. As the effect size leans towards the side where the results are smaller, and in the given graph, the diamond is entirely on the control side, we can conclude that water stress increased the MDA content.

On the other hand, Majeed et al. (2020) and Shao et al. (2018) analyzed the effect of NO on the plant under stress conditions in relation to the MDA content. By observing Figure 5.B, we can identify that the effect size is on the side of the sample that received NO, and the tips of the diamond do not touch the null effect line, indicating that the presence of NO decreases lipid peroxidation under stress conditions. When comparing the MDA content solely to assess the functionality of NO between control samples (Majeed et al. 2020 and Shao et al. 2018), it is observed that NO does not have a significant effect on the MDA content in samples without water stress (Figure 5.C).

When comparing control samples with samples under stress conditions in the presence of NO, it is evident that the presence of NO in the stressed sample results in a MDA content similar to that of the stress-free sample (Figure 5.D). MDA, a 3-carbon dialdehyde, is one of the main decomposition products of polyunsaturated fatty acid hydroperoxides formed during oxidative processes. Lipid peroxides are markers of oxidative stress and provide good indicators for assessing a plant's sensitivity to stress conditions (Morales and Munné-Bosch 2019).

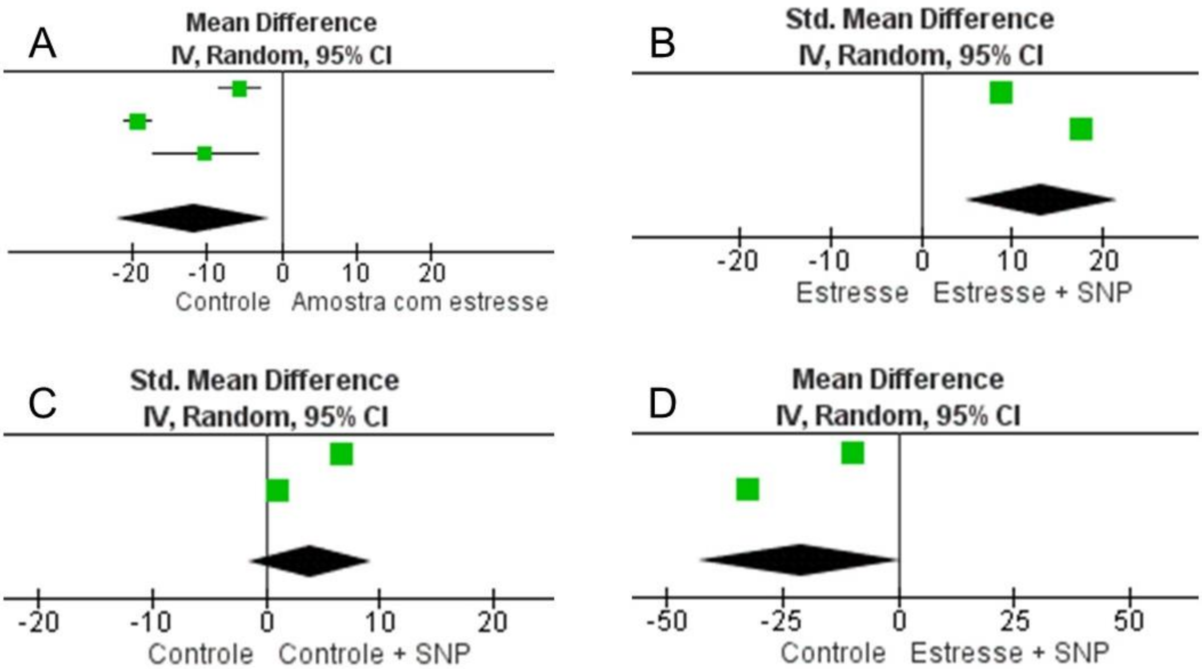


Figure 5 - Comparisons related to MDA content. (A) Comparison between control and stress sample, (B) Comparison between stress sample and stress sample + NO, (C) Comparison between control and control + SNP, (D) Comparison between control and stress sample + SNP.

In addition, there is a strong correlation between lipid peroxidation and antioxidant enzyme activity, as other studies have shown that increased antioxidant enzyme activity serves as a defense mechanism by degrading reactive oxygen species and reducing lipid peroxidation (Anjum et al. 2015). Superoxide radical is one of the primary reactive oxygen species produced in biological systems due to incomplete reduction of molecular oxygen. In plants, the production of superoxide radical is closely related to various abiotic stresses. The superoxide radical itself is not very harmful as its reactivity is relatively low, but it can give rise to hydrogen peroxide and hydroxyl radical, the latter being highly reactive and deleterious. Plants have a wide and sophisticated defense system to counteract the detrimental effects of reactive oxygen species. At the forefront of this protection system is superoxide dismutase (SOD), which converts superoxide radical into hydrogen peroxide. To complete the detoxification process, plants possess different peroxidases that remove hydrogen peroxide and prevent an increase in hydroxyl radical levels. Therefore, SOD activity serves as an important indicator of the plant's response to stress (Tan et al. 2023).

Hao et al. (2008), Majeed et al. (2020), and Sang et al. (2008) compared control samples with stressed samples to investigate the increase in SOD activity. Figure 6.A shows that water stress enhances SOD activity, as the effect size demonstrates significant results in this comparison. The same situation occurs when comparing control samples with stressed samples treated with NO (Figure 6.D). The same authors also compared stressed samples with stressed samples that received NO. These NO-treated samples exhibited increased SOD activity (Figure 6.B). Hao et al. (2008) and Majeed et al. (2020) also examined whether the presence of NO alone would induce an increase in enzyme function, and the effect size showed positivity for this situation (Figure 6.C).

The results demonstrate that any alteration occurring in the plant triggers an increase in SOD activity, which is associated with the plant's defense mechanisms in preparation for potential adverse conditions.

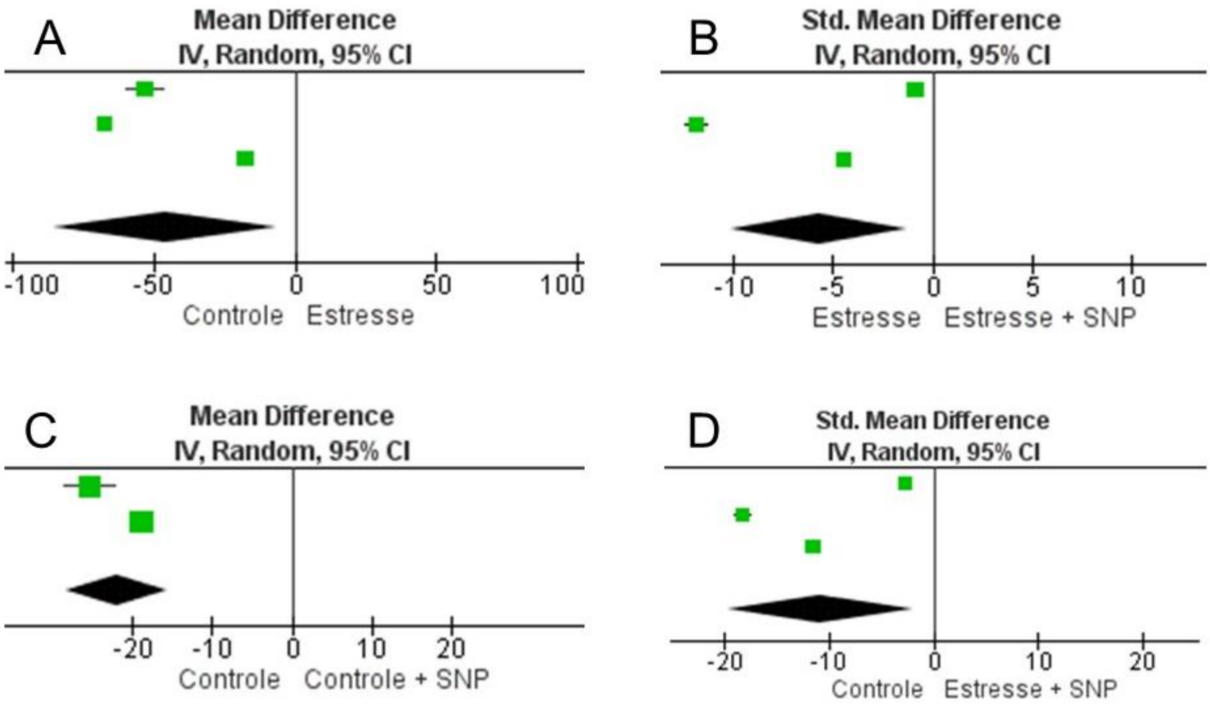


Figure 6 - Comparisons related to SOD activity. (A) Comparison between control and stress sample, (B) Comparison between stress sample and stress sample + NO, (C) Comparison between control and control + SNP, (D) Comparison between control and stress sample + SNP

The presence of NO is the main factor of analysis in the studies, and its concentration was also measured by some authors. Majeed et al. (2020) and Shao et al. (2018) examined the efficacy of the SNP donor in stressed samples. Figure 7.A shows that the concentration of NO significantly increased in the samples where SNP was applied.

The same authors, as well as Sang, Wang, and Shangguan (2008), examined the concentration of NO by comparing control samples with stressed samples (Figure 7.B). The result showed that water stress is capable of increasing the endogenous concentration of NO, indicating that NO plays a role in the plant's physiological process under stress conditions.

Majeed et al. (2020) and Shao et al. (2018) also investigated the concentration of NO in controls with SNP and stress with SNP, both compared with controls. The concentration of NO was higher in controls with SNP, as well as in stress with SNP (Figure 7.C and 7.D).

When comparing the Forest Plot graphs of Figures 7.C and 7.D, we can observe that the effect size is further away from the central line in Figure 7.D, symbolizing a potentiality in relation to its results. Thus, it can be said that stress factor, together with the application of SNP, promotes a higher concentration of NO, as these two important variables together favor such a result.

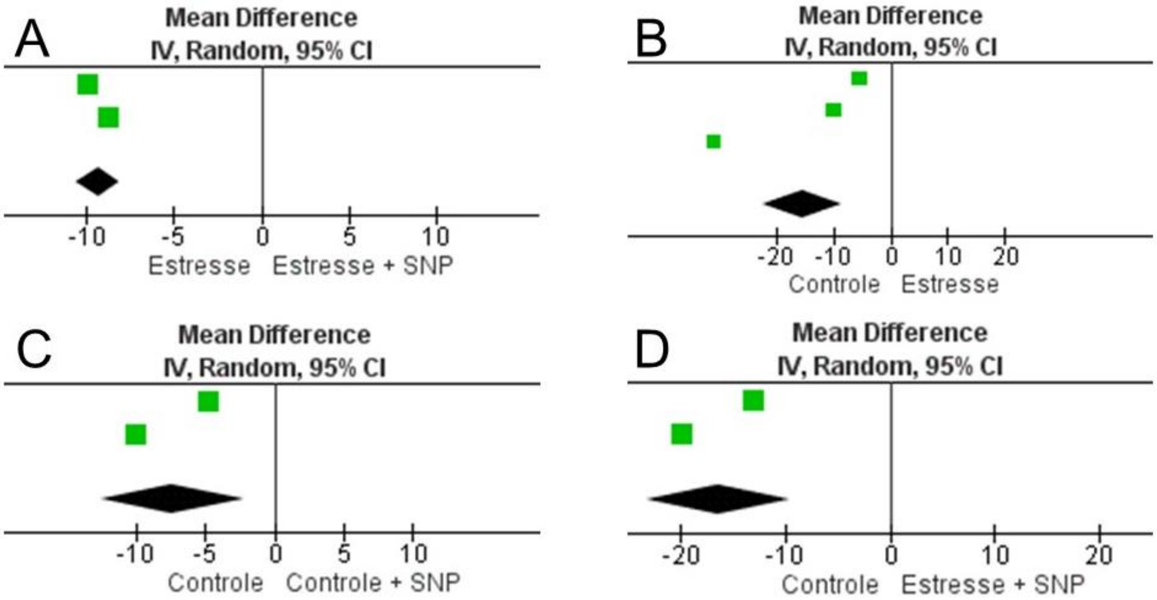


Figure 7 - Comparisons related to NO concentration. (A) Comparison between stress and stress + SNP sample, (B) Comparison between control sample and stress sample, (C) Comparison between control and control + SNP, (D) Comparison between control and stress + SNP sample.

CONCLUSION

Based on the presented results, it can be concluded that Nitric Oxide (NO) can act as a signaling molecule in the tolerance to water stress in maize plants, as significant differences were observed in the outcomes related to the conditions indicating such effects. The decrease in MDA content and the increase in SOD activity after SNP application are situations that demonstrate the action power of NO. Moreover, the water stress condition alone in the plant also influences the endogenous production of NO, indicating that the plant has its own defense mechanisms.

The number of publications regarding research on Nitric Oxide and maize plants under various abiotic stresses or as a study model has been increasing in recent years, demonstrating the interest of certain groups in utilizing NO as an alternative to reduce grain production losses associated with these types of stresses. Due to the challenges of handling a gas, certain NO donors, such as SNP, stand out for their efficient role in this process.

ACKNOWLEDGEMENTS

The authors would like to thank the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) and Fundação de Amparo à Pesquisa do Estado de Minas Gerais (FAPEMIG- APQ-01671-17) for finantial support.

REFERENCES

Amaro HTR, Fernandes HMF, Almeida PMA, Porto EMV, David AMSS (2023). Tratamento de sementes com bioestimulante e disponibilidade hídrica no desenvolvimento inicial do milho. **Magistra 23:** 2-9.

An L, Liu Y, Zhang M, Chen T. et al (2005). Effects of nitric oxide on growth of maize seedling leaves in the presence or absence of ultraviolet-B radiation. **Journal Of Plant Physiology 162:** 317-326.

Anjum NA, Sofo A, Scopa A, Roychoudhury A. et al (2014). Lipids and proteins major targets of oxidative modifications in abiotic stressed plants. **Environmental Science And Pollution Research 22:** 4099-4121.

Antunes JLF, Cardoso MRA (2015). Uso da análise de séries temporais em estudos epidemiológicos. **Epidemiologia e Serviços de Saúde 24**: 565-576.

Bai X, Yang L, Yang Y, Ahmad P. et al (2011). Deciphering the Protective Role of Nitric Oxide against Salt Stress at the Physiological and Proteomic Levels in Maize. **Journal Of Proteome Research 10:** 4349-4364.

Balduzzi S, Rücker G, Schwarzer G (2019). How to perform a meta-analysis with R: a practical tutorial. **Evidence Based Mental Health 22:** 153-160.

Boldizsár Á, Simon-Sarkadi L, Szirtes K, Soltész A . et al (2013). Nitric oxide affects salt-induced changes in free amino acid levels in maize. **Journal Of Plant Physiology 170:** 1020-1027.

Brouquisse R (2019). Multifaceted roles of nitric oxide in plants. **Journal of Experimental Botany 70:** 4319-4322.

Chen K, Li J, Tang J, Zhao FG. et al (2006). [Involvement of nitric oxide in regulation of salt stress-induced ABA accumulation in maize seedling]. **Journal of plant physiology and molecular biology 32**: 577–582.

Corpas FJ, Leterrier M, Valderrama R, Airaki M. et al (2011). Nitric oxide imbalance provokes a nitrosative response in plants under abiotic stress. **Plant Science 181:** 604–611.

Crawford NM, Galli M (2006). Response to Zemojtel et al: plant nitric oxide synthase: back to square one. **Trends in Plant Science11:** 526-527.

Díaz AS, Cruz YC, Duarte VP, Castro EM. et al (2021). The role of reactive oxygen species and nitric oxide in the formation of root cortical aerenchyma under cadmium contamination. **Physiologia Plantarum 173:** 2323-2333.

Donato H, Donato M (2019). Stages for Undertaking a Systematic Review. **Acta 32:** 227-235.

Guo F, Okamoto M, Crawford NM (2003). Identification of a plant nitric oxide synthase gene involved in hormonal signaling. **Science 302:** 100-103.

Hammond C, Mira MM, Ayele BT, Renault S. et al (2020). Over-expression of the Zea mays phytoglobin (ZmPgb1.1) alleviates the effect of water stress through shoot-specific mechanisms. **Plant Physiology And Biochemistry 155**: 384-395.

Hao G, Xing Y, Zhang J (2008). Role of Nitric Oxide Dependence on Nitric Oxide Synthase-like Activity in the Water Stress Signaling of Maize Seedling. **Journal Of Integrative Plant Biology 50:** 435-442.

Kaya C, Ashraf M, Alyemeni MN, Corpas FJ. et al (2020). Salicylic acid-induced nitric oxide enhances arsenic toxicity tolerance in maize plants by upregulating the ascorbate-glutathione cycle and glyoxalase system. **Journal Of Hazardous Materials 399:** 123020.

Kaya C, Polat T, Ashraf M, Kaushik P. et al (2021). Endogenous nitric oxide and its potential sources regulate glutathione-induced cadmium stress tolerance in maize plants. **Plant Physiology And Biochemistry 167:** 723-737.

Keyster M, Klein A, Ludidi N (2012). Caspase-like enzymatic activity and the ascorbate-glutathione cycle participate in salt stress tolerance of maize conferred by exogenously applied nitric oxide. **Plant Signaling & Behavior 7:** 349-360.

Khan M, Ali S, Azzawi TNIA, Yun B (2023). Nitric Oxide Acts as a Key Signaling Molecule in Plant Development under Stressful Conditions. **International Journal Of Molecular Sciences 24:** 2-21.

Kharbech O, Houmani H, Chaoui A, Corpas FJ (2017). Alleviation of Cr(VI)-induced oxidative stress in maize (Zea mays L.) seedlings by NO and H 2 S donors through differential organ-dependent regulation of ROS and NADPH-recycling metabolisms. **Journal Of Plant Physiology 219:** 71-80.

Kharbech O, Massoud MB, Sakouhi L, Djebali W. et al (2020b). Exogenous application of hydrogen sulfide reduces chromium toxicity in maize seedlings by suppressing NADPH oxidase activities and methylglyoxal accumulation. **Plant Physiology And Biochemistry 154**: 646-656.

Kharbech O, Sakouhi L, Mahjoubi Y, Massoud MB. et al (2022). Nitric oxide donor, sodium nitroprusside modulates hydrogen sulfide metabolism and cysteine homeostasis to aid the alleviation of chromium toxicity in maize seedlings (Zea mays L.). **Journal Of Hazardous Materials 424:** 127302.

Kharbech O, Sakouhi L, Massoud MB, Mur LAJ. et al (2020a). Nitric oxide and hydrogen sulfide protect plasma membrane integrity and mitigate chromium-induced methylglyoxal toxicity in maize seedlings. **Plant Physiology And Biochemistry 157:** 244-255.

Klein A, Hüsselmann L, Keyster M, Ludidi N (2018). Exogenous nitric oxide limits salt-induced oxidative damage in maize by altering superoxide dismutase activity. **South African Journal Of Botany 115**: 44-49.

Koshland Jr DE (1992). The molecule of the year. **Science 258:**1861-1861.

Kumar P, Tewari RK, Sharma PN (2010). Sodium nitroprusside-mediated alleviation of iron deficiency and modulation of antioxidant responses in maize plants. **Aob Plants 2010:** 1-10.

Li Z, Yang S, Long W, Yang G. et al (2013). Hydrogen sulphide may be a novel downstream signal molecule in nitric oxide-induced heat tolerance of maize (Zea mays L.) seedlings. **Plant, Cell & Environment 36**: 1564-1572.

Liu X, Yin L, Deng X, Gong D. et al (2020). Combined application of silicon and nitric oxide jointly alleviated cadmium accumulation and toxicity in maize. **Journal Of Hazardous Materials 395:** 122679.

Ma JH, Xing GF, Yang XH, Wang YG. et al (2015). [Effects of exogenous EBR and NO signal on antioxidant system and low response gene expression under cold stress on maize embryo]. **The journal of applied ecology 26:** 1411–1418.

Majeed S, Nawaz F, Naeem M, Ashraf MY. et al (2020). Nitric oxide regulates water status and associated enzymatic pathways to inhibit nutrients imbalance in maize (Zea mays L.) under drought stress. **Plant Physiology And Biochemistry 155:** 147-160.

Majláth I, Éva C, Hamow KÁ, Kun J. et al (2022). Methylglyoxal induces stress signaling and promotes the germination of maize at low temperature. **Physiologia Plantarum 174:**1-10.
Médica Portuguesa 32: 227-235.

Mira MM, Ibrahim S, Hill RD, Stasolla C (2021). Cold stress in maize (Zea mays) is alleviated by the over-expression of Phytoglobin 1 (ZmPgb1.1). **Plant Physiology And Biochemistry 167:** 901-910.

Moher D. et al (2015). Principais itens para relatar Revisões sistemáticas e Meta-análises: a recomendação prisma. **Epidemiologia e Serviços de Saúde 24:** 335-342.

Morales M, Munné-Bosch S (2019). Malondialdehyde: facts and artifacts. **Plant Physiology 180:** 1246-1250.

Neill SJ, Desikan R, Hancock JT (2003). Nitric oxide signalling in plants. **New Phytologist 159**: 11–35.

Okant M, Kaya C (2019). The role of endogenous nitric oxide in melatonin-improved tolerance to lead toxicity in maize plants. **Environmental Science And Pollution Research 26:** 1864-11874.

Oliveira HC, Gomes BCR, Pelegrino MT, Seabra AB (2016). Nitric oxide-releasing chitosan nanoparticles alleviate the effects of salt stress in maize plants. **Nitric Oxide 61:**10-19.

Praveen A (2022). Nitric oxide mediated alleviation of abiotic challenges in plants. **Nitric Oxide 128:** 37-49.

Ramos-Artuso F, Galatro A, Buet A, Santa-María GE. et al (2018). Key acclimation responses to phosphorus deficiency in maize plants are influenced by exogenous nitric oxide. **Journal Of Plant Physiology 222:** 51-58.

Rodrigues CL, Ziegelmann PK (2010). Metanálise: um guia prático. **Ver HCPA 30**: 436-447.

Sang J, Jiang M, Lin F, Xu S. et al (2008). Nitric Oxide Reduces Hydrogen Peroxide Accumulation Involved in Water Stress-induced Subcellular Anti-oxidant Defense in Maize Plants. **Journal Of Integrative Plant Biology 50:** 231-243.

Santos GO, Martins GR, Blat NR, Mendonça LB (2022). Disponibilidade hídrica e as anomalias climáticas no cultivo de soja e milho no Cerrado. **Journal Of Biotechnology And Biodiversity 10**: 214-222.

Shao R, Zhang J, Shi W, Wang Y. et al (2022). Mercury stress tolerance in wheat and maize is achieved by lignin accumulation controlled by nitric oxide. **Environmental Pollution 307:** 119488.

Shao R, Zheng H, Yang J, Jia S. et al (2018). Proteomics analysis reveals that nitric oxide regulates photosynthesis of maize seedlings under water deficiency. **Nitric Oxide 81:** 46-56.

Silva TRG, Costa MLA, Farias LRA, Santos MA. et a (2021). Fatores abióticos no crescimento e florescimento das plantas. **Research, Society And Development 10**: 1-9.

Simon-Sarkadi L, Ludidi N, Kocsy G (2014). Modification of cadaverine content by NO in salt-stressed maize. **Plant Signaling & Behavior 9:** 1-10.

Sterne JAC, Savović J, Page MJ, Elbers RG. et al (2019). RoB 2: a revised tool for assessing risk of bias in randomised trials. **Bmj:** 1-8.

Sun B, Jing Y, Chen K, Song L. et al (2007). Protective effect of nitric oxide on iron deficiency-induced oxidative stress in maize (Zea mays). **Journal Of Plant Physiology 164:** 536-543.

Tan Y, Duan Y, Chi Q, Wang R, Yin Y, Cui D, Sun H.(2023). The role of reactive oxygen species in plant response to radiation. **International Journal of Molecular Sciences 24**: 3346.

Teixeira lAR, Jadoski SO, Faggian R, Sposito V (2020). Efeito de alterações climáticas na aptidão agrícola para cultivo de milho na microrregião de Guarapuava, Paraná. **Research, Society And Development 9**: 1-21.

Tossi V, Amenta M, Lamattina L, Cassia R (2011). Retracted: nitric oxide enhances plant ultraviolet-b protection up-regulating gene expression of the phenylpropanoid biosynthetic pathway. **Plant, Cell & Environment 34:** 909-921.

Tossi V, Lamattina L, Cassia R (2009). An increase in the concentration of abscisic acid is critical for nitric oxide-mediated plant adaptive responses to UV-B irradiation. **New Phytologist 181:** 871-879.

USDA. United States Department of Agriculture. World agricultural production. (2021). Available at: <https://www.fas.usda.gov/data/world-agricultural-production>. Accessed on April 25, 2023.

Warsi MK, Howladar SM, Alsharif MA (2023). Regulon: an overview of plant abiotic stress transcriptional regulatory system and role in transgenic plants. **Brazilian Journal Of Biology 83**: 1-14.

Yamasaki H, Sakihama Y, Takahashi S (1999). An alternative pathway for nitric oxide production in plants: new features of an old enzyme. **Trends in Plant Science 4**: 128–129.

Zanganeh R, Jamei R, Rahmani F (2020). Pre- sowing seed treatment with salicylic acid and sodium hydrosulfide confers Pb toxicity tolerance in maize (Zea mays L.). **Ecotoxicology And Environmental Safety 206:** 111392.

Zhang A, Zhang J, Zhang J, Ye N. et al (2011). Nitric Oxide Mediates Brassinosteroid-Induced ABA Biosynthesis Involved in Oxidative Stress Tolerance in Maize Leaves. **Plant And Cell Physiology 52**: 181-192.

Zhang M, An L, Feng H, Chen T. et al (2003). The Cascade Mechanisms of Nitric Oxide as a Second Messenger of Ultraviolet B in Inhibiting Mesocotyl Elongations. **Photochemistry And Photobiology 77:**219.

Zhang Y, Wang L, Liu Y, Zhang Q. et al (2006). Nitric oxide enhances salt tolerance in maize seedlings through increasing activities of proton-pump and Na+/H+ antiport in the tonoplast. **Planta 224:** 545-555.

Zhang YY, Liu J, Liu YL (2004). [Nitric oxide alleviates growth inhibition of maize seedlings under NaCl stress]. **Journal of plant physiology and molecular biology 30:** 455–459.

4 CONSIDERAÇÕES FINAIS

O número de publicações a respeito de pesquisas sobre o Óxido Nítrico e planta de milho sob algum tipo de estresse abiótico ou como modelo de estudo, vem crescendo nos últimos anos, mostrando dessa forma que existe interesse por parte de determinados grupos em utilizar o NO como alternativa para redução de perdas na produção de grãos relacionadas a esses tipos estresse. Por se tratar de um gás de difícil manuseio, se destacam alguns doadores de NO, como por exemplo o SNP, que consegue desempenhar um papel eficiente nesse processo.

Os resultados obtidos foram condizentes com o objetivo proposto pelo estudo e diante dos mesmos, podemos dizer que, o Óxido Nítrico (NO) pode atua como molécula sinalizadora na tolerância ao estresse hídrico em plantas de milho.

REFERÊNCIAS

ABDRABBO, M. A. A.; SALEH, S. M.; FARAG, A. A. Water requirements for maize under climate change. **Journal of Applied Sciences Research,** [S.l.], v.12, p.19-28, 2016.

AMARO, H. T. R. *et al*. Tratamento de sementes com bioestimulante e disponibilidade hídrica no desenvolvimento inicial do milho. **Magistra,** [S.l], v. 23, p.2-9, 2023.

AN, L. *et al*. Effects of nitric oxide on growth of maize seedling leaves in the presence or absence of ultraviolet-B radiation. **Journal Of Plant Physiology**, [S.l.], v. 162, n. 3, p. 317-326, Mar. 2005. http://dx.doi.org/10.1016/j.jplph.2004.07.004.

ANJUM, N. A. *et al*. Lipids and proteins major targets of oxidative modifications in abiotic stressed plants. **Environmental Science And Pollution Research**, [S.l.], v. 22, n. 6, p. 4099-4121, Dec. 2014. http://dx.doi.org/10.1007/s11356-014-3917-1.

ANTUNES, J. L. F.; CARDOSO, M. R. A. Uso da análise de séries temporais em estudos epidemiológicos. **Epidemiologia e Serviços de Saúde**, [s.l.], v. 24, n. 3, p. 565-576, Sept. 2015.

ARAÚJO JÚNIOR, G. N. *et al*. Estresse hídrico em plantas forrageiras: uma revisão. **Pubvet**, [S.l.], v. 13, n. 1, p. 1-10, Jan. 2019. http://dx.doi.org/10.31533/pubvet.v13n01a241.1-10.

BAI, X. *et al*. Deciphering the protective role of nitric oxide against salt stress at the physiological and proteomic levels in maize. **Journal Of Proteome Research**, [S.l.], v. 10, n. 10, p. 4349-4364, Sept. 2011. http://dx.doi.org/10.1021/pr200333f.

BALDUZZI, S.; RÜCKER, G.; SCHWARZER, G. How to perform a meta-analysis with R: a practical tutorial. **Evidence Based Mental Health**, [S.l.], v. 22, n. 4, p. 153-160, 2019. http://dx.doi.org/10.1136/ebmental-2019-00117.

BERGAMASCHI, H. *et al*. Distribuição hídrica no período crítico do milho e produção de grãos. **Pesquisa Agropecuária Brasileira**, Brasília, [S.l.], v. 39, n. 9, p. 831-839, 2004. https://doi.org/10.1590/S0100-204X2004000900001.

BOLDIZSÁR, Á. *et al*. Nitric oxide affects salt-induced changes in free amino acid levels in maize. **Journal Of Plant Physiology**, [S.l.], v. 170, n. 11, p. 1020-1027, 2013. http://dx.doi.org/10.1016/j.jplph.2013.02.006.

BROUQUISSE, R. Multifaceted roles of nitric oxide in plants. **Journal of Experimental Botany**, [S.l.], v. 70, n. 17, p. 4319-4322, 2019.

CHEN, K. *et al*. [Involvement of nitric oxide in regulation of salt stress-induced ABA accumulation in maize seedling]. **Journal Of Plant Physiology And Molecular Biology,** [S.l.], v. 32, n. 5, p. 577–582, 2006.

CONAB. **Acompanhamento da safra brasileira de grãos: quarto levantamento, janeiro 2021-Safra 2020/21**. Brasília: CONAB. 2021. Disponível em: https://www.conab.gov.br/. Acesso em: 02 maio 2021.

COONEY, R.V. *et al*. Light mediated conversion of nitrogen dioxide to nitric oxide by carotenoids. **Environmental Health Perspective**, [S.l.], v. 102, p. 460-462, 1994.

CORPAS, F. J. *et al*. Nitric oxide imbalance provokes a nitrosative response in plants under abiotic stress. **Plant Science**, [S.l.], v. 181, n. 5, p. 604–611, 2011. http://dx.doi.org/10.1016/j.plantsci.2011.04.005.

CORPAS, F. J. *et al*. Nitric oxide imbalance provokes a nitrosative response in plants under abiotic stress. **Plant Science**, [S.l.], v. 181, n. 5, p. 604–611, 2011. http://dx.doi.org/10.1016/j.plantsci.2011.04.005.

CORPAS, F. J.; RÍO, L. A.; BARROSO, J. B. Need of biomarkers of nitrosative stress in plants. **Trends In Plant Science**, [S.l.], v. 12, n. 10, p. 436-438, Oct. 2007. http://dx.doi.org/10.1016/j.tplants.2007.08.013.

CRAWFORD, N. M. *et al*. Response to Zemojtel et al: plant nitric oxide synthase: back to square one. **Trends in Plant Science**, [S.l.], v. 11, n. 11, p. 526-527, 2006.

DÍAZ, A. S. *et al*. The role of reactive oxygen species and nitric oxide in the formation of root cortical aerenchyma under cadmium contamination. **Physiologia Plantarum**, [S.l.], v. 173, n. 4, p. 2323-2333, Oct. 2021. http://dx.doi.org/10.1111/ppl.13582.

DOMINGOS, P. *et al*. Nitric Oxide: A Multitasked Signaling Gas in Plants. **Molecular Plant**, [S.l.], v. 8, n. 4, p. 506-520, 2015. http://dx.doi.org/10.1016/j.molp.2014.12.010.

DONATO, H.; DONATO, M. Stages for undertaking a systematic review. **Acta Médica Portuguesa**, [S.l.], v. 32, n. 3, p. 227-235, 2019. https://doi.org/10.20344/amp.11923.

GARCÍA-MATA, C.; LAMATTINA, L. Nitric oxide induces stomatal closure and enhances the adaptive plant responses against droughtstress. **Plant Physiology**, [S.l.], v. 126, n. 3, p. 1196-1204, 2001. http://dx.doi.org/10.1104/pp.126.3.1196.

GERLAND, P. *et al*. World population stabilization unlikely this century. **Science**, [S.l.], v. 346, n. 6206, p. 234-237, 2014. https://doi.org/10.1126/science.1257469.

GUO, F,; OKAMOTO, M,; CRAWFORD, N. M. Identification of a plant nitric oxide synthase gene involved in hormonal signaling. **Science**, [S.l.], v. 302, n. 5642, p. 100-103, 2003.

HAMMOND, C. *et al*. Over-expression of the Zea mays phytoglobin (ZmPgb1.1) alleviates the effect of water stress through shoot-specific mechanisms. **Plant Physiology And Biochemistry**, [S.l.], v. 155, p. 384-395, Oct. 2020. http://dx.doi.org/10.1016/j.plaphy.2020.07.040.

HAO, G.; XING, Y.; ZHANG, J. Role of nitric oxide dependence on nitric oxide synthase-like activity in the water stress signaling of maize seedling. **Journal Of Integrative Plant Biology**, [S.l.], v. 50, n. 4, p. 435-442, Apr. 2008. http://dx.doi.org/10.1111/j.1744-7909.2008.00637.x.

KAYA, C. *et al*. Salicylic acid-induced nitric oxide enhances arsenic toxicity tolerance in maize plants by upregulating the ascorbate-glutathione cycle and glyoxalase system. **Journal Of Hazardous Materials**, [S.l.], v. 399, p. 123020, Nov. 2020. http://dx.doi.org/10.1016/j.jhazmat.2020.123020.

KAYA, C. *et al*. Endogenous nitric oxide and its potential sources regulate glutathione-induced cadmium stress tolerance in maize plants. **Plant Physiology And Biochemistry**, [S.l.], v. 167, p. 723-737, Oct. 2021. http://dx.doi.org/10.1016/j.plaphy.2021.08.030.

KEYSTER, M.; KLEIN, A.; LUDIDI, N. Caspase-like enzymatic activity and the ascorbate-glutathione cycle participate in salt stress tolerance of maize conferred by exogenously applied nitric oxide. **Plant Signaling & Behavior**, [S.l.], v. 7, n. 3, p. 349-360, Mar. 2012. http://dx.doi.org/10.4161/psb.18967.

KHAN, M. *et al*. Nitric oxide acts as a key signaling molecule in plant development under stressful conditions. **International Journal Of Molecular Sciences**, [S.l.], v. 24, n. 5, p.2-21, Mar. 2023. http://dx.doi.org/10.3390/ijms24054782.

KHARBECH, O, *et al*. Exogenous application of hydrogen sulfide reduces chromium toxicity in maize seedlings by suppressing NADPH oxidase activities and methylglyoxal accumulation. **Plant Physiology And Biochemistry**, [S.l.], v. 154, p. 646-656, Sept. 2020a. http://dx.doi.org/10.1016/j.plaphy.2020.06.002.

KHARBECH, O. *et al*. Alleviation of Cr(VI)-induced oxidative stress in maize (Zea mays L.) seedlings by NO and H 2 S donors through differential organ-dependent regulation of ROS and NADPH-recycling metabolisms. **Journal Of Plant Physiology**, [S.l.], v. 219, p. 71-80, Dec. 2017. http://dx.doi.org/10.1016/j.jplph.2017.09.010.

KHARBECH, O. *et al*. Nitric oxide donor, sodium nitroprusside modulates hydrogen sulfide metabolism and cysteine homeostasis to aid the alleviation of chromium toxicity in maize seedlings (Zea mays L.). **Journal Of Hazardous Materials**, [S.l.], v. 424, p. 127302, Feb. 2022. http://dx.doi.org/10.1016/j.jhazmat.2021.127302.

KHARBECH, O. *et al*. Nitric oxide and hydrogen sulfide protect plasma membrane integrity and mitigate chromium-induced methylglyoxal toxicity in maize seedlings. **Plant Physiology And Biochemistry**, [S.l.], v. 157, p. 244-255, Dec. 2020b. http://dx.doi.org/10.1016/j.plaphy.2020.10.017.

KLEIN, A. *et al*. Exogenous nitric oxide limits salt-induced oxidative damage in maize by altering superoxide dismutase activity. **South African Journal Of Botany**, [S.l.], v. 115, p. 44-49, Mar. 2018. http://dx.doi.org/10.1016/j.sajb.2017.12.010.

KOSHLAND JR, D.E. The molecule of the year. **Science**, [S.l.], v. 258, n. 5090, p. 1861-1861, 1992.

KUMAR, P.; TEWARI, R. K.; SHARMA, P. N. Sodium nitroprusside-mediated alleviation of iron deficiency and modulation of antioxidant responses in maize plants. **Aob Plants**, [S.l.], v. 2010, p. 1-10, Feb. 2010. http://dx.doi.org/10.1093/aobpla/plq002.

LAMATTINA, L. *et al*. Nitric oxide: the versatility of an extensive signal molecule. **Annual Review of Plant Biology**, [S.l.], v. 54, n. 1, p. 109-136, 2003. http://dx.doi.org/10.1146/annurev.arplant.54.031902.134752.

LI, Z. *et al*. Hydrogen sulphide may be a novel downstream signal molecule in nitric oxide-induced heat tolerance of maize (Zea mays L.) seedlings. **Plant, Cell & Environment**, [S.l.], v. 36, n. 8, p. 1564-1572, Apr. 2013. http://dx.doi.org/10.1111/pce.12092.

LIU, X. *et al*. Combined application of silicon and nitric oxide jointly alleviated cadmium accumulation and toxicity in maize. **Journal Of Hazardous Materials**, [S.l.], v. 395, p. 122679, Aug. 2020. http://dx.doi.org/10.1016/j.jhazmat.2020.122679.

MA, J. H. *et al*. [Effects of exogenous EBR and NO signal on antioxidant system and low response gene expression under cold stress on maize embryo]. **The journal of applied ecology,** [S.l.], v. 26, n. 5, p. 1411–1418, 2015.

MAJEED, S. *et al*. Nitric oxide regulates water status and associated enzymatic pathways to inhibit nutrients imbalance in maize (Zea mays L.) under drought stress. **Plant Physiology And Biochemistry**, [S.l.], v. 155, p. 147-160, Oct. 2020. http://dx.doi.org/10.1016/j.plaphy.2020.07.005.

MAJLÁTH, I. *et al*. Methylglyoxal induces stress signaling and promotes the germination of maize at low temperature. **Physiologia Plantarum**, [S.l.], v. 174, n. 1, p. 1-10, Dec. 2022. http://dx.doi.org/10.1111/ppl.13609.

MÂNCIO, V. O. *et al*. Óxido nítrico como mitigador de estresses em plantas. **Biomassa**: **recursos, aplicações e tecnologias em pesquisas**, [S.l.], v. 1. p. 115-126, 2022.

MARQUES JÚNIOR, N. K. Meta-análise para os estudos do esporte e da atividade física. **Revista Brasileira de Prescrição e Fisiologia do Exercício**, **Médica Portuguesa**, [S.l.], v. 32, n. 3, p. 227-235, 2019.

MILLER, G. *et al*. Reactive oxygen species homeostasis and signalling during drought and salinity stresses. **Plant Cell Environ**, [S.l.], v. 33, p. 453–467, 2010.

MIRA, M. M. *et al*. Cold stress in maize (Zea mays) is alleviated by the over-expression of Phytoglobin 1 (ZmPgb1.1). **Plant Physiology And Biochemistry**, [S.l.], v. 167, p. 901-910, Oct. 2021. http://dx.doi.org/10.1016/j.plaphy.2021.08.046.

MOHER, D. *et al*. Principais itens para relatar Revisões sistemáticas e Meta-análises: a recomendação prisma. **Epidemiologia e Serviços de Saúde**, [S.l.], v. 24, n. 2, p. 335-342, 2015. http://dx.doi.org/10.5123/s1679-49742015000200017.

MORALES, M.; MUNNÉ-BOSCH, S. Malondialdehyde: facts and artifacts. **Plant Physiology**, [S.l.], v. 180, n. 3, p. 1246-1250, 2019. http://dx.doi.org/10.1104/pp.19.00405.

MUCHATE, N. S. *et al*. Plant Salt Stress: adaptive responses, tolerance mechanism and bioengineering for salt tolerance.**The Botanical Review**, [S.l.], v. 82, n. 4, p. 371-406, Oct. 2016. http://dx.doi.org/10.1007/s12229-016-9173-y.

NEILL, S. J.; DESIKAN, R.; HANCOCK, J. T. Nitric oxide signalling in plants. **New Phytologist**, [S.l.], v. 159, p. 11–35, 2003. http://dx.doi.org/10.1046/j.1469-8137.2003.00804.x.

NISHIZAWA, A.; YABUTA, Y.; SHIGEOKA, S. Galactinol and raffinose constitute a novel function to protect plants from oxidative damage. **Plant Physiology,** [S.l.], v.147, n. 3, p. 1251–1263, 2008. http://dx.doi.org/10.1104/pp.108.122465.

OKANT, M.; KAYA, C. The role of endogenous nitric oxide in melatonin-improved tolerance to lead toxicity in maize plants. **Environmental Science And Pollution Research**, [S.l.], v. 26, n. 12, p. 11864-11874, Feb. 2019. http://dx.doi.org/10.1007/s11356-019-04517-3.

OLIVEIRA, H. C. *et al*. Nitric oxide-releasing chitosan nanoparticles alleviate the effects of salt stress in maize plants. **Nitric Oxide**, [S.l.], v. 61, p. 10-19, Dec. 2016. http://dx.doi.org/10.1016/j.niox.2016.09.010.

PRAVEEN, A. Nitric oxide mediated alleviation of abiotic challenges in plants. **Nitric Oxide**, [S.l.], v. 128, p. 37-49, 2022

RAMOS-ARTUSO, F. *et al*. Key acclimation responses to phosphorus deficiency in maize plants are influenced by exogenous nitric oxide. **Journal Of Plant Physiology**, [S.l.], v. 222, p. 51-58, Mar. 2018. http://dx.doi.org/10.1016/j.jplph.2018.01.001.

RODRIGUES, C. L.; ZIEGELMANN, P. K. Metanálise: um guia prático. **Ver HCPA,** [S.l.], v. 30, n. 4, p. 436-447, 2010.

RÜCKER, G.; SCHWARZER, G. Beyond the forest plot: the drapery plot. Research **Synthesis Methods**, [S.l.], v. 12, n. 1, p. 13-19, 2020. http://dx.doi.org/10.1002/jrsm.1410.

SANG, J. *et al*. Nitric oxide reduces hydrogen peroxide accumulation involved in water stress-induced subcellular anti-oxidant defense in maize plants. **Journal Of Integrative Plant Biology**, [S.l.], v. 50, n. 2, p. 231-243, Feb. 2008. http://dx.doi.org/10.1111/j.1744-7909.2007.00594.x.

SANTOS, E. J. F.; CUNHA, M. Interpretação crítica dos resultados estatísticos de uma meta-análise: estratégias metodológicas. **Millenium**, [S.l.] v. 44, n. 18, p. 85–98, 2013.

SANTOS, G. O. *et al*. Disponibilidade hídrica e as anomalias climáticas no cultivo de soja e milho no Cerrado. **Journal Of Biotechnology And Biodiversity**, [S.l.], v. 10, n. 3, p. 214-222, 2022. http://dx.doi.org/10.20873/jbb.uft.cemaf.v10n3.santos.

SHAO, R. *et al*. Mercury stress tolerance in wheat and maize is achieved by lignin accumulation controlled by nitric oxide. **Environmental Pollution**, [S.l.], v. 307, p. 119488, Aug. 2022. http://dx.doi.org/10.1016/j.envpol.2022.119488.

SHAO, R. *et al*. Proteomics analysis reveals that nitric oxide regulates photosynthesis of maize seedlings under water deficiency. **Nitric Oxide**, [S.l.], v. 81, p. 46-56, Dec. 2018. http://dx.doi.org/10.1016/j.niox.2018.09.004.

SHAPIRO, A. D. Nitric Oxide Signaling in Plants. In: LITWACK, G.(Org.). **Plant Hormones**. San Diego: Elsevier Academic Press, 2005.

SILVA, T. R. G. *et al*. Fatores abióticos no crescimento e florescimento das plantas. **Research, Society And Development**, [S.l.], v. 10, n. 4, p. 1-9, 2021. http://dx.doi.org/10.33448/rsd-v10i4.13817.

SIMON-SARKADI, L.; LUDIDI, N.; KOCSY, G. Modification of cadaverine content by NO in salt-stressed maize. **Plant Signaling & Behavior**, [S.l.], v. 9, n. 1, p. 1-10, Jan. 2014. http://dx.doi.org/10.4161/psb.27598.

STERNE, J. A. C. *et al*. RoB 2: a revised tool for assessing risk of bias in randomised trials. **Bmj**, [S.l.], p. 1-8, Aug. 2019. http://dx.doi.org/10.1136/bmj.l4898.

SUN, B. *et al*. Protective effect of nitric oxide on iron deficiency-induced oxidative stress in maize (Zea mays). **Journal Of Plant Physiology**, [S.l.], v. 164, n. 5, p. 536-543, 2007. http://dx.doi.org/10.1016/j.jplph.2006.02.011.

TAIZ, L.; ZEIGER, E. **Fisiologia vegetal**. 6. ed. Porto Alegre: Artmed, 2017. 858 p.

TAN, Y. *et al*. The role of reactive oxygen species in plant response to radiation. **International Journal Of Molecular Sciences**, [S.l.], v. 24, n. 4, p. 3346, Feb. 2023.

TEIXEIRA, L. A. R. *et al*. Efeito de alterações climáticas na aptidão agrícola para cultivo de milho na microrregião de Guarapuava, Paraná. **Research, Society And Development**, [S.l.], v. 9, n. 4, p. 1-21, Mar. 2020. http://dx.doi.org/10.33448/rsd-v9i4.2461.

TOSSI, V. *et al*. Retracted: nitric oxide enhances plant ultraviolet-b protection up-regulating gene expression of the phenylpropanoid biosynthetic pathway. **Plant, Cell & Environment**, [S.l.], v. 34, n. 6, p. 909-921, Mar. 2011. http://dx.doi.org/10.1111/j.1365-3040.2011.02289.x.

TOSSI, V.; LAMATTINA, L.; CASSIA, R. An increase in the concentration of abscisic acid is critical for nitric oxide-mediated plant adaptive responses to UV-B irradiation. **New Phytologist**, [S.l.], v. 181, n. 4, p. 871-879, Jan. 2009. http://dx.doi.org/10.1111/j.1469-8137.2008.02722.x.

UNITED STATES DEPARTMENT OF AGRICULTURE. **World agricultural production**. [S.l.], 2021. Disponível em: https://www.fas.usda.gov/data/world-agricultural-production. Acesso em: 25 abr. 2023.

WARSI, M. K.; HOWLADAR, S. M.; ALSHARIF, M. A. Regulon: an overview of plant abiotic stress transcriptional regulatory system and role in transgenic plants. **Brazilian Journal Of Biology**, [S.l.], v. 83, p. 1-14, 2023. http://dx.doi.org/10.1590/1519-6984.245379.

XIONG, J. *et al*. Drought-induced proline accumulation is uninvolved with increased nitric oxide, which alleviates drought stress by decreasing transpiration in rice. **Journal of Plant Research**, [S.l.], v. 125, n. 1, p. 155-164, 2012. http://dx.doi.org/10.1007/s10265-011-0417-y.

YAMASAKI, H.; SAKIHAMA, Y.; TAKAHASHI, S. An alternative pathway for nitric oxide production in plants: new features of an old enzyme. **Trends in Plant Science**, [S.l.], v. 4, n. 4, p. 128–129, 1999. http://dx.doi.org/10.1016/s1360-1385(99)01393-x.

ZANGANEH, R.; JAMEI, R.; RAHMANI, F. Pre- sowing seed treatment with salicylic acid and sodium hydrosulfide confers Pb toxicity tolerance in maize (Zea mays L.). **Ecotoxicology And Environmental Safety**, [S.l.], v. 206, p. 111392, Dec. 2020. http://dx.doi.org/10.1016/j.ecoenv.2020.111392.

ZHANG, A. *et al*. Nitric oxide mediates brassinosteroid-induced aba biosynthesis involved in oxidative stress tolerance in maize leaves. **Plant And Cell Physiology**, [S.l.], v. 52, n. 1, p. 181-192, Dec. 2011. http://dx.doi.org/10.1093/pcp/pcq187.

ZHANG, M. *et al*. The cascade mechanisms of nitric oxide as a second messenger of ultraviolet b in inhibiting mesocotyl elongations. **Photochemistry And Photobiology**, [S.l.], v. 77, n. 2, p. 219, 2003. http://dx.doi.org/10.1562/0031-8655(2003)0772.0.co;2.

ZHANG, Y. Y.; LIU, J.; LIU, Y. L. [Nitric oxide alleviates growth inhibition of maize seedlings under NaCl stress]. **Journal Of Plant Physiology And Molecular Biology,** [S.l.], v. 30, n. 4, p. 455–459, 2004.

ZHANG, Y. *et al*. Nitric oxide enhances salt tolerance in maize seedlings through increasing activities of proton-pump and Na+/H+ antiport in the tonoplast. **Planta**, [S.l.], v. 224, n. 3, p. 545-555, Feb. 2006. http://dx.doi.org/10.1007/s00425-006-0242-z.

ZHU, J. K. Abiotic stress signaling and responses in plants. **Cell**, Cambridge, v. 167, n. 2, p. 313-324, 2016. http://dx.doi.org/10.1016/j.cell.2016.08.029.