Potato Res. (2026) 69:138
https://doi.org/10.1007/s11540-026-10084-1

REVIEW

Systematic Review and Meta-Analysis of Potato Tuber Cracking

Reason R. Charachimwe[1,2] · Pauline Aarakit[1,2] · Arsenio D. Ndeve[1] · Rogerio M. Chiulele[1,2] · J. Martin Steyn[3] · Gudeta W. Sileshi[4]

Received: 4 January 2026 / Accepted: 23 May 2026 / Published online: 20 June 2026
© The Author(s) 2026

Abstract

Potato (*Solanum tuberosum* L.) is one of the most widely produced starchy tuberous crops, and it is currently grown in over 100 countries. However, the productivity and quality of the crop are compromised by tuber cracking. While individual studies on the etiology of cracking have provided valuable insights, the evidence remains fragmented and sometimes contradictory. Therefore, a systematic review was carried out to consolidate current evidence and identify research gaps, highlight consistencies and discrepancies across studies. Literature was searched in Scopus, PubMed, and Google Scholar, and 30 eligible studies were included in the review and meta-analysis. A three-tier screening process was employed, and bibliographic information, interventions evaluated, outcomes, and impacts were recorded and the findings were visualised in figures and tables. The overall mean percentage of tuber cracking was estimated at 8.7% (95% confidence limits 5.0–12.5%) using a random effects meta-analysis. Four groups of interventions were associated with tuber cracking, with agronomic management practices being the most studied. The review and subgroup analysis identified some association with viral and fungal pathogens, management practices (e.g., irrigation and spacing), environmental factors (e.g., water stress) and varietal differences. However, the etiology of tuber cracking could not be rigorously assessed due to the small number of studies available on most of the variables and the variability of methods used. Therefore, it is recommended that future research should focus on establishing the real causes using standardised methods to quantify and report tuber cracking.

Keywords Etiology · Management practices · Moisture stress · Pathogen exposure · *Solanum tuberosum*

Extended author information available on the last page of the article

Introduction

Potato *(Solanum tuberosum* L.) is a widely produced and consumed tuber crop worldwide (Spooner et al. 2014). Globally, potato is fourth in terms of the quantity produced following maize, wheat, and rice (Scott et al. 2013; Spooner et al. 2014; FAOSTAT 2025). Currently, potato is grown in over 100 countries, ranging from temperate to tropical climates, underscoring the crop's versatility (Spooner et al. 2014; Reddy et al. 2018; Ríos et al. 2023). Potato has gained popularity due to its ability to deliver greater economic output per unit area, adaptability and health-related benefits, which makes it a vital source of sustenance and income for millions of people worldwide (Scott et al. 2013; Hill et al. 2021). Although it is not regarded as a staple crop in some countries, potato plays a crucial role in food and nutrition security, where it provides a reliable source of calories and nutrients at a relatively low cost. Nutritionally, the crop is a rich source of carbohydrates, vitamins especially vitamin C and B6, minerals like potassium and magnesium, and dietary fiber, making it a double-edged sword for both food and nutrition security (Muthoni and Shimelis 2023). Almost 85% of the biomass of a potato plant is edible, compared to the 50% of cereal crops, making it ideal for most poor people (Vos 1997).

Despite its significant potential, potato yield among small-holder farmers is alarmingly decreasing in some parts of the world (Muthoni and Shimelis 2022). This is attributed to factors such as limited access to quality seed potatoes, inadequate irrigation infrastructure, insufficient market access, suboptimal agronomic practices, pests, and diseases (Muthoni and Shimelis 2023; Ríos et al. 2023). Among the various constraints, tuber cracking has emerged as an important challenge impacting the marketability of potato tubers (Harper et al. 1963; Carnegie and McCreath 2010; Muzhinji et al. 2014; Dash 2018). Although tuber cracking does not predispose potatoes to rot, it severely compromises the appearance of tubers and lowers quality, rendering cracked tubers unmarketable and thus contributing to substantial economic losses (Zotarelli et al. 2012; Robinson 2018; Jiang et al. 2022). However, the underlying causes of tuber cracking are not fully understood. Many abiotic and biotic factors were implicated but none has been confirmed in the etiology of cracking, thus constraining evidence-informed development of mitigation strategies (Fiers et al. 2010; Gush 2020; Jiang et al. 2022).

While individual investigations have provided valuable insights, the evidence remains fragmented, limited and sometimes contradictory, warranting a systematic review. Therefore, the objectives of this work were (1) to determine the environmental, agronomic, genetic, physiological and biochemical processes driving potato tuber cracking and identify effective management strategies for reducing cracking, and (2) to identify research gaps, and highlight consistencies and discrepancies across studies so as to provide a reliable foundation for evidence-based decision-making in future research to effectively manage tuber cracking. The hypotheses being tested were as follows: (1) environmental factors can cause the occurrence and severity of potato tuber cracking, (2) the incidences and presence of certain pathogens can significantly increase the occurrence and severity

Table 1 PICO components guiding the review

PICO components	Description
Population/Problem (P)	Potato (*Solanum tuberosum*) tuber cracking of various cultivars
Intervention (I)	Relevant interventions; environmental, agronomic/management practices, varietal/cultivar and pathogen association
Comparison (C)	Comparators included, tubers or plots under standard or recommended agronomic/environmental conditions, cultivars or genotypes with contrasting susceptibility to cracking
Outcome (O)	Types of tuber cracking, incidence and severity of cracking, skin blemish lastly
Timing (T):	Interventions or observations focusing on tuber growth cracking only
Setting (S):	Field trials, observational studies, greenhouse experiments, and controlled environment studies from both temperate and tropical potato-growing regions and also smallholder and commercial farming systems

of potato tuber cracking, (3) potato tuber cracking can be influenced by certain agronomic management practices, and (4) potato variety has a significant effect on the incidences and severity of tuber cracking.

Materials and Methods

Protocol and Registration

The systematic review was conducted in accordance with the PRISMA 2020 guideline (Page et al. 2021). The review protocol was preregistered on the Open Science Framework (OSF; https://doi.org/10.17605/OSF.IO/ECN4D) to ensure transparency and methodological rigor.

Scope of the Review and Analytic Framework

The scope of this systematic review is global covering studies published on potato tuber cracking between 1935 and June 2025. The review focused on studies examining environmental, abiotic, biotic and agronomic factors influencing potato tuber cracking. Specifically, studies that presented substantial quantitative and qualitative data on potato tuber cracking incidences and severity were included, while those focusing on post-harvest tuber cracking were excluded. The review extends to both greenhouse and open-field potato production systems across diverse climatic zones. To define research questions and guide the inclusion criteria, the review was structured around the PICO framework which explicitly set out the population/problem, intervention, comparison and outcome (Table 1).

Table 2 Search strings used for Scopus and PubMed Databases

Search strings
(potato OR "Solanum tuberosum") AND ("tuber cracking" OR "growth crack*" OR "skin defect*" OR "skin blemish*")
(potato OR Solanum tuberosum") AND ("tuber crack*"OR "growth crack*" OR "tuber defect*" OR "skin blemish*") AND (irrigation OR drought OR "water stress" OR "water fluctuation*")
(potato OR "Solanum tuberosum") AND ("tuber crack*" OR "growth crack*" OR "tuber defect*" OR "skin blemish*") AND temperature
(potato OR "Solanum tuberosum") AND ("tuber crack*" OR "growth crack*" OR "tuber defect*" OR "skin blemish*") AND (fertilizer OR boron OR calcium OR nitrogen)
(potato OR "Solanum tuberosum") AND ("tuber crack*" OR "growth crack*" OR "tuber defect*" OR "skin blemish*") AND ("plant density" OR spacing)
(potato OR "Solanum tuberosum") AND ("tuber crack*" OR "growth crack*" OR "tuber defect*" OR "skin blemish*") AND ("management practice*" OR "cultural practice*")
(potato OR "Solanum tuberosum") AND ("tuber crack*" OR "growth crack*" OR "tuber defect*" OR "skin blemish*") AND (disease* OR pathogen*)
(potato OR "Solanum tuberosum") AND ("tuber crack*" OR "growth crack*" OR "tuber defect*" OR "skin blemish*") AND ("genetic variation" OR variety*)
(potato OR "Solanum tuberosum") AND ("tuber crack*" OR "growth crack*" OR "tuber defect*" OR "skin blemish*") AND (control OR "mitigation measures")
(potato OR "Solanum tuberosum") AND ("tuber cracking" OR "growth crack*" OR "skin defect*" OR "skin blemish*") AND cause*

Search Strategy

The systematic review followed the Updated Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement (Page et al. 2021) to search available literature on potato tuber cracking. A comprehensive and exhaustive search strategy was employed in two major databases, namely, Scopus and PubMed. The search was performed in June 2025. Guided by the PICO model, the search utilised ten structured search strings with no limits on the search (Table 1). In order to broaden the search and capture relevant studies, another search was done separately using shorter search strings on Google Scholar through the Publish or Perish (PoP) software (Harzing 2025). The search was limited to the first 100 retrievable records because Google Scholar ranks results using a relevance-based algorithm and citation frequency, with higher-ranked studies generally reflecting greater academic impact. Therefore, concentrating on the first 100 hits ensured more focus on the most relevant studies while maintaining a manageable and high-quality dataset for the review. Beyond the top-ranked results, there is a likelihood of including less relevant studies and duplicates (Haddaway et al. 2015). In all databases, the search combined keywords and their synonyms with Boolean operators (AND OR), truncation (*) for words with multiple endings and nesting ("…") to ensure retrieval of articles related to potato tuber cracking. Table 2 shows the search strings used. All references retrieved were imported to Mendeley for storage and removal of duplicates. Then a CSV file of the studies was imported to Microsoft Excel in structured columns for bibliographic details, screening decisions and analysis.

Eligibility Criteria

Eligibility criteria were formulated to ensure that only relevant articles were included in the review. Studies were included if they met all the following criteria: (1) randomised and replicated primary studies published in peer-reviewed journal articles, conference proceedings; (2) studies focusing on potato tuber growth cracking; (3) studies published between 1935 until June 2025; and (4) studies analysing physiological, biochemical, agronomic, environmental, and genetic factors. Conversely, studies were excluded if they did not fulfil one of the listed criteria above or if they are (1) review articles without primary research data, (2) studies not focused on potato tuber cracking, (3) studies with limited or no experimental data, and (4) information presented in fact sheets or bulletins.

Screening

Two authors performed a three-tier screening process: (1) titles, (2) abstract, and (3) full text reading, to assess the appropriateness of the studies retrieved by the search strategy to ensure that not only relevant studies but also studies with sound methodology were included. Whenever there was doubt in regards to certain studies at each screening level, the article was included in the next step until a consensus was reached by all reviewers. Articles that were not retrieved as full text through online searching were requested from authors through the use of platforms like ResearchGate. However, despite all the efforts some articles could not be accessed and were excluded from the study. All articles excluded after the full text were recorded and assigned a reason for exclusion.

Risk of Bias Assessment

The methodological quality of the included studies was assessed using the Cochrane revised Risk of Bias tool (RoB2), following the guidelines of the Intervention Process and Reporting Guidelines (IPRG) (Cochrane Collaboration 2019). However, the use of standardised risk-of-bias tools developed for clinical studies was not directly applicable, due to the nature of the studies included which are field-based agronomic and observational studies. Hence, a domain-based framework was adopted and adjusted to evaluate the methodological factors that could influence the reliability and interpretability of the reported diversity estimates. Guided by the RoB2 algorithm, the potential sources of bias were evaluated across five domains, coding each study as “Low risk”, “Some concerns”, and “High risk”, depending on how they address each domain based on the following criteria. The five domains used are briefly described below.

a) Bias due to the randomisation process

This domain was used to evaluate whether studies used clearly defined randomisation process on allocation of treatments. Study was assigned low risk of

bias if the randomisation of treatments was clearly reported, some concern if the randomisation of treatments was not clearly mentioned and high risk if there was no randomisation of the treatments.

b) Bias due to deviation from intended intervention

This domain was used to evaluate the extent to which researchers adhered to the prescribed objectives and methodology. A study was assigned low risk of bias if trial was carried out as prescribed by the methodology and aligned with objectives, some concern if the implementation was not clearly mentioned and high risk if the implementation did not follow the prescribed methodology with some deviations.

c) Bias due to missing outcome data

This domain was used to assess whether or not all the outcome data were reported. Studies were assigned low risk if there were no missing data reported or if there were missing data and there was a clear explanation of the causes and how the researcher overcome, some concerns if there was no clear explanation on the missing data and high risk if there were missing data across treatments without mentioning the causes and how it was addressed.

d) Measurement of the outcome

This domain was used to assess whether or not appropriate statistical methods were applied and clearly reported. A study was assigned low risk of bias if appropriate statistical methods were applied and clearly reported, some concern when the statistical method was mentioned but not properly described and high risk if the study used inappropriate statistical methods or the methods were not properly described.

e) Bias in selection of the reported result

This domain was used to determine whether or not the researcher reported all the outcomes in accordance with the pre-specified methodology. Studies were judged to be at low risk of bias where there was no selective reporting of outcomes, some concerns if there was no clear mention of the data to be reported in the methodology and high risk if there was evidence of selective reporting with relevant outcomes omitted.

Overall risk of bias was assigned for each study based on the domain-level assessment as follows: (i) If the results of all domains are low risk, study was assigned a low risk of bias rating, (ii) if the results of one domain are of some concern, study was assigned some concern risk of bias rating, (iii) if the results of at least two domains are of some concern, study was assigned a high risk of bias rating, and (iv) if the results of at least one domain indicate a high risk, study was assigned a high risk.

Data Extraction and Coding

The following variables were extracted from the articles and arranged in structured columns in Microsoft Excel in preparation for data analysis: (i) bibliographic details (e.g., author, title, journal name, etc.), (ii) location of study, (iii) study design, (iv) intervention management practices evaluated, (v) type of cracking observed, and (vi) outcome/results of the study and cracking percentage. In the database, the practices evaluated were categorised into the following categories: fertilization, viral infection, fungal infection, herbicide application, irrigation, moisture stress, ridging, spacing, and potato varieties/genotype. The groups were used for subgroup analysis and the narrative synthesis carefully discussing the outcomes and types of cracking observed. The coding process was conducted by one author and reviewed by the second author to reduce bias. Excel pivot tables and charts were used to summarise and visualise the results including studies per country, studies published per year, practices evaluated and type of cracking observed.

Meta-analysis

Only 20 studies had adequate quantitative data expressed as percentage of tuber cracking to perform the meta-analysis. A random effects meta-analysis was performed using the percentage tuber cracking data from these studies. The meta-analysis was performed using the MAJOR module of Jamovi, an open-source software package that performs random effects meta-analysis using an extension of the *metafor* package of R (JAMOVI 2024). Then the percentage of tuber cracking and the 95% confidence limits (CLs) at both the individual study level and the pooled effect size were estimated. Between-study heterogeneity was examined using the H^2, I^2, τ^2, and Q statistics generated by the random effects models. Normally, τ^2 is used as a measure of the amount of true variance in the effect sizes across the population of studies (24). The I^2 represents the proportion of total variation in effect size estimates that is due to between-study heterogeneity (25). When the value of I^2 is 0, all variability in effect size estimates is assumed to be due to sampling error within studies, while $I^2 > 50\%$ indicates significant heterogeneity between studies (24). Cochran's Q provides a test of the hypothesis that the true treatment effects are the same in all the primary studies included in a meta-analysis. From the 20 studies, subgroup analysis was performed using the following categories: fertilization, viral infection, fungal infection, herbicide application, irrigation, moisture stress, ridging, spacing, potato varieties/genotypes. The mean percentage cracking and the associated standard errors for each category were first generated using a linear mixed effects model where the category was entered as the fixed effect and study was entered as the random effect. This step was necessary to correctly estimate the standard errors because the original papers had only reported the percentage tuber cracking. Then, a random effects model was fitted to estimate the 95% confidence intervals and the pooled percentage tuber cracking.

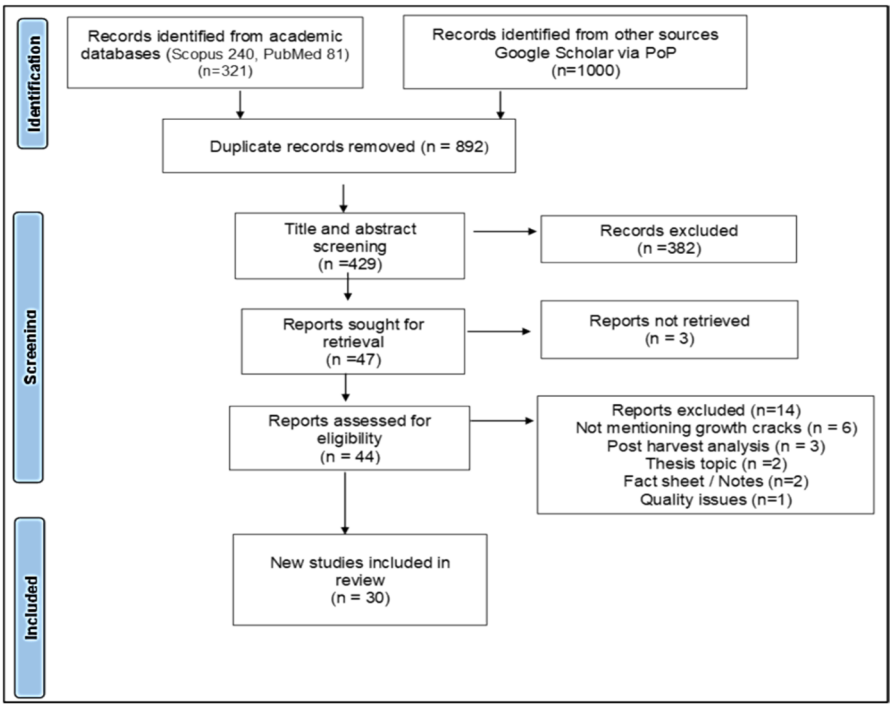


Fig. 1 PRISMA Flow chart for the study identification, screening, and selection process

Results

Literature Search Results

The literature search resulted in a total of 1321 references; 240 in Scopus, 81 in PubMed and 1000 in Google Scholar (Fig. 1). After removal of duplicates a total of 429 studies were retained for further screening. The screening of titles and abstracts resulted in a total of 47 articles, and these retrieved for full text review. Of these, 3 studies were not retrieved because authors failed to access full papers and 14 were excluded for not meeting the inclusion criteria. Ultimately, 30 studies were included in the systematic review (Table 3) and amore detailed approach on study selection and data retrieval process is provided in the PRISMA flowchart (Fig. 1).

Characteristics of the Reviewed Studies

The included evidence base comprised 30 unique studies spanning Africa, Asia, Europe, and North-America. The reviewed studies were conducted under diverse conditions and experimental settings including different locations, seasons and management practices to assess potato tuber cracking. Most studies were

Table 3 Summary of study characteristics and key findings of reviewed studies

#	Author	Title	Country	Type of study	Intervention/Category	Type of cracking	Outcome
1	Parker 1986	Evaluation of potato cultivar resistance to common scab, black scurf and tuber cracking	Scotland	Field experiment	Varietal studies	Not specified	Cracking % varied among cultivars
2	Siano et al. 2024	Effects of Abiotic Stress Associated with Climate Change on Potato Yield and Tuber Quality Under a Multi-environment Trial in New Zealand	New Zealand	Field experiment	Environmental conditions (Heat stress)	Not specified	Cracking increased with heat and moisture stress
3	Benedict et al. 2015	Tuber Symptoms Associated with Recombinant Strains of Potato virus Y in Specialty Potatoes Under Western Washington Growing Conditions	USA	Observational and field experiment	Pathogen/disease exposure (recombinant potato virus Y (PVY) strains	Canoe-shaped cracks	Tuber cracking associated with PVY infection More cracked tubers on plants positive for PVY
4	Carnegie and McCreath 2010	Mosaic virus symptoms in potato crops and the occurrence of growth cracking in Tubers	Scotland	Observational and field experiment	Pathogen or disease exposure (Mosaic virus)	Not specified	Tuber cracking was associated with mosaic symptomatic plants
5	Inglis and Gundersen 2015	Impact of Potato virus Y on the quality of specialty potato tubers	USA	Observational and field experiment	Pathogen or diseases exposure (PVY)	Canoe-shaped	Tuber cracking associated with PVY foliar infection

Table 3 (continued)

#	Author	Title	Country	Type of study	Intervention/Category	Type of cracking	Outcome
6	Dhiman et al. 2024	Nano-boron foliar application reduced the proportion of cracked tuber yield in potato	India	Field experiment	Management/agronomic practice (Fertilizer-B)	Not specified	Nano boron reduced cracking significantly
7	Essah and Holm 2020	Air Injection of Subsurface Drip Irrigation Water Improves Tuber Yield and Quality of Russet Potato	USA	Field experiment	Management/agronomic practice (irrigation method)	Not specified	Tuber external defects reduced with aerated subsurface drip irrigation
8	Essah et al. 2012	Cover crops can improve potato tuber yield and quality	USA	Field experiment	Management/agronomic practice (Cover crops and irrigation)	Not specified	Cover crops reduced external defects
9	Mansour and Abu El-Fotoh (2019)	Effect of planting date, irrigation level and foliar spray with calcium and/or boron on potato crop performance	Egypt	Field experiment	Management/agronomic practice (Planting date, irrigation and fertilizer type)	Not specified	Tuber cracking reduced by late planting (October), 75% FC water and spraying with Ca + B
10	Fiers et al. 2010	Diversity of microorganisms associated with atypical superficial blemishes of potato tubers and pathogenicity assessment	France	Observational and field experiment	Pathogen/disease exposure (Fungi and bacteria)	Mixed (Polygonal corky cracks star-like corky lesions)	No correlation between Skin blemishes and specific microorganisms

Table 3 (continued)

#	Author	Title	Country	Type of study	Intervention/Category	Type of cracking	Outcome
11	Gundersen et al. 2019	Foliar and Tuber Reactions of Three Strains of Potato virus Y on Five Fresh Market Potato Cultivars through Three Successive Potato Generations	USA	Green house and field experiment	Pathogen/disease exposure (PVY strain)	Not specified	Tuber cracking associated with PVY seed tuber transmission Some cultivars are sensitive
12	Harper et al. 1963	Growth cracking and bacterial soft rot in potato tubers	Scotland	Field experiment	Management/agronomic practice (Fertilizer rates)	Irregular V-shaped groove	Tuber cracking associated with higher rates of fertilizer
13	Henriksen et al. 2007	Potato tuber yield and quality and soil inorganic nitrogen as affected by timing of ridging with and without catch crops	Denmark	Field experiment	Management/agronomic practice (Ridging, catch crops)	Not specified	Ridging reduced tuber cracking
14	Jiang et al. 2022	Irrigation effect on Yield, Skin Blemishes, Phellem Formation, and Total Phenolics of Red Potatoes	Canada	Field experiment	Management/agronomic practice (Irrigation)	Surface cracking	Tuber cracking was associated with rainfed while irrigation reduced
15	Robins and Domingon 1956	Potato yield and Tuber Shape as Affected by Severe Soil-Moisture Deficits and Plant Spacing	USA	Field experiment	Management/agronomic practice (moisture stress and spacing)	Not specified	Tuber cracking increased with mid-season moisture stress and lower stem population

Table 3 (continued)

#	Author	Title	Country	Type of study	Intervention/Category	Type of cracking	Outcome
16	MacKerron and Jefferies 1985	Observations on the effects of relief of late water stress in potato	Scotland	Field experiment	Management/agronomic practice (moisture stress)	Not specified	Relief of water stress caused cracking
17	Reis et al. 2018	Carryover of tembotrione and atrazine affects yield and quality of potato tubers	Brazil	Field experiment	Management/agronomic practice (Herbicides)	Not specified	Tuber cracking was associated with herbicide (Tembotrione)
18	Nogueira et al. (1996)	Potato yield and quality under potassium and gypsum levels in Southeastern Brazil	Brazil	Field experiment	Management/agronomic practice (Fertilization)	Not specified	Tuber cracking decreased with application of KCl + gypsum residue
19	Painter and Augustin 1976	The effect of soil moisture and nitrogen on yield and quality of the Russet Burbank potato	USA	Field experiment	Management/agronomic practice (Fertilization and moisture stress)	Mixed	Tuber cracking associated with higher rates of N, banding of N and moisture stress
20	Ghongtham et al. 2018	Effect of boron application on yield, quality and economics of Potato (Solanum tuberosum L.)	India	Field experiment	Management/agronomic practice (Fertilization)	Not specified	Tuber cracking increased with higher NPK levels. Foliar 0,1% boric reduced
21	Kumar et al. 2021	Effect of water stress on tuber quality (dumbel, pointed, cracks and total deformed tubers) in potato (Solanum tuberosum L.)	India	Field experiment	Management/agronomic practice (Variety and moisture stress)	Mixed (dumbel, pointed, crack)	Tuber cracking associated with water stress at tuber enlargement stage

Table 3 (continued)

#	Author	Title	Country	Type of study	Intervention/Category	Type of cracking	Outcome
22	Chongtham, et al. 2016	Effect of Different Fertility Levels on Tuber Yields, Input Use Efficiency and Economics of potato Variety Kufri Chipsona-3	India	Field experiment	Management/agronomic practice (Fertilization)	Not specified	Tuber cracking associated with higher rates of NPK
23	Dash 2018	Management of tuber cracking in potato (Solanum tuberosum L.) cv. Kufri Chipsona-3 through boron application	India	Field experiment	Management/agronomic practice (Fertilization)	Not specified	Tuber cracking reduced by recommended dose of NPK and along with 0.1% Boron
24	Gush 2020	Elucidating the role of microbial factors and water stress in causing corky crack blemishes on potato tubers in South Africa	South Africa	Observational and field experiment	Pathogen/and Management practice (Rhizoctonia solani and moisture stress)	Elephant hide, Corky cracks	No fungal species were isolated from growth cracks Elephant hide symptoms were observed
25	Singh and Sadawarti 2024	Effect of irrigation methods and nutrient management practices on production and economics of potato under different preceding …	India	Field experiment	Management/agronomic practice (Irrigation and Fertilization)	Not specified	Tuber cracking was associated with drip irrigation

Table 3 (continued)

#	Author	Title	Country	Type of study	Intervention/Category	Type of cracking	Outcome
26	Dharmasena et al. 2024	Determination of effective nitrogen level to optimize yield and quality of potato varieties of Connect and Masai	Sri Lanka	Field experiment	Management/agronomic practice (Fertilization)	Not specified	No association between N levels and cracked tubers
27	Washington and Edmundson 1935	Distance of planting Rural New Yorker No. 2 and Triumph potatoes as affecting yield, hollow heart, growth cracks, and second-growth tubers	USA	Field experiment	Management/agronomic practice (Spacing)	Not specified	Growth cracking associated with wider spacing
28	Zarzyńska and Boguszewska-Mańkowska 2024	Commercial Quality of Potato Tubers of Different Varieties from Organic and Conventional Production System	Poland	Field experiment	Management (Production systems)	Not specified	More cracking associated with conventional system
29	Zimmerman-Gries and Blodgett 1963	Some skin defects of potatoes in Israel	Israel	Not specified	Pathogen/disease and varietal	Skin cracking	No correlation between virus infection and skin defects
30	Zimudzi et al. 2017	Pathogenicity of Fungi Isolated from Atypical Skin Blemishes on Potatoes in South Africa and Zimbabwe	Zimbabwe and South Africa	Observational and field experiment	Pathogen/disease (Fungi and variety)	Corky cracks	Tuber cracking and elephant hide associated with *R. solani* AG 3-PT and BR AG A

field-based experiments (22), followed by those which combined observational and field experiments (6) and lastly green house and unspecified (1;1 respectively). Tuber cracking was evaluated under different interventions ranging from management practices, pathogen exposure, potato varieties and environmental conditions. The comprehensive study-by-study summary is provided (Table 3).

Trends and Geographical Distribution of Reviewed Studies

The literature search did not apply a filter to delimit years of publication to broaden the search. This decision was informed by a pilot search, which revealed that the subject of tuber cracking had limited information. Therefore, the review identified one publication (3.3%) in 1935, and two (6.7%) in 1963. From 1963 to 2007 research on tuber cracking was done once in every 10 years, but from 2007 onwards, every other year there were either one or two publications on tuber cracking and the largest number of global studies published on tuber cracking was recorded in 2024 (17%) (Fig. 2).

The geographical distribution of these studies revealed a higher concentration in Northern America (9 studies) followed by Asia and Europe with 8 and 7 studies, respectively. The African continent had 3 studies, followed by South America (2 studies) and Oceania which had the least 1 study published across the continents (Fig. 2).

Type of Cracking Observed in Reviewed Studies

Most studies (20) did not disclose the type of cracking observed but just generalised it as cracking (Fig. 3). Among those studies that actually identify the different types of cracking, canoe-shaped cracking was reported in 2 studies, while irregular V-shaped cracks, dumbel-pointed cracks, corky cracks, elephant hide, skin or surface cracking were reported by one study each (Table 3; Fig. 3).

Intervention or Categories Evaluated on Reviewed Studies

The studies included in the review featured four broad categories of interventions and the most studied interventions fall under agronomic management practices mentioned in 13 studies (43.3%). Out of the 13 studies, 7 studies were on fertilization (rates and/or type), with boron and NPK being specifically explored. The other management practices explored include irrigation method, herbicide application, production systems and plant spacing. Some studies applied a combination of management practices (Table 3). A total of 10 studies (33.3%) explored a combination of interventions, with variety and moisture stress being the most evaluated while others combined fertilizer and variety. Studies that examined the association between tuber cracking and pathogen infections formed the third category reported in 5 studies (17%). Of these, Potato Virus Y (PVY) was the most studied (3), infections by fungal and bacterial pathogens

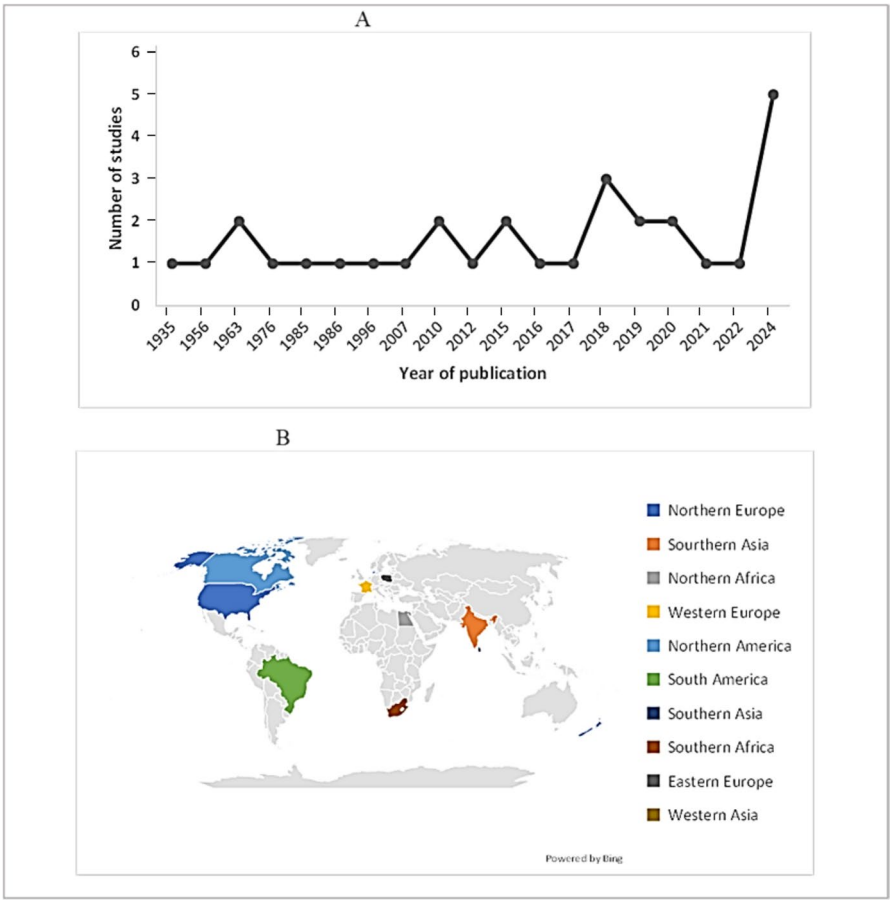


Fig. 2 Number of studies published **A** per year; **B** per region on tuber cracking

were also explored. The least represented categories were heat stress and varietal differences in tuber cracking which recorded 1 study each (Table 3).

Meta-analysis

The random effects meta-analysis showed that the overall mean percentage of tuber cracking is 8.7 (95% CL 5.0–12.5), but significantly varying across studies (Fig. 4). Significant between-study heterogeneity was also evident in the high values of T^2 (61.5), H^2 (246), and a significant Q (1147.2; $P < 0.001$). The I^2 values of 99.6% show that over 99% of the variance is due to study level variability in cracking. The smallest cracking percentage (0.24%) was observed in a study that examined timing of ridging and catch crops, while the largest (28.3%)

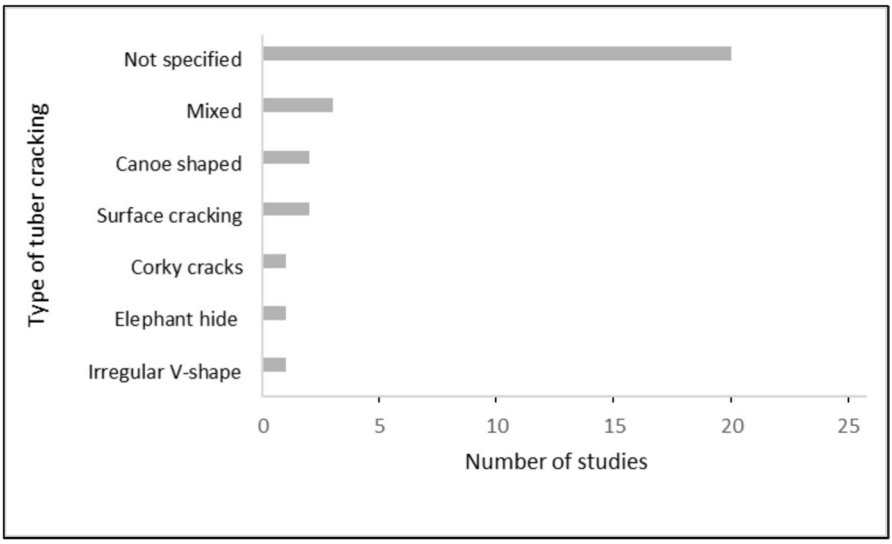


Fig. 3 Type of tuber cracking on reviewed studies

was observed in a study on boron fertilization. The funnel plot (Fig. 4) shows significant asymmetry (Egger's regression $P < 0.01$). Nevertheless, the Fail-safe number shows that the random effects estimate is robust (Fig. 4). No significant differences were noted between the categories of interventions in the subgroup analysis, but moisture stress, infections by fungal or viral pathogens and plant spacing appear to be associated with significantly increased tuber cracking compared with the other interventions (Fig. 5). The number of studies and observations were too few in most cases, and this hindered rigorous statistical comparisons between interventions because the 95% intervals could not be accurately estimated.

Risk of Bias Assessment of Reviewed Studies

The results of the risk of bias assessment are summarised in Fig. 6, and the overall risk of bias assessment of the studies shown in Fig. 7. Results indicated that most studies 23 (76.7%) randomised treatments, while 4 (13.3%) did not randomise. All studies included in the review did not deviate from the intended interventions and stuck to plan for analysis 30 (100%), while only one study (3.3%) had some missing data. Overall, the risk of bias assessment results indicated that from the 30 studies, 22 (73.3%), were rated at low risk of bias, while the least 3 (10%), were rated at some concerns of bias. Few studies 5 (16.7%) were rated high risk of bias (Fig. 7).

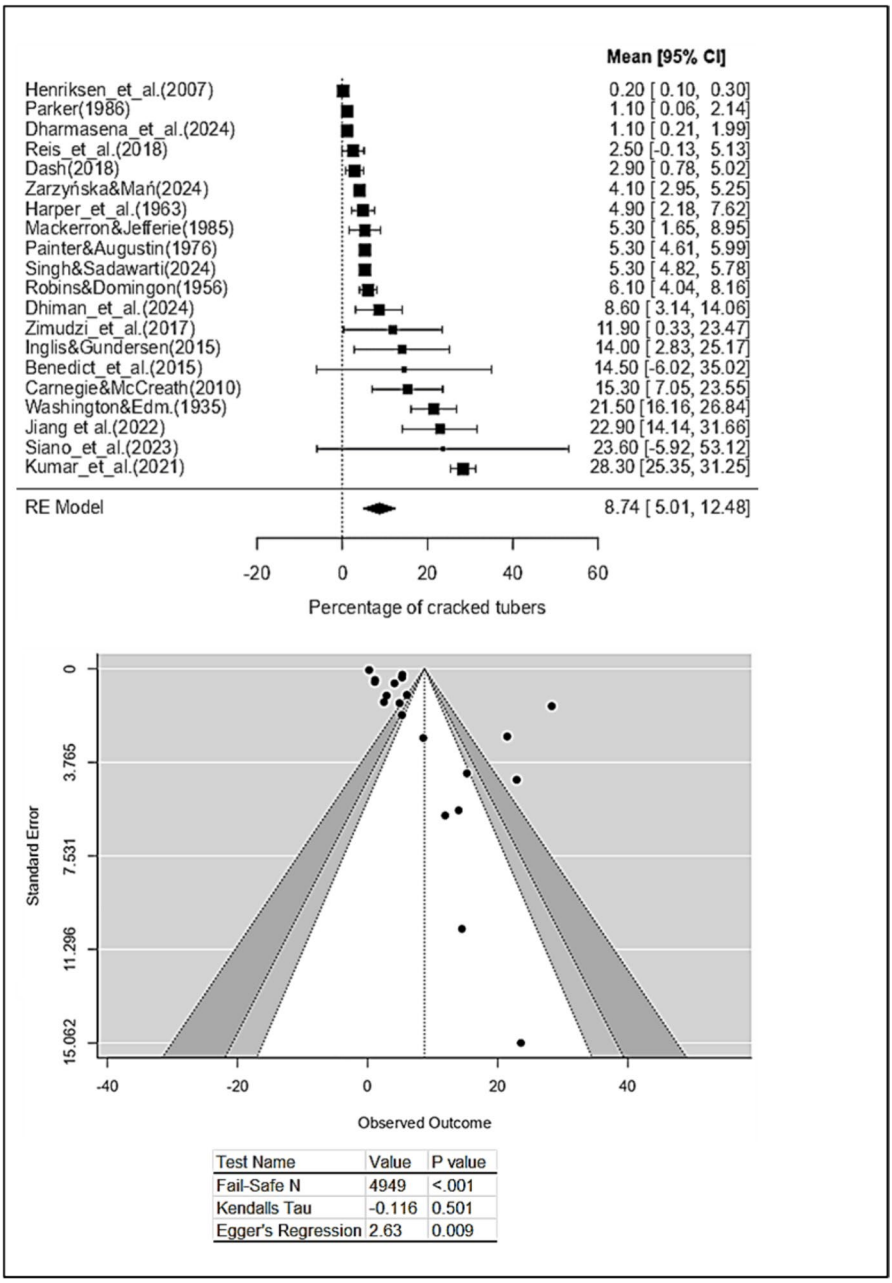


Fig. 4 Forest plot (top) and funnel plot (bottom) for the percentage of cracked potato tubers. RE in the forest plots represents the random effects estimate of tuber cracking

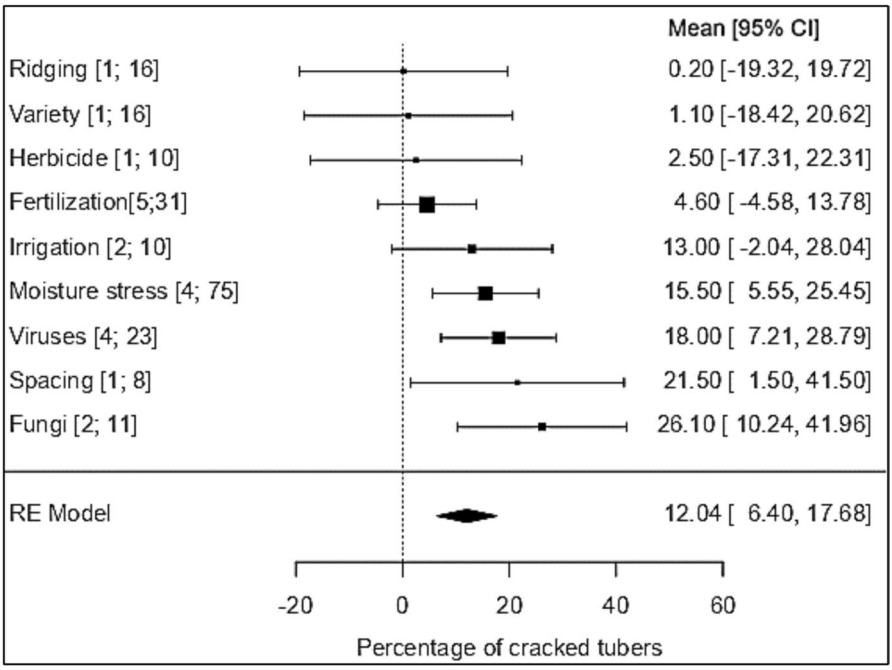


Fig. 5 Subgroup analysis showing variation with interventions

Discussion

Trends and Geographic Distribution of Reviewed Studies

The review recorded one publication in 1935, indicating that potato tuber cracking is not a new phenomenon in potato production. Evidence from literature indicates that potato tuber cracking dates back to the early nineteenth century, as early as 1925 where scientist from Michigan were conducting some research on hollow heart and also discovered growth cracking to be a common characteristic of hollow heart in potatoes (Edmundson 1935). Later on, around 1963 potato tuber cracking was reported in Israel on some varieties that were imported from Great Britain and Scotland and researches were carried out (Zimmerman-Gries and Blodgett 1963). Results indicated that from 1976 up to 2017, there has been a fluctuation in numbers of studies published in regards to potato tuber growth cracks, and this can be attributed to more research work that was done in potato to fight against diseases and more information available for farmers to reduce the incidence of tuber cracking. However, as evidenced by the results of this review in 2018 and 2024 an increase was observed in the number of studies published showing a sharp and drastic surge of potato tuber cracking reports in several parts of the world (Chongtham et al. 2016; Dash et al. 2018; Reis et al. 2018; Mansour and Abu El-Fotoh (2019); Gundersen et al. 2019; Gush 2020; Essah and Holm 2020; Kumar et al. 2021; Jiang et al. 2022; Siano et al. 2024; Zarzyńska and

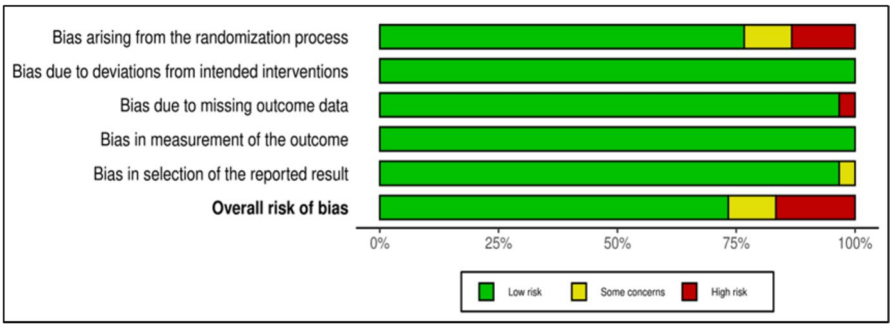


Fig. 6 Summary bar plot of risk-of-bias assessment across domains for included studies

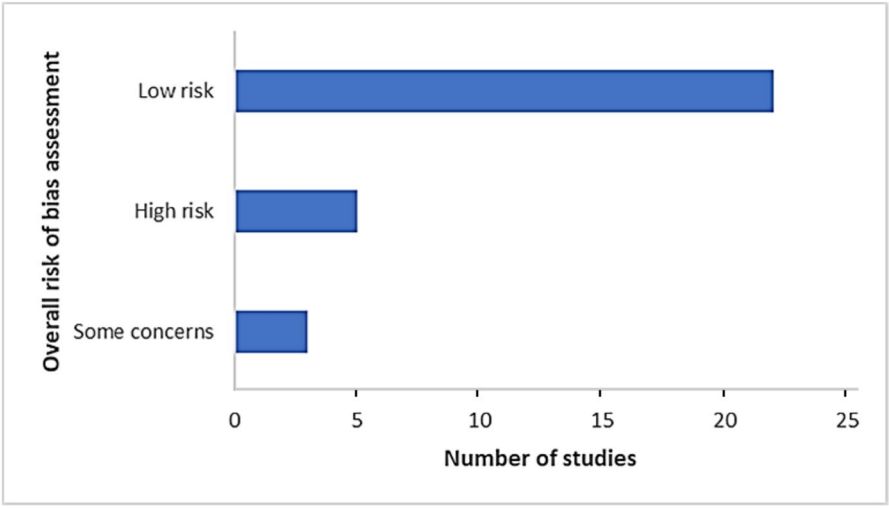


Fig. 7 Overall risk of bias assessment of the included studies

Boguszewska-Mańkowska 2024; Dhiman et al. 2024). This sharp increase in the twenty-first century can be attributed to the rapid expansion of the potato processing industry (French fry) where specific regulations were enacted to ensure that quality of potato tubers is maintained. Specifically, the USDA standards have determined that the proportion of tubers exhibiting defects in processing should not exceed 10%, of which not more than 5 and 2%, respectively, should have defection within the vascular ring and freezing injury (Ngobese 2014). Hence, in reaction to such laws and policies more studies have been carried out to address potato tuber appearances.

On the other hand, the geographical distribution of these studies reveals a higher concentration in the Northern America and Asian region while there were few studies in Africa. This distribution highlights the regional research gaps in Africa, revealing dearth of information on critical issues of production which

may affect productivity of the potato crop. It can be argued that, in principle there might not be any discrepancy among studies addressing tuber cracking, but recently there has been a high demand of washed potatoes in America and most European countries and the European commission has made it a mandate for potatoes to be washed (Commission of the European Union 2007; Fiers et al. 2010). As opined by Fiers et al. (2010), this radical procedure by the commission has adverse effects of highlighting tuber skin defects and as a consequence, the visual quality of tubers has become a very important aspect on marketability. Therefore, more research has been carried out in these regions to address the arising problems and ensure marketability and profitability of potatoes. Similarly, research has indicated that in South Africa, consumers are also now demanding for washed potatoes, hence the surge in research work for tuber blemish and cracking (Muzhinji et al. 2014; Gush 2020).

Type of Cracking

Results indicated that most studies did not disclose the type of cracking observed but just generalised it as growth cracking. This can be attributed to the fact that there has been limited research in regards to categorising types of tuber cracking which led to a dearth of information (Fiers 2011; Zimudzi et al. 2017). The results are supported by Fiers et al. (2008), who opined that tubers are affected by either typical or atypical blemishes, where the typical are the most commonly researched and their causal agents have been established while the atypical are still unknown, and sometimes putative and not scientifically identified. Therefore, it could have been difficult for most authors to specifically mention the type of cracking observed and ended up just saying growth cracking. This shows a serious research gap in the consensual scientific classification nomenclature of potato tuber cracking.

However, a few studies managed to identify the type of cracking and results of this systematic review indicated that a certain type of tuber cracking was consistent with certain conditions (Table 3). For instance, corky cracks and star-like lesions were reported to be associated with fungal pathogen attacks (Fiers et al. 2010; Zimudzi et al. 2017). Similarly, Muzhinji et al. (2014), Zimudzi et al. (2017), and Gush (2020) reported that dry-core blemishes like corky and star-like lesions are mostly associated with *R. solani*. Conversely, some authors argue that these corky layers seem to only appear when the tuber is mechanically or naturally wounded, ruling out pathogens to be the primary cause of the corky cracks but rather deeming it a secondary infection (Nærstad et al. 2012). This is because, tuber wound responses and wound healing involve many biological processes, but the most important is wound-induced suberization which normally occurs when and whenever the plant needs to form a physical barrier. Wounding activates superoxide radical formation that may have a role in the suberin synthesis. In support of this opinion, Nærstad et al. (2012) indicated that atypical blemishes offer entry points for pathogens that may lead to more severe disease symptoms. Similarly, other authors quoted corky crack as a physiological reaction to growth stress, such as water fluctuation and irregular water uptake during the growing

season (Zotarelli et al. 2012; Gush 2020; Kumar et al. 2021). Accordingly, during a period of drought the tuber stops growing, and when rewatered the water uptake induces a rapid rehydration of the tuber and the internal turgor pressure becomes stronger than the peridermal resistance, causing splitting of cells. The periderm breaks and heals progressively afterwards leaving a rough corky skin appearance (Zotarelli et al. 2012; Gush 2020; Kumar et al. 2021). Therefore, these suggestions indicate that both abiotic and biotic factors play a critical role in the development of corky cracks and under such circumstances, it is practical to speculate that corky cracks may have more than one causal agent from both microbial and abiotic origin.

Another outstanding type of cracking is the irregular V-shaped groove or polygonal cracking. This was reported to be associated with higher rates of fertilizer (Harper et al. 1963). This type of cracking was described to resemble a shape that is formed when a fine-bladed knife is pressed along the tuber leaving a widened irregular V-shaped groove (Harper et al. 1963). In some instances, this type of cracking is described as a crack that starts at the bud or apical end of the potato and extends lengthwise and is well healed with intact skins and the severity varies depending on the stage of growth during the initial cracking occurred (Nxumalo 2018; Hill et al. 2021).

Other studies however, have suggested that V-shaped cracks are associated with high moisture content or excess organic matter in the soil (Selman et al. 2008; Zotarelli et al. 2012). In support of this, Fiers et al. (2010) reported that high moisture and a physiological reaction of the plant could be the cause of the irregular polygonal symptom on potato tubers. Kumari and Sharma (2025) reported that this type of cracking can be due to fluctuations in soil moisture levels, when a dry spell is followed by heavy rainfall or excessive irrigation leading to rapid moisture absorption, accelerated growth, and a sudden increase in size. These results conclusively concur with Kumar et al. (2021), who reported that large growth cracks are due to desynchronised growth between inner and outer tuber tissue which is caused by rapid and uneven uptake of water. This sudden rapid growth of internal tuber tissue or bursting causes shallow or deeper longitudinal fissures that can extend the entire length of the tuber.

Canoe-shaped, surface cracking and elephant hide were reported to be associated with pathogen infections. Specifically canoe-shaped cracking was reported to be more associated with PVY foliar infection (Carnegie and McCreath 2010; Inglis and Gundersen 2015). This was further supported by Benedict et al. (2015) who ruled out the well-known reports that cracking in general is caused by rapid uptake of water into the tubers after re-wetting dry fields (MacKerron and Jefferies 1985). In their findings, evidence showed that canoe-shaped cracking was more associated with plants showing mosaic symptoms, and they went on to claim that their findings were the first report to show that infection by mosaic-causing virus (PVA, PVV, PVY) can affect tuber quality and increase the incidences of tuber cracking.

Elephant hide cracking was reported to be more associated with *R. solani* or *Streptomyces* species (Harper et al. 1963; Zimudzi et al. 2017; Gush 2020). These findings corroborate the findings of Muzhinji et al. (2014), who reported elephant hide symptoms to be related to *R. solani* AG3-PT. Consequently, these findings overwrite earlier research (Fiers et al. 2010), that failed to prove Koch's postulate and endorsed that *R. solani* can cause elephant hide and tuber cracking in potatoes.

Other studies reported surface or skin cracking to be associated with moisture stress (Zimmerman-Gries and Blodgett 1963; Jiang et al. 2022). Jiang et al. (2022) described the skin cracking as shallow cracks on the tuber skin which present a rough, latticed tuber skin, while Zimmerman-Gries and Blodgett (1963) described it as the cracks that extend deeper, resembling scars on the tuber surface. These studies showed evidence of the severity differences in potato skin cracking, corroborating reports of several authors (Selman et al. 2008; Zotarelli et al. 2012; Kumari and Sharma 2025).

Agronomic Intervention and Other Categories Associated with Tuber Cracking

This systematic review examined four interventions that were evaluated in relation to tuber cracking (Table 3). The most evaluated interventions were the management/agronomic practices effects on potato tuber cracking and several issues were evaluated under this category. These include fertilizer rates or type, moisture stress, irrigation method, herbicides, cover crops, production systems, and plant spacing. Studies that combined interventions formed the second category followed by those that examined association between pathogen or disease infections and tuber cracking. The least represented category was focusing on heat stress and varietal influences on tuber cracking (Table 3).

Fertilization

From the management or agronomic practices, most studies were focusing on fertilizer rate or type, with Boron and NPK being specifically explored (Table 3). Application of higher rates of NPK fertilizer has been reported to improve yield in potatoes; however, our review indicated that there are negative effects related to tuber skin quality which ultimately results in marketable yield reduction. Specifically, higher rates of nitrogen (N) resulted in higher percentage of malformed, dumbel and cracked tubers (Painter and Augustin 1976). This is because higher doses of N fertilizer cause excessive tuber growth which results in tuber cracking due to immense internal pressure beyond the tensile strength of surface tissue during tuber development (Harper et al. 1963; Kumar Chongtham and Patel 2016). Additionally, method of fertilizer application proved to influence tuber skin quality (Painter and Augustin 1976), and banding of nitrogen was reported to produce more tubers with growth cracks, culls and reduced yield when compared to broadcasting. This was attributed to the fact that banding enhances uptake of N on concentrated regions, hence broadcasting was recommended (Painter and Augustin 1976).

Most studies evaluated the effects of boron, and reported that boron deficiency in potatoes resulted to highest number of cracked tubers that are not marketable (Table 3). This can be attributed to the breakdown of tissue of boron-deficient plants, which rupture the cell wall and cause cracking (Dhiman et al. 2024). However, the combination of recommended rates of NPK and boron fertilizer resulted in reduction of cracking in potato tubers, because boron alone does not have a direct influence on yields or related attributes of potato but rather plays a supplementary role

(Chongtham et al. 2018). When boron is applied, it enhances calcium absorption and accumulation in cell walls, which improves formation of cell walls with better functioning and strength while reducing internal breakdown of tubers in potato (Chongtham et al. 2018; Dash 2018). It was noted that compared to soil application, foliar application of boron is more effective in reducing the incidences and severity of tuber cracking due to continuous availability of nutrients during tuber bulking phases. Unlike when soil-applied boron faces more resistance due to the antagonistic effects of macronutrients like phosphorus, making it unavailable for uptake (Chongtham et al. 2018; Dash 2018; Dhiman et al. 2024).

Time of Planting and Irrigation

Results of this review indicated a relationship between skin defects and rainfed crops, late-planted and drip-irrigated crops. It was reported that air injection of subsurface drip irrigation can reduce external defects such as growth cracks, knobs and misshapes on potato tubers (Essah and Holm 2020). In addition, corky cracks were reported to be more associated with moisture stress related to rainfed production. This is because tubers of rainfed crops form more suberized cell layers which create phellem, a defensive layer which possesses a waxy component that protects then against cell desiccation, and a protective suberin biopolymer, which provides a barrier to pathogens and other intrusions. This serves as a protective barrier in the periderm tissue layers, controlling water and ion transport, restricts infection, maintains integrity and protects against biotic and abiotic stresses (Jiang et al. 2022). On the other hand, using drip irrigation resulted in cracked tubers compared to furrow irrigation (Singh and Sadawarti 2024).

Ridging and Cover Crops

Ridging and the use of cover crops reduced cracking, malformed and enhanced crop quality (Henriksen et al. 2007). The results suggest that both the belowground material and the aboveground litter left behind after harvesting the cover crop for hay can play an important role, potentially contributing to soil biological and biogeochemical factors that may be providing the mechanism for the potato physiological response. However, time of ridging is very important; early ridging should be avoided in sandy soils because it promotes leaching of essential nutrients (Henriksen et al. 2007). Depending on soil cover available, ridging in winter increased nitrogen availability which results in higher yields as compared to ridging in autumn. Use of cover crops has a potential to improve potato tuber quality by reducing incidences of skin defects such as cracks, knobs, and misshapes (Essah et al. 2012). Although there is no clear understanding on how cover crops reduce cracking, the possible mechanisms could include but are not necessarily limited to soil biology, suppression of diseases, biogeochemistry pathways and availability of macro and micro nutrients, and the physiological responses by the crop. Results also indicated that the effectiveness of this mechanism is dependent on the type of cover crop used (Henriksen et al. 2007; Essah et al. 2012).

Herbicide Application and Plant Spacing

Herbicide drift and residual effect can significantly impact potato production, by reducing growth and causing growth cracking (Reis et al. 2018). Specifically, sulfonylureas, imidazolinones, auxin mimics, glyphosate, tembotrione, and atrazine have been reported to cause serious impacts on subsequent potato tubers if not properly used or if used in heavy clay soils (Reis et al. 2018). These results are substantiated by the restriction period information for the cultivation of potatoes after application of certain products. For instance, Reis et al. (2018) reported that in the USA, there are some restriction period information included on the label for tembotrione (Laudis®), yet in other countries it is not stated (Reis et al. 2018). This indicates some loop holes in chemical industry which in turn affect potato producers hence, research needs to be carried out to establish the effects of herbicides on tuber quality.

Results of this review established that in-row and interrow spacing of potato can also have significant influence on the quality of tubers produced. Although wider spacing results in large tubers, it also leads to hollow heart and growth cracking of potato tubers (Washington and Edmundson 1935). This is because, widely spaced plants tend to grow rapidly and bigger due to reduced competition for water and nutrients. Hence it might be the possible cause for cracking in widely spaced potato tubers, which received sufficient nutrients and water and expanded rapidly causing bursting of the periderm. This is supported by Kumar et al. (2021) who opined that cracking of tubers is common in large expanded tubers. Therefore, it is very important to maintain moderate spacing so as to reduce these internal and external effects on potato tubers.

Production System

It was established that a production system can significantly influence potato tuber quality. Conventional production system promotes rapid crop growth which are susceptible to cracking, while organic produce small tubers which are less prone to cracking but not favourable on the market (Zarzyńska and Boguszewska-Mańkowska 2024). This can be ascribed to the fact that conventional systems are characterised by the use of synthetic fertilizer that are readily available for crop uptake while organic systems depend on use of organic manures that are not easily available for plant uptake (Charachimwe et al. 2018). Due to slow release of nutrients in organic system, potatoes tend to grow slow-producing small tubers that are not prone to cracking. These reports are supported by several authors who reported that large and elongated tubers are more susceptible to cracking (Harper et al. 1963; Parker 1986; Kumar et al. 2021; Siano et al. 2024).

Moisture Stress

Most of the reviewed studies indicated an increase in the number of deformed and cracked tubers when plants were imposed to moisture stress. However, it was

established that the extent, type and intensity of cracking or deformation differ with time when stress is imposed (Robins and Domingon 1956; Kumar et al. 2021). According to Kumar, tuber cracking is more severe when moisture stress is imposed at tuber enlargement stage than during tuber maturation stage (Kumar et al. 2021). This is supported by Robins and Domingon (1956), who reported that moisture deficits during mid-season followed by adequate moisture results in growth cracking. On intensity of the cracking, large growth cracks are reported to be due to desynchronised growth between inner and outer tuber tissue which is caused by rapid and uneven uptake of water (Zotarelli et al. 2012; Kumar et al. 2021). As opined by Kumar et al. (2021), the uneven availability of soil moisture and rapid, uneven uptake of water cause sudden rapid growth of inner tissues which is not consistent with the tensile strength of the surface tissues, hence causing bursting. To control cracking related to moisture stress, it was widely reported that maintaining even soil moisture condition and application of correct dosages of fertilizer during the entire growth stage is essential (Selman et al. 2008; Zotarelli et al. 2012). Contrary, in the same report by Kumar et al. (2021), it was concluded that cracking cannot be strictly tied to moisture stress as other stresses like heat can also play a significant role. In support, MacKerron and Jefferies (1985), in his experiment, concluded that although the occurrence of growth cracking is generally associated with fluctuating water stress, results of their findings failed to certify this. In his argument, increased water uptake and rapid tuber growth may be necessary for the onset of growth cracking, but they are not in themselves sufficient conditions. This clearly indicates a research gap where the real cause of tuber cracking needs to be established.

Plant Pathogenic Fungi and Viruses

Results of this review indicated that tuber cracking is associated with incidences and severity of certain pathogens (Table 2). Among the pathogens, viruses (PVA, PVV, PVY) were the most reported, with PVY being the most frequently evaluated. This can be attributed to the fact that among the viruses in potato, PVY is the oldest and most studied due to the rampant spread of the new recombinant strains in Northern America (Carnegie and McCreath 2010; Benedict et al. 2015). Despite, several studies reporting an association between PVY plant infections and subsequent cracking of progeny tubers, there was no specific explanation on the physiological mechanism of how the virus causes physical fractures in all the studies. However, it is important to note that the association is determined by several factors such as point of virus introduction, cultivar, seasonal virus titter levels and cultural management practice (Carnegie and McCreath 2010; Benedict et al. 2015). This lack of clear explanation on the physiological mechanism of the virus and cracking shows a huge research gap that need to be addressed.

Although studies did not show any causality or relationship between fungal strain or a complex of strains and the occurrence of the blemishes (Zimmerman-Gries and Blodgett 1963; Fiers et al. 2010), binucleate *Rhizoctonia* (BNR) AG-A, BNR AG-R and *Rhizoctonia solani* were the most predominant fungal pathogens isolated from the

cracked tubers (Carnegie and McCreath 2010; Inglis and Gundersen 2015; Zimudzi et al. 2017; Inglis et al. 2019; Gundersen et al. 2019; Gush 2020). These findings corroborate the findings of Gush (2020), who indicated that frequently isolated pathogens from atypical blemishes fall in the genera *Rhizoctonia*, *Fusarium*, *Alternaria*, *Penicillium*, *Clonostachys*, and *Streptomyces.* Interestingly, irregular polygonal sunken, corky lesions were observed on non-inoculated plants, suggesting that some atypical blemish could as well be a reaction of the plant to stressful environmental conditions, supporting claims that *Fusarium* species are opportunistic pathogens on plant surfaces, attacking plant tissues that are weakened by primary pathogens or abiotic stresses (Fiers et al. 2008; Muzhinji et al. 2014; Gush 2020). These findings diverge from the long-standing assumptions that, "tuber cracking is solely influenced by moisture stress or water fluctuation" (MacKerron and Jefferies 1985; Inglis and Gundersen 2015). In support to this, Benedict et al. (2015) indicated that from time immemorial tuber cracking has been believed to be caused by rapid water uptake after re-wetting dry fields, but their findings revealed otherwise. There is a possible threat to most countries who share germplasm especially in some parts of Africa where phytosanitary policies are just a decorate of the law. This is because earlier studies have demonstrated seed borne disease transmission (Inglis and Gundersen 2015).

Heat Stress

From the studies reviewed, only one study evaluated the impacts of heat stress on tuber cracking (Table 3). It was established that heat stress can increase the incidence of malformation, growth cracks, spindled tubers and second growth in tubers reducing the total and marketable yields (Siano et al. 2024). This is supported by earlier research that reported tuber disorders at different phenological stages due to heat stress (Nxumalo 2018). Sensitivity of potato to heat stress in different varieties has been associated with specific characteristics such as reduction in yield due to the redirection of photo assimilates to plants shoots rather than tubers. However, most researchers have focused on the effects on internal defects such as hollow heart, stem ends and internal necrosis, yet research on external defects are rare (Siano et al. 2024; Gautam et al. 2024). A positive correlation between hollow heart and growth cracks and also between hollow heart and internal heat necrosis was reported in heat stressed plants (Siano et al. 2024; Gautam et al. 2024).

Varietal Differences

Only one study reported the effects of varietal differences on tuber cracking as a stand-alone factor (Table 3). Most studies combined variety with other categories, but generally reports indicated that cultivars possess diverse levels of tolerance to tuber cracking. Results indicated that cultivars with large and elongated tubers are more susceptible to cracking (Harper et al. 1963; Parker 1986; Kumar et al. 2021; Siano et al. 2024). This is supported by the findings of the survey that was carried out in Swaziland that indicated that varieties with larger tubers like Mondial were more susceptible to cracking (Nxumalo 2018). However, tuber cracking on certain cultivars indicated

that cultivars may be susceptible under certain conditions, for instance a greenhouse pathogenicity study carried out to test corky cracks on Mondial variety, found out that a combination of *R. solani* strains was needed to consistently produce corky crack in the variety Mondial (Gush 2020). This suggests that certain varieties might be susceptible to cracking but only under certain conditions which trigger cracking.

Limitations of the Review

To our knowledge, this is the first systematic review exploring the causes of tuber cracking to date. However, from a globally scooped review only 30 studies met the inclusion criteria for this systematic review. This can be as a result of the inclusion criteria which only included studies with empirical evidence excluding reports and fact sheets. However, from the literature it was noted that most findings on potato tuber cracking are reported in disease bulletins or fact sheets which lack empirical evidence that can be used for a review or neither meta-analysis. Hence, this lack of empirical evidence on tuber cracking shows a serious research gap that requires to be explored to provide evidence-based recommendations. Additionally, due to institutional limitation a few studies were not accessed and excluded from the review.

Out of the 30 studies selected for the systematic review, 10 did not report either the proportion or the number of tubers cracked. Therefore, it was not possible to include them in the meta-analysis. More rigorous subgroup analysis could also not be performed due to the small sample sizes available in the different variables (e.g., varietal differences, agronomic practices, pathogens, etc.) implicated in tuber cracking. Exhaustive subgroup analysis could not be performed with other categories because the number of studies per category were too few, i.e., either one or two. Lack of standardised methods to enumerate and report tuber cracking appears to have caused variability in the studies on tuber cracking.

Conclusions

Based on the findings of this review, it is concluded that tuber cracking is not a new phenomenon as research on this topic dates back to the early twentieth century. However, the rapid growth of the potato processing industry has prompted the introduction of new regulations and policies which in turn have stimulated research aimed at maintaining tuber quality. Although tuber cracking is mostly reported in the European countries, results of this review indicated that reports are increasing in the African region and specifically in southern Africa. This review has identified several causes. Moisture stress, heat stress, fungal and viral pathogens, agronomic management practices including fertilization, spacing, irrigation and herbicide application, and varietal differences were implicated in the etiology of tuber cracking. Some researchers regard cracking as a biotic disorder caused by viral or fungal pathogens, while others regard it as a physiological disorder caused by abiotic effects. It was not possible to conclusively establish the real cause of cracking in this review. It is also possible that the causal agents could be context-specific. Therefore, future research is highly recommended to establish the

real causes of tuber cracking and the context in which it occurs. The use of standardised methods is also recommended to quantify and report tuber cracking in a consistent manner.

Funding This research was funded by the Centre of Excellence in Agri-Food Systems and Nutrition (CE-AFSN) under World Bank in Mozambique.

Data Availability The data supporting this study will be shared upon request to the corresponding author.

Declarations

Ethical Approval and Consent to Participate Not applicable.

Consent for Publication The authors agreed to publish this paper.

Competing interests The authors declare no competing interests.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

References

Benedict CA, McMoran DW, Inglis DA, Karasev AV (2015) Tuber symptoms associated with recombinant strains of Potato virus Y in specialty potatoes under Western Washington growing conditions. Am J Potato Res 92(5):593–602. https://doi.org/10.1007/s12230-015-9472-6

Carnegie SF, McCreath M (2010) Mosaic virus symptoms in potato crops and the occurrence of growth cracking in tubers. Potato Res 53(1):17–24. https://doi.org/10.1007/s11540-010-9147-0

Charachimwe R, Tembo L, Mhungu S (2018) Response of pig weed *Amaranthus cruentus* to organic and inorganic fertilizers. Int J Agron Agric Res 13(1):1–10

Chongtham SK, Patel JK (2016) Effect of different fertility levels on tuber yields, input use efficiency and economics of potato variety Kufri Chipsona-3. Int J Agric Sci 8:2066–2068. https://doi.org/10.13140/RG.2.2.20591.48809

Dash SK (2018) Management of tuber cracking in potato (Solanum tuberosum L.) cv. Kufri Chipsona-3 through boron application. Dissertation, Orissa University of Agriculture and Technology. Accessed 28 June 2025.

Dharmasena WGCP, Herath HMSK, Ranawana SRWMCJK, Wanigasekara RBHK (2024) Determination of effective nitrogen level to optimize yield and quality of potato varieties of Connect and Masai. Trop Agric Res Ext 27(4):204–212. https://doi.org/10.4038/tare.v27i4.5716

Dhiman D, Kalia A, Sharma SP, Taggar MS, Dheri GS (2024) Nano-boron foliar application reduced the proportion of cracked tuber yield in potato. Biocatal Agric Biotechnol 58:103182. https://doi.org/10.1016/j.bcab.2024.103182

Edmundson WC (1935) Distance of planting Rural New Yorker No. 2 and Triumph potatoes as affecting yield, hollow heart, growth cracks, and second-growth tubers. US Department of Agriculture Circular No 338.

Essah SY, Holm DG (2020) Air injection of subsurface drip irrigation water improves tuber yield and quality of Russet Potato. Am J Potato Res 97(4):432–438. https://doi.org/10.1007/s12230-020-09792-2

Essah SYC, Delgado JA, Dillon M, Sparks R (2012) Cover crops can improve potato tuber yield and quality. Hort Technology 22(2):185–190. https://doi.org/10.21273

FAOSTAT (2025) FAOSTAT: Production- Crops and livestock products. Available online at: https://www.fao.org/faostat/en/#data/TCL. Accessed 28 August 2025

Fiers M, Chatot C, Edel-Hermann V, Le Hingrat Y, Konate AY, Gautheron N, Guillery E, Alabouvette C, Steinberg C (2010) Diversity of microorganisms associated with atypical superficial blemishes of potato tubers and pathogenicity assessment. Eur J Plant Pathol 128(3):353–371. https://doi.org/10.1007/s10658-010-9657-2

Fiers M, Chatot C, Edel-Hermann V, Guillery E, Le Hingrat Y, Gautheron N, Alabouvette C, Steinberg C (2008) Identification of soil pathogens associated with superficial blemishes on potato tubers. InPotato for a changing world 2008; 17. Treiennal Conference of European Association for Potato Research: Brasov 2008, Brasov, ROU, 2008–07–06–2008–07–10, p. 130 2008.

Gautam S, Pandey J, Scheuring DC, Koym JW, Vales MI (2024) Genetic basis of potato tuber defects and identification of heat-tolerant clones. Plants Basel 13(5):616. https://doi.org/10.3390/plants13050616

Ghongtham S, Patel J, Zapadiya D (2018) Effect of boron application on yield, quality and economies of potato (Solanum tuberosum L). Gau Res J 43:62–65

Gundersen B, Inglis DA, Pavek M, Karasev AV (2019) Foliar and tuber reactions of three strains of Potato virus Y on five fresh market potato cultivars through three successive potato generations. Am J Potato Res 96(6):519–531. https://doi.org/10.1007/s12230-019-09738-3

Gush SL (2020) Elucidating the role of microbial factors and water stress in causing corky crack blemishes on potato tubers in South Africa (Doctoral dissertation, University of Pretoria. Accessed 29 June 2025.

Harper PC, Boyd AEW, Graham DC (1963) Growth cracking and bacterial soft rot in potato tubers. Plant Pathol 12(4):139–142. https://doi.org/10.1111/j.1365-3059.1963.tb00235.x

Harzing AW (2007) Publish or Perish, version 8.18.5252.9447 Computer software, available online https://harzingcom/resources/publish-or-perish. Accessed 27 June 2025

Henriksen CB, Rasmussen J, Mølgaard JP (2007) Potato tuber yield and quality and soil inorganic nitrogen as affected by timing of ridging with and without catch crops. Soil Tillage Res 94(1):36–46. https://doi.org/10.1016/j.still.2006.06.009

Hill D, Nelson D, Hammond J, Bell L (2021) Morphophysiology of potato (*Solanum tuberosum*) in response to drought stress: paving the way forward. Front Plant Sci 11:597554

Inglis DA, Gundersen B (2015) Impact of Potato virus Y on the quality of specialty potato tubers. In Washington-Oregon Potato Conference, Kennewick, Washington pp7–14).

Inglis DA, Gundersen B, Beissinger A, Benedict C, Karasev AV (2019) Potato virus Y in seed potatoes sold at garden stores in western Washington: prevalence and strain composition. Am J Potato Res 96(3):235–243. https://doi.org/10.1007/s12230-018-09695-3

Jamovi (2024) Open statistical software for the desktop and cloud https://www.jamovi.org/. Accessed 10 October 2025

Jiang M, Shinners-Carnelley T, Gibson D, Jones D, Joshi J, Wang-Pruski G (2022) Irrigation effect on yield, skin blemishes, phellem formation, and total phenolics of red potatoes. Plants (Basel) 11(24):3523. https://doi.org/10.3390/plants11243523

Kumar S, Kumar D, Singh B, Singh YP, Singh P, Kumar A (2021) Effect of water stress on tuber quality (dumbel, pointed, cracks and total deformed tubers) in potato (*Solanum tuberosum* L.). Ann Hortic 14(1):84–88. https://doi.org/10.5958/0976-4623.2021.00016.5

Kumari S, Sharma A (2025) Physiological disorders of potato: their symptoms, causes and management. GreenariA 03(10):55–58

MacKerron DKL, Jefferies RA (1985) Observations on the effects of relief of late water stress in potato. Potato Res 28(3):349–359. https://doi.org/10.1007/BF02357588

Mansour FYO, Abu El-Fotoh HM (2019) Effect of planting date, irrigation level and foliar spray with calcium and/or boron on potato crop performance 2. Yield and its components, cracking phenomenon and tuber quality. In J Product Dev 24(1)

Muthoni J, Shimelis H (2023) An overview of potato production in Africa. In: Potato Production Worldwide. Elsevier, pp 435–456. https://doi.org/10.1016/b978-0-12-822925-5.00020-7

Muzhinji N, Woodhall JW, Truter M, Van der Waals JE (2014) Elephant hide and growth cracking on potato tubers caused by *Rhizoctonia solani* AG3-PT in South Africa. Plant Dis 98(4):570–570. https://doi.org/10.1094/PDIS-08-13-0815-PDN

Nærstad R, Dees MW, Le VH et al (2012) Occurrence of skin blemish diseases (scab and scurf) in Norwegian potato production. Potato Res 55:225–239. https://doi.org/10.1007/s11540-012-9221-x

Ngobese NZ (2014) Characterisation of potato cultivars recently released in South Africa for frozen french fries. Doctoral dissertation, University of KwaZulu-Natal Pietermaritzburg. Accessed 29 June 2025.

Nogueira FD, De Pádua JG, Guimarães PTG, De Paula MB, Silva EB (1996) Potato yield and quality under potassium and gypsum levels in Southeastern Brazil. Commun Soil Sci Plant Anal 27(9–10):2453–2475. https://doi.org/10.1080/00103629609369715

Nxumalo KA (2018) Common physiological disorders of white/Irish potato (*Solanum tuberosum*) tubers produced in Swaziland: a review. Agronomy & Agricultural Science 1:1–9. https://doi.org/10.24966/AAS-8292/100001

Page MJ, McKenzie JE, Bossuyt PM et al (2021) The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 372:n71. https://doi.org/10.1136/bmj.n71. (**Accessed 18 June 2025.**)

Painter CG, Augustin J (1976) The effect of soil moisture and nitrogen on yield and quality of the Russet Burbank potato. Am Potato J 53(8):275–284. https://doi.org/10.1007/BF02855025

Parker A (1986) Evaluation of potato cultivar resistance to common scab, black scurf and tuber cracking. Ann Appl Biol 108:158–159. https://doi.org/10.1111/aab.1986.108.s1.158

Reddy BJ, Mandal R, Chakraborty M et al (2018) A review on potato (*Solanum tuberosum* L.) and its genetic diversity. International Journal of Genetics 10:360. https://doi.org/10.9735/0975-2862.10.2.360-364

Reis MR, Aquino LÂ, Melo CAD, Silva DV, Dias RC (2018) Carryover of tembotrione and atrazine affects yield and quality of potato tubers. Acta Sci Agron 40(1):35355. https://doi.org/10.4025/actasciagron.v40i1.35355

Ríos D, Devaux A, Ruiz de Galarreta JI (2023) Ancient potato varieties of the Canary Islands: their history, diversity and origin of the potato in Europe. Potato Res. https://doi.org/10.1007/s11540-023-09672-2

Robins JS, Domingo CE (1956) Potato yield and tuber shape as affected by severe soil-moisture deficits and plant spacing. Agron J 48(11):488–492. https://doi.org/10.2134/agronj1956.00021962004800110003x

Robinson A (2018) Weird and Wild World of Physiological Disorders Extension Potato Agronomist NDSU / U of M @spudology

Scott GJ, Labarta R, Suarez V (2013) Benchmarking food crop markets in Southern Africa: the case of potatoes and potato products 1961–2010. Am J Potato Res 90:497–515

Selman L, Andrews N, Stone A, Mosley A (2008). What's Wrong with My Potato Tubers? Diagnosing Tuber Abnormalities in Western Oregon and Washington. In Oregon State University Extension Service and Western Region Sustainable Agriculture Research and Education. http://extension.oregonstate.edu/catalog/pdf/em/em8948-e.pdf. Accessed 12 August 2025.

Siano AB, Roskruge N, Kerckhoffs H, Sofkova-Bobcheva S (2024) Effects of abiotic stress associated with climate change on potato yield and tuber quality under a multi-environment trial in New Zealand. Potato Res 67(4):1603–1624. https://doi.org/10.1007/s11540-024-09695-3

Singh SP, Sadaworti M, Sharma S, Singh R, Rawal S, Kumar M, Sharma J, Katare S (2024) Effect of irrigation methods and nutrient management practices on production and economics of potato under different preceding crop sequences in central India. Potato Journal 51(1). https://doi.org/10.56093/potatoj.v51i1.142833

Spooner DM, Ghislain M, Simon R et al (2014) Systematics, diversity, genetics, and evolution of wild and cultivated potatoes. Bot Rev 80:283–383. https://doi.org/10.1007/s12229-014-9146-y

Vos J (1997) The nitrogen response of potato (*Solanum tuberosum* L.) in the field: nitrogen uptake and yield, harvest index and nitrogen concentration. Potato Res 40(2):237–248

Zarzyńska K, Boguszewska-Mańkowska D (2024) Commercial quality of potato tubers of different varieties from organic and conventional production system. Agronomy Basel 14(4):778. https://doi.org/10.3390/agronomy14040778

Zimmerman-Gries S, Blodgett EG (1963) Some skin defects of potatoes in Israel. Eur Potato J 6(3):191–200. https://doi.org/10.1007/BF02365787

Zimudzi J, Coutinho TA, Van Der Waals JE (2017) Pathogenicity of fungi isolated from atypical skin blemishes on potatoes in South Africa and Zimbabwe. Potato Res 60(2):119–144. https://doi.org/10.1007/s11540-017-9345-0

Zotarelli L, Hutchinson C, Byrd S, Gergela D, Rowland DL (2012) Potato physiological disorders - growth cracks. HS930/HS182, Edis 2012(5):1–2. https://doi.org/10.32473/edis-hs182-2012

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Authors and Affiliations

Reason R. Charachimwe[1,2] · Pauline Aarakit[1,2] · Arsenio D. Ndeve[1] · Rogerio M. Chiulele[1,2] · J. Martin Steyn[3] · Gudeta W. Sileshi[4]

✉ Reason R. Charachimwe
reaschara@gmail.com

Pauline Aarakit
paulineaarakit14@gmail.com

Arsenio D. Ndeve
ndevegod@gmail.com

Rogerio M. Chiulele
chiulelerogerio@gmail.com

J. Martin Steyn
martin.steyn@up.ac.za

Gudeta W. Sileshi
sileshiw@gmail.com

[1] Faculty of Agronomy and Forestry Engineering, Eduardo Mondlane University, Avenida Julius Nyerere, No. 3453, Campus Universitario, Maputo, P.O. Box 257, 1100, Mozambique

[2] Centre of Excellence in Agri-Food Systems and Nutrition (CE-AFSN), Eduardo Mondlane University, 25 De Junho Square, Rectorate Building, 5th floor, Maputo,, P.O. Box 257, Mozambique

[3] Department of Plant and Soil Sciences, University of Pretoria, Pretoria, South Africa

[4] Department of Plant Biology and Biodiversity Management, Addis Ababa University, Addis Ababa, Ethiopia