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TEMPERATURE EFFECTS ON GROWTH RATES OF *Aspergillaceae* FUNGI: A COMPARATIVE SYSTEMATIC REVIEW OF *Aspergillus* AND *Penicillium* GENERA

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ABSTRACT
This systematic review explores the impact of temperature variations on the growth of *Aspergillaceae* fungi, focusing on how environmental temperature influences the growth rates of the genera *Aspergillus* and *Penicillium*. By analyzing studies published between 2015 and 2025, the review examines fungal responses to low and high particularly those beyond their optimal growth conditions. Research articles were systematically gathered from Google Scholar, ScienceDirect, Web of Science, PubMed, and SpringerLink to identify the key temperature conditions affecting the growth of *Aspergillus* and *Penicillium*. Using PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines, 10 studies were selected based on criteria such as temperature variation, relative humidity, sporulation/ colony diameter, and exposure duration. Findings indicate that *Aspergillus* and *Penicillium* exhibit growth responses influenced by exposure duration, with *Aspergillus* achieving faster and broader thermal adaptation while *Penicillium* attains optimal growth under humid, moderate conditions. Maximum fungal growth occurred between 10–16 days, with *Aspergillus* shows thriving at warmer temperatures and *Penicillium* shows 0.68-0.85 cm/day favoring humid, moderate conditions, supporting optimal expansion and reflecting their ecological adaptation to environmental factors.

Keywords:
Exposure duration, Relative Humidity, optimal growth, adaptation

INTRODUCTION

The *Aspergillaceae* family, particularly fungi of the genus *Aspergillus*, is widely recognized for its adaptability and extensive roles across environmental, industrial, agricultural, and health-related contexts. These fungi are integral to essential biological processes, including biodegradation, fermentation, and bioconversion, allowing the breakdown of complex organic substrates and the production of valuable enzymes, organic acids, and secondary metabolites. However, they are also capable of producing mycotoxins potent secondary metabolites that can contaminate food and feed, posing serious risks to human and animal health (Siqueira et al., 2023). This dual functionality underscores the importance of understanding the environmental factors that influence their physiology and metabolic output.

Industrial and Biotechnological Relevance. In industrial microbiology and biotechnology, *Aspergillaceae* fungi are exploited for the production of enzymes, organic acids, and bioactive compounds. Temperature is a critical environmental parameter that influences their growth rate, sporulation, enzyme activity, and metabolite synthesis. Optimizing temperature conditions is essential for maximizing industrial yields and ensuring consistent product quality. For example, slight deviations from the optimal temperature can significantly alter enzyme production or fermentation efficiency, affecting industrial processes such as citric acid production and biomass conversion (Okereke et al., 2015; Abdullah et al., 2015). Understanding these temperature-dependent physiological responses allows for the design of controlled cultivation systems that enhance productivity while minimizing undesirable by-products.

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Agricultural and Ecological Implications. In agricultural settings, *Aspergillaceae* fungi, particularly *Aspergillus flavus*, are significant due to their capacity to produce aflatoxins carcinogenic compounds that threaten crop safety and food security. Temperature fluctuations influence aflatoxin biosynthesis, fungal growth, and competitive interactions with other microorganisms, ultimately shaping fungal population dynamics in soil and stored crops (Chai et al., 2023; Abdullah et al., 2015). Managing environmental temperature, alongside other cultivation and storage conditions, is therefore a critical strategy to minimize contamination and protect food quality. Additionally, understanding the ecological responses of *Aspergillaceae* to temperature helps predict their behavior under changing climatic conditions, informing sustainable agricultural practices and risk management strategies.

Health and Safety Considerations. Temperature-dependent growth and secondary metabolite production also have direct implications for public health. High or fluctuating temperatures can increase mycotoxin production, leading to contamination of food and feed with compounds such as aflatoxins that are toxic, carcinogenic, and immunosuppressive. By elucidating how temperature influences these fungi, it becomes possible to develop evidence-based interventions for storage, processing, and handling of agricultural products to reduce exposure and health risks (Abdullah et al., 2015).

Despite extensive individual studies on temperature effects, there is a need for a systematic synthesis to clarify patterns and consolidate current knowledge. This review employs a PRISMA-guided (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) approach, analyzing studies published between 2015 and 2025 from multiple databases, including Google Scholar, ScienceDirect, Web of Science, PubMed, and SpringerLink. The focus is on quantitative measures such as colony size, growth rate, spore germination, enzymatic activity, and mycotoxin production (Siqueira et al., 2023; Okereke et al., 2015).

By rigorously applying inclusion and exclusion criteria, this review aims to provide a comprehensive understanding of temperature-dependent responses in *Aspergillaceae* fungi. The findings are expected to inform future research, improve industrial and biotechnological applications, guide agricultural management strategies, and enhance food safety practices. Ultimately, this synthesis highlights the critical interplay between environmental temperature and fungal physiology, emphasizing its relevance across biotechnology, agriculture, and public health domains growth, reproduction, metabolism, and production of secondary compounds in *Aspergillaceae* species. Changes in temperature can markedly affect fungal physiology, impacting not only their growth rates but also the production of enzymes and toxins, which are critical considerations in both applied and medical mycology (Okereke et al., 2015; Abdullah et al., 2015).

Understanding how *Aspergillaceae* fungi respond to temperature changes is essential for improving industrial applications such as fermentation and bioconversion, as well as for devising effective methods to manage fungal contamination in food storage and agriculture. For example, temperature fluctuations can influence the level of aflatoxin produced by *Aspergillus flavus*, a toxin that presents serious health hazards to humans and animals alike (Abdullah et al., 2015). Additionally, temperature affects the competitive abilities and ecological success of these fungi, thereby shaping their population dynamics in both natural and controlled environments (Chai et al., 2023).

Although many individual studies have examined these effects, there is still a need to systematically gather and analyze the existing research to clarify how temperature influences the growth and physiology of *Aspergillaceae* fungi. This review addresses that need by employing a systematic approach guided by PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses). It compiles and critically evaluates studies published between 2015 and 2025 from multiple academic databases such as Google Scholar, ScienceDirect, Web of Science, PubMed, and SpringerLink. The focus is on quantitative measures including colony size, growth rate, spore germination, enzyme activities, and mycotoxin production (Siqueira et al., 2023; Okereke et al., 2015).

Through strict inclusion and exclusion criteria, this review aims to present a comprehensive understanding of how temperature affects *Aspergillaceae* fungi, offering insights that will support future scientific inquiry and practical applications in fungal biology, biotechnology, and food safety.

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OBJECTIVES

This study aims to evaluate the growth and physiological responses of selected *Aspergillaceae* species under varying temperature conditions and exposure durations to determine the factors that promote or inhibit fungal growth and mycotoxin production. Specifically, it seeks to compare the growth rates of different *Aspergillaceae* species, including *Aspergillus flavus*, *A. niger*, and *A. fumigatus*, across a range of temperature settings. In addition, the study aims to assess the effect of exposure duration on fungal proliferation and mycotoxin production. Finally, it intends to identify the specific temperature conditions that either maximize or suppress fungal growth and toxin synthesis.

METHODOLOGY

The study applied a systematic review approach design. The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) was used as a guideline to establish a structured method for identifying, selecting, and assessing relevant publications on the impact of temperature on the growth and development of fungi belonging to the *Aspergillaceae* family, published between 2015 and 2025.

Data Sources

All published studies used in this review were collected using a systematic approach to ensure a thorough and reliable synthesis of the available studies on the effects of temperature on the *Aspergillaceae* growth and metabolism. The process began by selecting a range of academic databases, including Google Scholar, ScienceDirect, Web of Science, PubMed, and SpringerLink, to identify relevant studies. All retrieved publications were systematically evaluated following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to maintain methodological consistency and reliability.

Literature Search

To ensure an effective search strategy, the selected databases were queried using relevant keywords and Boolean operators such as AND and OR. Multiple keyword combinations were employed to retrieve pertinent literature.
The first set of terms targeted temperature effects, fungal physiology, and *Aspergillaceae* growth, incorporating keywords such as "*Aspergillus*," "*Aspergillaceae*," "temperature," "growth rate," and "sporulation."
To align the study with contemporary research trends, the database search prioritized peer-reviewed journal articles and experimental research published between 2015 and 2025 that matched the predefined keywords. To supplement these, books and technical reports related to fungal physiology and environmental microbiology were also included without strict publication year restrictions.
During the initial screening phase, all retrieved publications were evaluated based on title, authors, publication date, and source journals to eliminate duplicates. Irrelevant studies were excluded, and the remaining articles underwent a detailed abstract and full-text review to ensure compliance with the inclusion criteria.

Inclusion and Exclusion Criteria

This review systematically evaluated studies based on inclusion and exclusion criteria to ensure the quality and relevance of selected research. Studies were included if they: (1) Were original research or peer-reviewed experimental studies published between 2015 and 2025; (2) All studies were required to match predefined keywords related to the effects of temperature on the growth, development, and physiological responses of fungi belonging to the *Aspergillaceae* family; (3) Available in full-text English versions; and (4) provided relevant parameters such as colony diameter, growth rate, spore germination percentage, enzyme activity, or mycotoxin production. Additionally, studies examining the physiological or metabolic responses of *Aspergillaceae* species to temperature variations were considered. Studies were excluded if they: (1) were review articles, conference abstracts, or opinion papers without original data; (2) lacked quantitative assessments on the species or strain of *Aspergillus* study; (3) focused solely humidity, pH, or water activity without isolation temperature as a variable; (4) were published before 2015; (5) were not available in English or as full-text publications; or (6) examined factors unrelated to temperature, such as light intensity, substrate composition, or pH, as the primary variable. Furthermore, studies with insufficient methodological details or those conducted under unrealistic or non-reproducible laboratory conditions were excluded to ensure reliability and ecological relevance of the findings.

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Search Results

A total of 87 studies were initially identified through the combination of search terms applied across five academic databases, including Google Scholar, ScienceDirect, Web of Science, PubMed, and SpringerLink. To maintain relevance and focus, the search was limited to peer-reviewed experimental research articles and English-language publications between 2015 and 2025, specifically addressing the effects of temperature on the growth and production of fungi within the *Aspergillaceae* family. This initial search excluded 27 studies that were outside the date range, written in non-English languages, or lacked direct relevance to temperature-dependent fungal growth. After removing 20 duplicate records, 40 studies remained for title and abstract screening. Screening was performed using the predefined inclusion criteria, which required studies to: (1) assess the investigate the influence of temperature on growth, sporulation, or metabolic activity of *Aspergillaceae* species;; (2) identify the specific *Aspergillus* or *Penicillium* species examined; (3) describe temperature conditions or gradients used in the experiment; and (4) report measurable growth or physiological parameters such as colony diameter, growth rate, enzyme activity, or mycotoxin production. Based on these criteria, 30 studies were excluded for reasons such as insufficient quantitative data, lack of temperature parameter reporting, absence of species identification, or focus on non-*Aspergillaceae* fungi. The remaining 10 full-text articles were then assessed for eligibility, all of which met the inclusion criteria and were included in the qualitative synthesis. These studies collectively examined the temperature-dependent growth responses of *Aspergillus* and *Penicillium* species, including *A. flavus, A. fumigatus, A. niger*, *A. ochraceus*, and *P. crustosum*, under a range of environmental and incubation conditions. The identification, screening, eligibility assessment, and inclusion process are summarized in the PRISMA flow diagram (Figure 1).

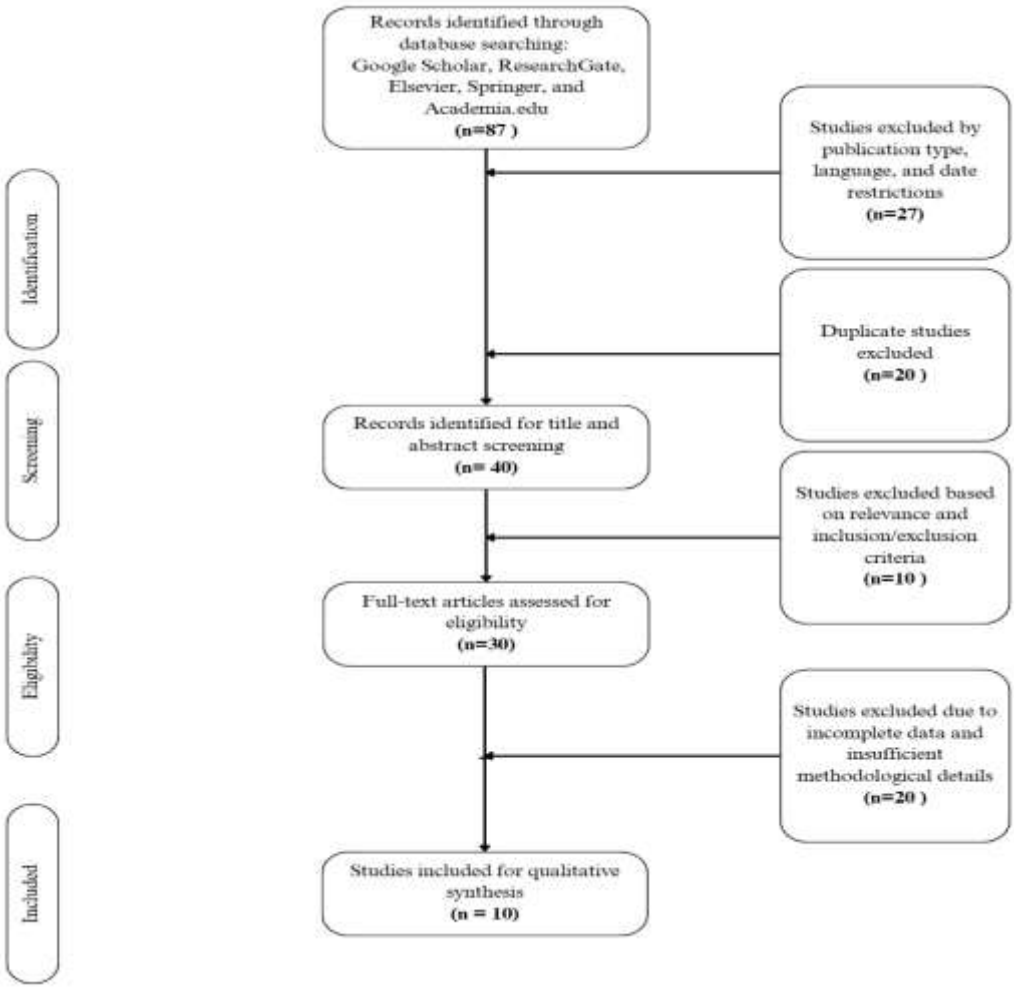

Figure 1. PRISMA Flow Diagram Showing the Stages of Study Identification, Screening, and Inclusion

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Data Extraction

In this study, 10 studies out of the 87 studies were extracted for detailed analysis based on the established eligibility criteria. The systematic review focused exclusively on experimental studies investigating the effects of temperature on the growth and physiological responses of *Aspergillaceae* species. Relevant data were gathered on fungal species and strain, temperature range and incubation conditions, growth rate or colony diameter, spore germination percentage, enzyme activity, and mycotoxin production levels, where applicable. These parameters allowed comparison of how varying temperatures influenced both morphological and metabolic performance among different *Aspergillus* and *Penicillium* species. The extracted datasets formed the basis for the qualitative synthesis of this review, enabling the identification of optimal growth temperatures, thermal tolerance limits, and patterns of temperature-dependent metabolic change across the *Aspergillaceae* family.

Risk of Bias Assessment

This systematic review's methodological rigor was evaluated through a risk of bias assessment. Potential sources of bias included selection bias (if the inclusion criteria excluded lesser-known *Aspergillus* species), measurement bias (arising from variations in experimental design, incubation duration, and temperature calibration), and reporting bias (due to selective publication of significant results such as optimal growth findings, while omitting inhibitory data). To mitigate these risks, the review documented its search strategy, standardized data extraction, and evaluated heterogeneity among studies in terms of temperature range, incubation time, and culture medium. Without such measures, the risk of bias could range from moderate to high, potentially influencing conclusions regarding the thermal adaptability of *Aspergillaceae* species.

RESULTS AND DISCUSSION

Table 1. Growth Rates of Aspergillaceae Species from the genus Aspergillus and Penicillium under Different Temperature, Humidity, and Exposure Conditions.

Species Name (Scientific)	Temperature	Humidity (RH)	Exposure Duration (days)	Growth Rate (cm/day)	Findings	Citations
Aspergillus amstelodam	4 °C 16 °C 29 °C 40 °C	75%	10	0 0.4 0.45 0.15	Growth increased from 0 cm/day at 4 °C to 0.45 cm/day at 29 °C, then declined at 40 °C (0.15 cm/day), indicating an optimum near 29 °C under 75 % RH.	Jumade & Pal, (2021)
Aspergillus brasiliensis	8 °C 16 °C 23 °C 27 °C 33 °C 37 °C 40 °C 44 °C	97%	14	0 0.30 0.91 1.13 1.32 0.79 0.27 0	Exhibited progressive growth from 0 cm/day at 8 °C to 1.32 cm/day at 33 °C; thermal inhibition began above 37 °C. Optimum range = 27–33 °C under 97 % RH.	Zdeňková et al., (2024)
Aspergillus candidus	10 °C 10 °C 10 °C 10 °C 20 °C 20 °C 20 °C 20 °C	12% 44% 76% 98% 12% 44% 76% 98%	14	0.18 0.25 0.32 0.36 0.22 0.33 0.42 0.45	Growth rose steadily with both temperature and humidity, peaking at 0.52 cm/day at 40 °C and 98 % RH; best growth in warm, moist conditions.	Mannaa & Kim (2018)

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	30 °C 30 °C 30 °C 30 °C 40 °C 40 °C 40 °C 40 °C	12% 44% 76% 98% 12% 44% 76% 98%		0.30 0.38 0.45 0.50 0.35 0.44 0.49 0.52		
Aspergillus candidus	30 °C 35 °C 40 °C	None	7	0.67 0.91 0.42	Grew rapidly between 30–35 °C (0.67–0.91 cm/day) but declined at 40 °C (0.42 cm/day), confirming optimum near 35 °C.	Naseer et al., (2020)
Aspergillus flavus	10 °C 10 °C 10 °C 10 °C 20 °C 20 °C 20 °C 20 °C 30 °C 30 °C 30 °C 30 °C 40 °C 40 °C 40 °C 40 °C	12% 44% 76% 98% 12% 44% 76% 98% 12% 44% 76% 98% 12% 44% 76% 98%	14	0.10 0.22 0.27 0.30 0.32 0.43 0.50 0.54 0.45 0.65 0.78 0.85 0.50 0.70 0.82 0.90	Growth rate increased with temperature and humidity, peaking around 30–37 °C (0.78–1.63 cm/day); inhibition occurred ≥ 40 °C.	Mannaa & Kim, (2018)
Aspergillus flavus	15 °C 15 °C 25 °C 25 °C 25 °C 25 °C 37 °C 37 °C 37 °C 37 °C 37 °C 37 °C 37 °C 37 °C	99% 99% 99% 99% 91% 91% 99% 99% 94% 94% 91% 91% ≤ 88% ≤ 88%	7 28 7 28 7 28 7 28 7 28 7 28 7 28	0 0 ≈ 1.2 ≈ 1.4 ≈ 0.2 ≈ 0.3 ≈ 1.63 ≈ 1.5 ≈ 0.8 ≈ 0.7 ≈ 0.09 ≈ 0.06 0 0	Maintained rapid growth between 25–37 °C, highest near 30–33 °C (≈ 1.2–1.5 cm/day); no growth below 15 °C or above 40 °C.	Lahouar et al., (2016)
Aspergillus flavus	30 °C 35 °C 40 °C	None	7	0.15 0.05 0.27	Moderate growth at 30 °C (0.15 cm/day) and 40 °C (0.27 cm/day); minimal at 35 °C (0.05 cm/day).	Naseer et al., (2020)

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Aspergillus flavus	25 °C 30 °C 35 °C 40 °C	80% 85% 90% 95%	7	0.45	Growth increased from 0.45 cm/day (25 °C) to 0.90 cm/day (40 °C) under 80–95 % RH; optimal range 30–35 °C.	Adetunji & Adeniran (2015)
Aspergillus flavus KSU 107	34 °C 37 °C 42 °C	95%	9	0.72 0.58 0.25	Optimum growth 0.72 cm/day at 34 °C and 95 % RH; rate declined with rising temperature (0.25 cm/day at 42 °C).	Al-Zaban (2023)
Aspergillus flavus KSU 114	34 °C 37 °C 42 °C	95%	9	0.68 0.50 0.20	Similar pattern with maximum 0.68 cm/day at 34 °C and drop to 0.20 cm/day at 42 °C.	
Aspergillus flavus KSU 121	34 °C 37 °C 42 °C	95%	9	0.61 0.45 0.15	Grew fastest (0.61 cm/day) at 34 °C then sharply decreased to 0.15 cm/day at 42 °C.	
Aspergillus fumigatus	10 °C 10 °C 10 °C 10 °C 20 °C 20 °C 20 °C 20 °C 30 °C 30 °C 30 °C 30 °C 40 °C 40 °C 40 °C 40 °C	12% 44% 76% 98% 12% 44% 76% 98% 12% 44% 76% 98% 12% 44% 76% 98%	14	0.18 0.25 0.30 0.33 0.28 0.38 0.45 0.50 0.42 0.60 0.73 0.83 0.50 0.70 0.82 0.90	Growth accelerated from 0.18 cm/day (10 °C) to 0.90 cm/day (40 °C) at high RH; optimal 30–35 °C, consistent with thermotolerant behavior.	Mannaa & Kim (2018)
Aspergillus fumigatus	30 °C 35 °C 40 °C	None	7	0.95 0.04 0.32	Highest growth (0.95 cm/day) at 30 °C, decreasing at 35 °C (0.04 cm/day); moderate at 40 °C (0.32 cm/day).	Naseer et al., (2020)
Aspergillus niger	30 °C 35 °C 40 °C	None	7	0.17 0.06 0.50	Moderate growth (0.17 cm/day) at 30 °C; increased at 40 °C (0.50 cm/day); optimum around 35–40 °C.	
Penicillium crustosum	15 °C 20 °C	98% 98%	16 16	0.36 0.43	Growth rose from 0.36 cm/day (15 °C) to 0.50	Gao et al. (2025)

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	22 °C 22 °C 22 °C 25 °C 30 °C	98% 94% 98% 98% 98%	16 10 10 16 16	0.47 0.39 0.46 0.5 0.28	cm/day (25 °C) at 98 % RH; decreased at 30 °C (0.28 cm/day). Optimal = 25 °C, 98 % RH.	
Penicillium expansum	4 °C 8 °C 16 °C 25 °C 30 °C	99%	14	0.05 0.20 0.50 0.67 0.35	Showed continuous rise from 0.05 cm/day (4 °C) to 0.67 cm/day (25 °C); decreased at 30 °C (0.35 cm/day). Optimum near 25 °C.	Tannous et al., (2015)
Penicillium fellutanum	10 °C 10 °C 10 °C 10 °C 20 °C 20 °C 20 °C 20 °C 30 °C 30 °C 30 °C 30 °C 40 °C 40 °C 40 °C 40 °C	12% 44% 76% 98% 12% 44% 76% 98% 12% 44% 76% 98% 12% 44% 76% 98%	14	0.10 0.18 0.24 0.28 0.22 0.33 0.40 0.45 0.35 0.50 0.65 0.70 0.42 0.58 0.70 0.78	Growth increased with both temperature and humidity, from 0.10 cm/day (10 °C) to 0.70–0.78 cm/day (40 °C at 98 % RH).	Mannaa & Kim (2018)
Penicillium islandicum	10 °C 10 °C 10 °C 10 °C 20 °C 20 °C 20 °C 20 °C 30 °C 30 °C 30 °C 30 °C 40 °C 40 °C 40 °C 40 °C	12% 44% 76% 98% 12% 44% 76% 98% 12% 44% 76% 98% 12% 44% 76% 98%	14	0.12 0.20 0.26 0.30 0.24 0.34 0.40 0.46 0.38 0.53 0.65 0.70 0.45 0.60 0.70 0.76	Grew steadily from 0.12 cm/day (10 °C) to 0.76 cm/day (40 °C at 98 % RH); optimal growth under warm, humid conditions.	
Penicillium paneum OM1	25 °C 20 °C	97%	7	0.85 0.68	High growth rates (0.68–0.85 cm/day) under 20–25 °C and 97 % RH; favored moderate temperature and high moisture.	Zhao et al., (2024)

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The table above consolidates quantitative growth rate data for various *Aspergillaceae* species across different temperature, humidity, and exposure conditions. The table demonstrates that temperature exerts the most dominant influence on the growth dynamics of both *Aspergillus* and *Penicillium* genera, while relative humidity (RH) and exposure duration act as key modulators of fungal metabolism and development.

Temperature Effects Across the *Aspergillaceae* Family

The compiled data reveal a clear temperature-dependent growth trend. Growth rates generally increase from 10–15 °C toward an optimum between 25 °C and 35 °C, beyond which a decline is observed due to thermal stress. For instance, *Aspergillus flavus* exhibited a gradual rise from 0.10 cm/day at 10 °C to 0.90 cm/day at 40 °C under high RH conditions (Mannaa & Kim, 2018), but other strains demonstrated peak growth slightly below 37 °C (Lahouar et al., 2016). Similarly, *A. brasiliensis* achieved its highest rate of 1.32 cm/day at 33 °C, with significant reductions at both lower and higher extremes (Zdeňková et al., 2024). This pattern suggests that *Aspergillus* species possess robust thermotolerance, thriving in warm environments typical of subtropical and tropical ecosystems.

In contrast, *Penicillium* species such as *P. crustosum* and *P. expansum* reached their maximal growth between 22 °C and 25 °C, with respective rates of 0.47–0.50 cm/day and 0.67 cm/day (Gao et al., 2025; Tannous et al., 2015). Above 30 °C, *Penicillium* growth was notably inhibited, suggesting a preference for moderately warm and humid conditions, reflecting their ecological adaptation to cooler storage environments and fruit substrates.

Role of Relative Humidity (RH)

Relative humidity further differentiates species performance. Data show that *Aspergillus* can sustain moderate growth at 75–80% RH, whereas *Penicillium* typically requires RH levels exceeding 95% for optimal development. For example, *P. crustosum* demonstrated faster growth at 98% RH (0.46 cm/day) compared to 94% RH (0.39 cm/day) under identical thermal conditions (Gao et al., 2025). Conversely, *Aspergillus flavus* maintained substantial growth (0.5–0.8 cm/day) even at RH between 80–90% (Adetunji & Adeniran, 2015), signifying greater tolerance to drier environments.

Exposure Duration and Growth Optimization

Exposure duration also contributed to growth variability, with most *Aspergillus* and *Penicillium* species reaching steady-state or maximum expansion after 10–16 days. Shorter durations (7–9 days) yielded lower mean rates, as observed in *P. paneum* OM1 (0.68–0.85 cm/day; Zhao et al., 2024), suggesting that prolonged incubation allows more complete exploitation of nutrient substrates and spore maturation. Overall, Table 1 reveals that *Aspergillus* species exhibit faster and broader thermal adaptation than *Penicillium*, aligning with their ecological roles in warmer climates and soil environments. *Penicillium*, however, excels in humid, moderate-temperature niches, which explains its predominance in post-harvest fruit spoilage and cold storage decay. These inter-generic distinctions illustrate evolutionary adaptations tied to spore structure, enzyme activity, and metabolic regulation.

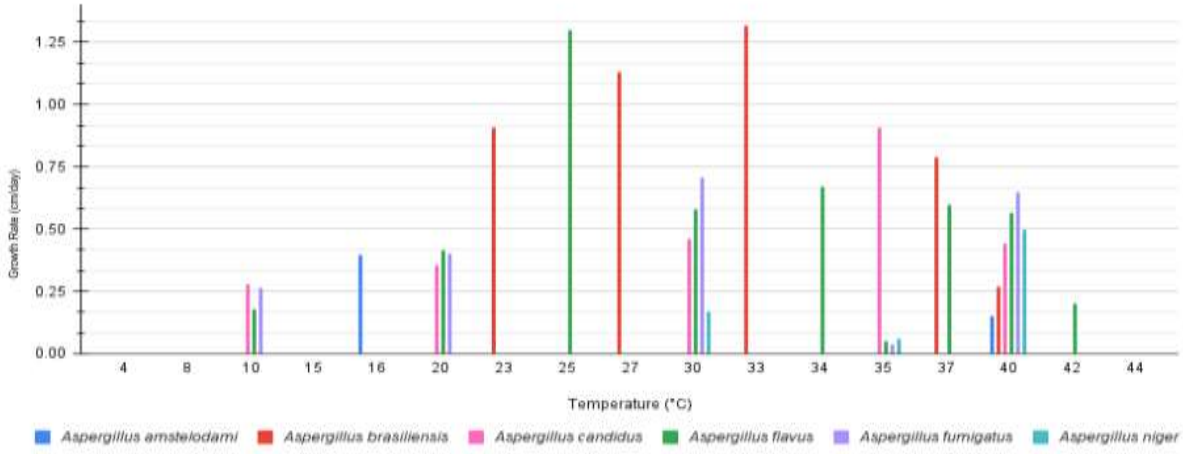

Figure 1. Growth Rates of Species under the genus of Aspergillus in Different Temperatures.

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Figure 1 illustrates the relationship between temperature and growth rate among *Aspergillus* species, highlighting a distinct bell-shaped thermal response curve. Growth increases gradually from low temperatures (4–10 °C), peaks between 30–37 °C, and declines beyond 40 °C, confirming the mesophilic nature of this genus. Species such as *A. brasiliensis*, *A. flavus*, and *A. fumigatus* demonstrate clear thermal optima, typically between 25 °C and 35 °C, where enzymatic activities involved in cell wall synthesis and metabolic respiration reach maximum efficiency. The rapid decline above 37 °C suggests enzyme denaturation and membrane instability at higher temperatures (Naseer et al., 2020). Moreover, interspecies variability is evident: *A. flavus* maintains relatively high growth rates up to 40 °C (0.9 cm/day), while *A. niger* and *A. amstelodam* exhibit reduced rates beyond 30 °C, indicating narrower thermal tolerance windows. The figure also reinforces the ecophysiological flexibility of *Aspergillus* spp., many of which function as xerophilic and thermotolerant molds capable of colonizing dry grains, nuts, and soils in warm regions. Their broad temperature range reflects evolutionary adaptation to fluctuating climatic conditions and supports their role as dominant agents in food spoilage and opportunistic pathogenesis.

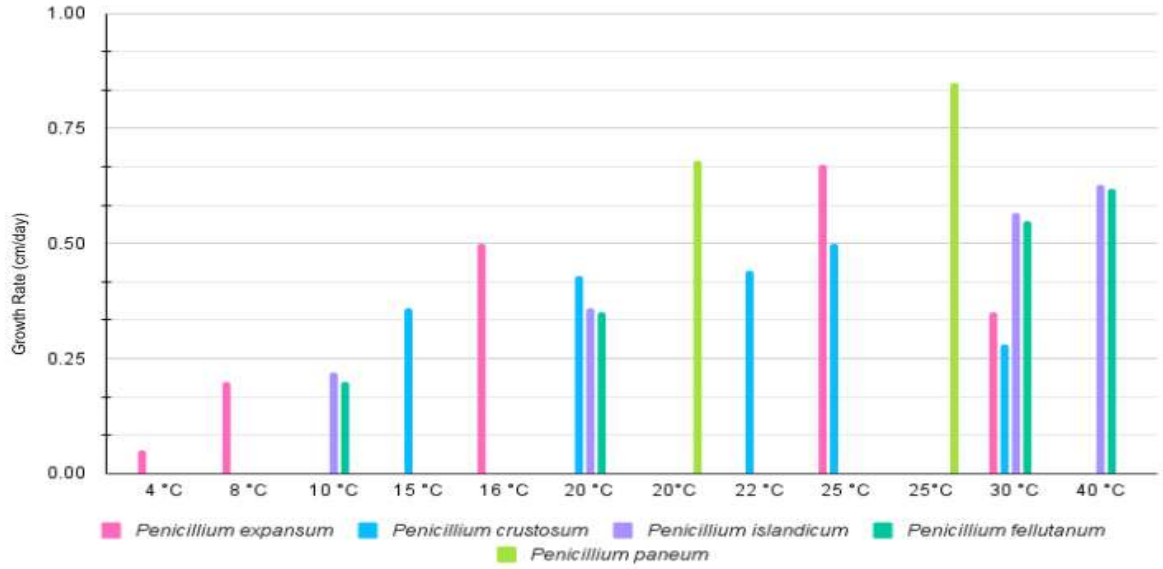

Figure 2. Growth Rates of Species under the genus of Penicillium in Different Temperatures.

For this figure, it presents the temperature-growth relationship for *Penicillium* species, showing a moderate optimum range (20–25 °C) and a more pronounced decline in growth rate beyond 30 °C compared to *Aspergillus*. Also, *P. crustosum* OM1, *P. expansum*, and *P. fellutanum* exhibit strong growth responses in this moderate zone, achieving rates between 0.45 and 0.70 cm/day, while performance at 10 °C and 40 °C was notably suppressed (≤0.3 cm/day). These findings emphasize that *Penicillium* species are mesophilic to psychrotolerant, thriving in cool, moist environments such as refrigerated fruit storage and damp food matrices. The figure also indicates that humidity significantly modulates temperature effects. For instance, *P. crustosum* and *P. expansum* required RH ≥ 95% for sustained mycelial development, whereas at 94% RH, growth was visibly restricted. This dependency reflects their sensitivity to water availability, a critical factor for hyphal turgor and metabolic flux. Compared to *Aspergillus*, *Penicillium* demonstrates narrower adaptability but greater persistence under constant moisture, explaining its dominance in post-harvest decay rather than arid soil ecosystems. The reduced growth beyond 30 °C suggests that *Penicillium* spp. are less competitive in high-temperature environments but are excellent colonizers under storage or temperate climatic conditions.

The findings from Table 1 and Figures 1–2 reveal that temperature is the primary factor influencing the growth of *Aspergillaceae* fungi, specifically *Aspergillus* and *Penicillium*. Most species showed optimal mycelial growth between 25 °C and 30 °C under high relative humidity (95–99%). *Aspergillus* species demonstrated greater thermal tolerance and faster growth rates, thriving in warmer environments up to 35–37 °C, with *A. flavus* and *A. brasiliensis* showing peak rates of 0.85–1.63 cm/day and 1.32 cm/day, respectively. In contrast, *Penicillium*

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species such as *P. crustosum* and *P. expansum* favored moderately warm and humid conditions, with optimal growth at 25 °C and rates of 0.50–0.67 cm/day. Growth declined sharply above 30 °C, indicating lower thermotolerance. Relative humidity significantly influenced development; fungal expansion decreased below 90% RH, confirming the importance of moisture for spore germination and hyphal elongation. Most species achieved maximal colony size after 10–16 days of incubation. Overall, *Aspergillus* species are adapted to warmer, drier climates, while *Penicillium* species thrive in cooler, humid environments such as stored food and fruits. These findings highlight the crucial interaction between temperature and humidity in regulating fungal growth and provide practical insights for controlling spoilage and mycotoxin contamination under varying climatic conditions.

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CONCLUSION

The collected evidence clearly demonstrates that temperature exerts a dominant influence on the growth performance of *Aspergillaceae* fungi, specifically those under the genera *Aspergillus* and *Penicillium*. Growth consistently increased as temperatures approached each species' optimum, revealing predictable thermal-dependent patterns across the reviewed studies. *Aspergillus* species showed broader tolerance to temperature fluctuations, reaching rapid growth rates within 30 °C to 35 °C, supported by metabolic and enzymatic systems suited for warm environments. In contrast, *Penicillium* species achieved their highest growth at lower and more moderate temperatures, generally between 20 °C and 25 °C, and experienced a noticeable decline in colony expansion as temperatures exceeded 30 °C. High relative humidity, particularly values at or above 90%, strengthened fungal development by enhancing spore germination, increasing hyphal turgor, and supporting consistent nutrient uptake.

Clear ecological distinctions emerged between the two genera based on their responses to environmental conditions. *Aspergillus* species including *A. flavus, A. brasiliensis, and A. fumigatus* maintained active growth even at temperatures reaching 37–40 °C. This capacity reflects physiological adaptations that allow them to colonize soil, grains, nuts, and other substrates found in warm or semi-arid regions, where rapid metabolic activity is advantageous for survival. *Penicillium* species, on the other hand, demonstrated adaptations associated with cooler, humid habitats. Species such as *P. expansum, P. crustosum, and P. paneum* performed best in conditions similar to refrigerated storage and moisture-rich food environments. Their sensitivity to elevated temperatures explains their dominance in post-harvest spoilage of fruits, dairy products, and refrigerated goods, where temperature rarely exceeds their physiological limit.

The reviewed studies also reveal that exposure duration plays an essential role in fungal development, with most species reaching their maximum colony diameter between 10 and 16 days. Short incubation periods produced lower growth rates, while extended durations allowed full exploitation of available nutrients and completion of sporulation cycles. The combined findings strengthen current understanding of how temperature and humidity shape the behavior, competitiveness, and toxin-producing potential of *Aspergillaceae* fungi. These insights contribute significantly to designing effective management strategies in food safety, agricultural storage, environmental monitoring, and industrial processing. Identifying the conditions that favor or restrict these fungi provides a scientific foundation for preventing spoilage, reducing mycotoxin contamination, and improving control measures in systems where temperature and moisture regulation are crucial.

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