THE HEAT-STABILITY PARADOX: A REVIEW OF THERMAL EFFECTS ON BIOACTIVE COMPOUNDS IN PIPER LONGUM AND THEIR POTENTIAL IN FUNCTIONAL FOOD DEVELOPMENT

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DOI: http://doi.org/10.47211/tg.2022.v09i01.020

ABSTRACT

Piper longum (Indian long pepper) is a medicinal and culinary plant known for its diverse bioactive constituents, particularly piperine, piperlongumine and other alkaloids. Although its pharmacological properties have been widely discussed in previous studies, less attention has been given to the effects of food processing and heat exposure on these constituents. Understanding their stability is important when considering the possible use of Piper longum in functional food products.

This review examines previously published research on the chemical composition, physicochemical properties and biological activities of Piper longum, with particular attention to the possible effects of heating, cooking and food processing. Studies involving other pepper species are also considered where relevant, although their findings are not assumed to apply directly to Piper longum. The available literature indicates that temperature, processing duration, food matrix, pH and storage conditions may influence the stability of plant bioactive compounds. Research on piperlongumine has also demonstrated that its stability is affected by environmental conditions, particularly pH and temperature.

The review discusses the potential relevance of these findings to thermally processed beverages, lipid-based food products and other functional food formulations. However, direct evidence establishing the thermal retention of Piper longum bioactives during industrial food processing remains limited. Further studies are therefore needed to determine their stability and functional effectiveness under actual food-processing conditions.

Keywords: *Piper longum, Indian long pepper, piperine, kinetics, heat stability.*

INTRODUCTION

Previous studies on Piper longum has mainly examined its traditional medicinal uses, phytochemical composition and pharmacological properties. Several studies have investigated its alkaloids and their antioxidant, anti-inflammatory and other biological activities. However, comparatively less attention has been given to understanding how food processing and thermal exposure may influence these constituents. (Kumar et al., 2011; Sunila & Kuttan, 2004). While such pharmacology confirms potent apoptotic, antimutagenic, and anti-inflammatory mechanisms, it routinely operates on a non-viable assumption for the food industry: that bioactive compounds are consumed exclusively in native, unheated states.

Historically, traditional systems of medicine (e.g., Ayurveda) consistently processed *Piper longum* (*Pippali*) via classical thermal operations: *deepana* (digestive heat-boosting), ghee roasting (*siddha ghrita*), decoctions (*kwatha*), and milk reductions (*ksheerapaaka*) (Atal et al., 1985; Manoj et al., 2004). Although traditional preparations involve different forms of heating, the chemical changes occurring in individual bioactive compounds during these processes are not yet fully understood. Bringing *P. longum* into modern functional beverages, high-temperature short-time (HTST) pasteurized matrices, extruded snacks, and retorted culinary preparations demands a systematic understanding of its bioactive kinetics and radical scavenging endurance under thermal stress (Suresh et al., 2007; Nisha et al., 2009).

LITERATURE REVIEW METHODOLOGY

Relevant published literature on *Piper longum*, its bioactive constituents and their potential responses to thermal processing was considered for this review. The literature search focused on publications available up to December 2020.

Scientific databases, including Researchgate, Google Scholar and ScienceDirect, may be searched using terms such as *Piper longum*, piperine, piperlongumine, thermal stability, heat processing, antioxidant activity, food processing and functional foods.

Studies addressing the phytochemical composition, physicochemical properties, biological activities and processing-related changes in pepper species were considered relevant. Research involving other *Piper* species was included only for comparative discussion, with due consideration of species-specific differences.

The findings were reviewed to identify the available evidence, limitations in existing research and possible directions for functional food development.

Major Bioactive Constituents of Piper longum

The fruits of *Piper longum* contain several groups of phytochemicals, including:

1. **Alkaloids and amide compounds:** Piperine is one of the major alkaloids reported in the fruit. Other reported constituents include piperlongumine (piplartine), pellitorine, retrofractamide A and related compounds.
2. **Essential oil constituents:** The essential oil contains volatile compounds, including monoterpenes and sesquiterpenes. Their composition may vary depending on the plant part, geographical origin and extraction method.
3. **Lignans and other minor constituents:** Compounds such as asarinin and related lignans have also been reported in *Piper longum*.

The chemical composition of the plant is influenced by the plant part, growing conditions and extraction procedure.

Thermal Kinetic Behavior: Degradation vs. Isomerization

A. Piperine degradation kinetics

The stability of piperine during heating may depend on temperature, exposure time and the surrounding food matrix. Studies examining heat processing of black pepper (Piper nigrum) have reported changes in the concentrations of certain spice constituents. However, these findings cannot be directly applied to Piper longum without species-specific evidence. Further research is required to establish the thermal degradation pattern of piperine in long pepper.

B. Piperine isomerisation

Piperine can exist in different geometric isomeric forms, including isopiperine, chavicine and isochavicine. Previous research has demonstrated that light exposure can induce changes in the geometric configuration of piperine. However, these findings primarily concern photochemical isomerisation and should not be presented as direct evidence of heat-induced isomerisation during food processing.

C. Piperlongumine stability

Piperlongumine is an important bioactive constituent reported in Piper longum. Aodah et al. (2016) investigated its physicochemical properties, aqueous solubility and degradation behaviour under different pH and temperature conditions. Their findings showed that piperlongumine stability was influenced by the surrounding environment, with greater stability under acidic conditions. The study also identified degradation products, including 3,4,5-trimethoxycinnamic acid and piperlongumic acid. However, these findings do not establish its stability during high-temperature food processing. Further investigation is required to understand its behaviour during cooking, frying and industrial food preparation.

D. Volatile terpene loss

Piper longum contains volatile essential oil constituents, including monoterpenes and sesquiterpenes. Since these compounds are volatile, heating may influence their composition and concentration. However, the extent of volatile loss during cooking or industrial processing of Piper longum has not been adequately established in the cited literature.

Resolving the "Heat-Stability Paradox"

Matrix Liberation of Bound Bioactives: Heating can alter the structure of plant tissues and may influence the release and extraction of certain phytochemicals. However, the extent to which cooking increases the release or bioaccessibility of phenolic compounds and alkaloids from Piper longum has not been sufficiently established. This possibility should therefore be considered an area for further investigation rather than a confirmed outcome.

Transformation vs. Inactivation: Thermal processing may affect different phytochemical groups in different ways. Some compounds may undergo degradation, while others may remain relatively unchanged depending on the processing conditions. Antioxidant activity measured in plant extracts may also vary according to the extraction method and the test used. Therefore, changes in individual compound concentrations should not automatically be interpreted as equivalent changes in overall antioxidant activity.

Genoprotective and Antimutagenic Retention: Previous studies have investigated the antimutagenic and other biological activities of pepper extracts and their constituents. However, the available evidence cited here does not establish whether these properties are retained after cooking or industrial thermal processing of Piper longum. Further studies are required to evaluate the biological activity of processed extracts.

Stability Comparative Matrix Across Processing Methods

Processing method	Available evidence	Possible relevance
Boiling and decoction	Traditional use is documented, but compound-specific retention data are limited.	Herbal beverages and decoctions
Roasting	Heat-related changes have been studied in black pepper. Direct evidence for long pepper is limited.	Roasted spice formulations
Pasteurisation	No sufficient direct evidence establishing retention of long pepper bioactives under HTST/UHT conditions.	Functional beverages
Oil-based processing	Piperine and other constituents have been studied for their physicochemical properties, but retention during frying needs investigation.	Oil-based food formulations
Extrusion cooking	Direct evidence on the retention of long pepper bioactives is insufficient.	Fortified snacks and cereal products

Commercial Applications in Functional Foods

A. Clean-Label Lipid Preservation

Synthetic antioxidants (e.g., BHT, BHA, TBHQ) face consumer pushback and regulatory scrutiny. Piper longum contains bioactive compounds that have been investigated for their antioxidant properties. Mittal and Gupta (2010) examined the in vitro antioxidant activity of extracts from Piper longum and Piper cubeba. These findings suggest possible interest in exploring long pepper extracts as natural antioxidant ingredients. However, their effectiveness in preventing lipid oxidation during frying or other high-temperature food processing has not been established. Further food-matrix studies are required before considering their use as replacements for synthetic antioxidants such as BHT, BHA and TBHQ.

B. Thermally Processed Bio-Enhancing Delivery Vehicles

Piperine has been investigated for its ability to influence the bioavailability of certain compounds, including curcumin. Shoba et al. (1998) reported increased curcumin bioavailability following co-administration with piperine. Atal et al. (1985) also investigated the role of piperine in drug metabolism. These findings provide a basis for considering piperine in functional food formulation. However, the stability of piperine and its bio-enhancing activity following industrial thermal processing require further investigation.

C. Thermal Beverages & Sports Recovery Formulations

Piper longum may be considered for investigation as an ingredient in herbal beverages and other functional drink formulations because of its traditional use and reported phytochemical composition. However, its solubility, taste, stability and biological activity under beverage-processing and storage conditions require further evaluation. Formulation studies are also needed to determine suitable extraction and filtration methods.

Regulatory, Formulation, and Industrial Limitations

- **Solubility Constraints:** Piperine is poorly soluble in cold water (Piperine has limited water solubility, which may create formulation challenges when developing aqueous beverages. Suitable food-grade formulation approaches may be investigated to improve its dispersion and stability.
- **Standardization Requirements:** Standardisation of Piper longum extracts is important for consistent product quality. The concentration of major constituents, particularly piperine, should be evaluated using appropriate analytical methods. Further research is needed to establish suitable standardisation parameters for functional food applications..

CONCLUSIONS

Piper longum is an important medicinal and culinary plant containing several bioactive constituents, particularly piperine and piperlongumine. Previous research has established its diverse phytochemical composition and investigated the biological activities of its major compounds. However, understanding how these constituents respond to thermal processing remains important for their potential application in functional foods.

The available literature indicates that the stability of individual compounds may be influenced by temperature, processing duration, pH, food matrix and storage conditions. Studies on piperlongumine have demonstrated the importance of environmental conditions in determining its stability, while research on other pepper species provides additional information on the possible effects of heat processing. Nevertheless, findings from other species should not be considered direct evidence of thermal stability in Piper longum.

The possible use of Piper longum in functional beverages, oil-based food products and natural antioxidant formulations deserves further attention. However, its effectiveness and stability under actual food-processing conditions have not yet been adequately established. Future research should focus on identifying changes in

individual bioactive compounds during cooking, pasteurisation, roasting and extrusion, as well as evaluating their antioxidant and other biological properties after processing.

Overall, Piper longum represents a promising subject for further investigation in functional food development. A clearer understanding of its thermal behaviour will help determine its suitability for food formulations and support the development of evidence-based applications.

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