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Impact of Stir-frying with Different Vegetable Oils on Phytochemical Composition and Pyruvic Acid Content in *Allium sativum* and *Allium ampeloprasum* Cultivars

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Abstract

Background: Thermal processing can markedly affect the stability of bioactive phytochemicals in Allium vegetables, which are valued for their health-promoting properties. **Aim:** This study aimed to evaluate the impact of stir-frying using different vegetable oils on pyruvic acid content and phytochemical composition of *Allium sativum* and *Allium ampeloprasum* cultivars. **Methods:** Bulb samples of *A. sativum* (AS1, AS2) and A. ampeloprasum (AA1, AA2) were stir-fried using sesame, refined sunflower, and olive oils at controlled temperatures (160–200°C). Extracts were prepared using solvents of varying polarity. Pyruvic acid content was determined spectrophotometrically, and phytochemical profiling included qualitative screening, total phenolic content (TPC), total flavonoid content (TFC), and FTIR analysis. Statistical analysis was performed using one-way ANOVA followed by Tukey's post-hoc test ($p < 0.05$). **Results:** Stir-frying significantly reduced pyruvic acid, TPC, and TFC compared to raw controls ($p < 0.05$). Sesame oil exhibited the highest retention of pyruvic acid (17.81 ± 0.1 µmol g^{-1} in AS1) and phytochemicals, whereas sunflower oil showed the greatest degradation. Non-polar solvent extracts demonstrated enhanced recovery of bioactive compounds, and FTIR analysis confirmed the preservation of key functional groups in sesame oil–processed samples**. Conclusion:** The type of cooking oil significantly influences phytochemical stability during stir-frying, with sesame oil providing superior protection against thermal degradation and better preservation of nutritional quality in Allium species.

Major Findings: Sesame oil retained the highest levels of phytochemicals and pyruvic acid. Sunflower oil showed maximum degradation of bioactive compounds. Oil composition critically influences phytochemical stability during cooking.

Keywords: *Allium ampeloprasum*, *Allium sativum*, FTIR Analysis, Pyruvic acid, Vegetable Oils

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1. Introduction

Allium vegetables, particularly garlic (*Allium sativum*) and elephant garlic (*Allium ampeloprasum*), have been integral to human diets and traditional medicine for centuries. These vegetables are widely recognised for their diverse therapeutic properties, including antioxidant, antimicrobial, anti-inflammatory, and cardiometabolic benefits. The health-promoting effects of *Allium* species are primarily attributed to their rich profile of bioactive phytochemicals, such as organosulfur compounds, phenolic acids, and flavonoids[1,2]. Additionally, pyruvic acid serves as a crucial indicator of the pungency and flavour intensity

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in these vegetables, reflecting the enzymatic breakdown of sulfur-containing precursors that contribute to their characteristic aroma and biological activity[3].

In culinary practices, *Allium* vegetables are rarely consumed raw; they are frequently subjected to various thermal processing methods, with stir-frying being one of the most common techniques in Asian and Mediterranean cuisines. Thermal processing can significantly alter the phytochemical landscape of these vegetables. While some studies suggest that mild heating can enhance the extractability of certain phenolics, high-intensity cooking methods like frying often lead to the degradation of labile sulfur compounds and a reduction in overall antioxidant capacity[4,5]. The extent of these changes is heavily influenced by cooking parameters such as temperature, duration, and the type of frying medium used. The choice of vegetable oil as a frying medium plays a pivotal role in the stability and retention of phytochemicals during cooking. Different oils, such as sesame, sunflower, and olive oil, possess distinct fatty acid profiles and varying levels of intrinsic antioxidants. Sesame oil, for instance, is highly valued for its exceptional oxidative stability during heating, which is largely credited to the presence of unique lignans like sesamol and sesamin[6]. These components not only protect the oil from degradation but may also provide a more stable environment for the vegetable bioactives during stir-frying[7]. In contrast, oils like sunflower and olive oil may exhibit different behaviours under high heat, potentially affecting the final phytochemical composition and nutritional value of the cooked *Allium* vegetables[8,9]. Despite the widespread use of these oils in cooking *Allium* vegetables, comparative research on how different frying media specifically impact the phytochemical retention and pyruvic acid content across various cultivars is limited. Understanding these interactions is essential for optimising cooking methods that preserve the functional properties of these medicinal vegetables. Therefore, the objective of this study is to investigate the phytochemical composition and pyruvic acid levels of *A. sativum* and *A.ampeloprasum* cultivars when stir-fried in sesame, sunflower, and olive oils. By evaluating these parameters, this research seeks to provide insights into how the frying medium influences the bioactive profile and quality of common *Allium* vegetables, ultimately contributing to better dietary recommendations for maximising their health benefits[10,11].

2. Materials and Methods

2.1 Materials

Edible sesame oil, refined sunflower oil and olive oil were procured from the local grocery store. Chemicals of analytical grade for Pyruvic acid assay, qualitative and quantitative phytochemical analysis were procured from HiMedia Laboratories, India. Water obtained through double distillation was used.

2.2 Stir-frying Treatment and Experimental Design

Bulbs of *A. sativum* (AS1 and AS2) and *A. ampeloprasum* (AA1 and AA2) cultivars were peeled, washed under tap water, and rinsed thrice with distilled water. The samples were air-dried, finely chopped, and stored in airtight containers. A standardised volume (50 mL) of sesame oil was heated to 200°C, and the chopped samples were stir-fried for a fixed duration of 5 minutes until a consistent cooking endpoint was reached. Similar procedures were followed for sunflower oil (160°C) and olive oil (190°C). A raw, untreated sample served as the control. After cooling, samples were ground into fine powder and stored in airtight containers for further analysis. Raw, untreated samples were used as controls for comparative analysis.

2.2.1 Extract Preparation

Solvents in the polar, mid-polar and non-polar range were selected for extract preparation. The cold extraction method was used, in which the powders were enclosed in glass jars along with the solvent and allowed to stand for 72 hours. Sesame oil, sunflower oil and olive oil stir-fried powders of AS1, AS2, AA1 and AA2 were taken in individual screw cap bottles to which methanol, ethanol, acetone, chloroform, distilled water, petroleum ether and hexane (mg/ml concentration) were added, respectively. The bottles were closed tightly and placed in an orbital shaker for 72 hours. Later, the mixtures were filtered, and the solvents were evaporated to obtain the extracts.

2.2.2 Pyruvic Acid Assay

1 mg/mL of each extract of the four cultivars was taken in individual test tubes. To this, 0.5 ml of DNPH was added and vortexed. The tubes were incubated for 20 minutes at 37°C. After the incubation, 10 ml of the

prepared alkaline solution (NaOH solution) was added, and the contents were mixed thoroughly. The mixtures were then assessed at 540 nm. To different aliquots of Sodium pyruvate (standard) solution, the reagent was added and incubated, followed by the addition of the alkaline solution. These tubes were measured for absorbance at the same wavelength and were used to plot the standard curve. The values were expressed as µmol g^{-1}. The experiments were performed in triplicates[12].

2.2.3 Qualitative Phytochemical Screening

Qualitative phytochemical screening was carried out for the prepared extracts. Primary and secondary metabolites were evaluated using different tests[3,13].

2.2.4 Determination of Total Phenol and Flavonoid Content

The total content of phenols and flavonoids in stir-fried *A. sativum* and *A. ampeloprasum* cultivar extracts was determined individually. The Folin-ciocalteau method was used for the determination of phenols, and the aluminium chloride method was used for the determination of flavonoids.

i. Folin-ciocalteau method for phenols: To 1ml of the extracts, 0.5 mL of Folin-ciocalteau reagent was added and mixed thoroughly. 5% Sodium carbonate solution was prepared, and 2.5 mL of this solution was added to all the tubes. The mixture was allowed to react by incubating it at room temperature for 30 minutes. After 30 minutes, the absorbance of the incubated solution was measured using a spectrophotometer at 725 nm. Gallic acid was employed as the standard to extrapolate the findings. Values were given as Gallic acid equivalents (µg GAE/mg)[14]. The experiments were performed in triplicate.
ii. Aluminium chloride method for flavonoids:1mL of stir-fried *A. sativum* and *A. ampeloprasum* cultivar extracts were added to individual tubes. To these tubes, 2 mL of Aluminium chloride was added and mixed well. 6 ml of Sodium acetate was pipetted into the tubes, vortexed and allowed to stand for 5 minutes at room temperature. The absorbance of the mixture was measured using a UV-VIS spectrophotometer at a wavelength of 430 nm. Quercetin was used as the standard to plot the calibration curve, and the results were expressed as Quercetin equivalent[15]. The experiments were performed in triplicate.

2.2.5 Fourier Transform Infra-Red Spectroscopy (FTIR) Analysis

Screening of functional groups in stir-fried *A. sativum* and *A. ampeloprasum* cultivars was performed using a Perkin Elmer FTIR spectrophotometer. The hexane extracts of the stir-fried cultivars of both plants were selected based on the results from the phytochemical screening for further analysis. Potassium bromide (KBr) was used as the carrier for the dried pellets since it is optically transparent and does not exhibit absorption in the 4000-400 cm^{-1} range. The samples were mixed with KBr and pressed into a pellet individually. The pellet was scanned, and the absorption was recorded[16].

2.2.6 Statistical Analysis

All experiments were conducted in triplicate (n = 3), and results are expressed as mean ± Standard Deviation (SD). Statistical significance among groups was determined using one-way ANOVA followed by Tukey's post-hoc test. A p-value < 0.05 was considered statistically significant. Analysis was performed using SPSS software.

3. Results and Discussion

3.1 Effect of Oil-mediated Stir-frying on Pyruvic Acid Content

Pyruvic acid content was quantified in *Allium sativum* (AS1, AS2) and *Allium ampeloprasum* (AA1, AA2) cultivars following stir-frying in sesame, refined sunflower, and olive oils to evaluate the influence of oil-mediated thermal processing on pungency-related metabolites. Pyruvic acid is widely accepted as an indirect indicator of alliinase activity and organosulfur compound integrity in *Allium* species. A marked variation in pyruvic acid levels was observed across cultivars and cooking oils (Table 1). Among the three oils tested, sesame oil consistently enabled greater retention of pyruvic acid in both *A. sativum* and *A. ampeloprasum* cultivars. The highest pyruvic acid content was recorded in AS1 stir-fried in sesame oil (17.81 ± 0.1 µmol g^{-1}), followed by AA1 (12.30 ± 0.1 µmol g^{-1}). In contrast, cultivars stir-fried in refined sunflower oil exhibited the lowest pyruvic acid levels, with AA2 showing a minimum value of 3.74 ± 0.07 µmol g^{-1}. Moderate retention of pyruvic acid was observed in olive oil–processed samples; however, these values

were significantly lower than those obtained with sesame oil. The drastic reduction observed in pyruvic acid following stir-frying, when compared to reported values in raw garlic (117.92 μmol g^{-1}), highlights the pronounced impact of high-temperature oil-mediated processing on sulfur metabolism. Thermal processing is known to suppress alliinase activity, thereby limiting the conversion of alliin to allicin and its subsequent degradation products, including pyruvic acid. Previous studies have demonstrated that exposure to temperatures above 60°C leads to incomplete activation and rapid denaturation of alliinase, with up to 50% loss of enzyme activity within 15 min of heat exposure. The lower pyruvic acid content observed in sunflower oil–processed samples may be attributed to enhanced oxidative degradation and lower thermal stability of organosulfur intermediates in this medium.

The comparatively superior retention observed in sesame oil could be associated with its intrinsic antioxidant components, such as lignans and tocopherols, which may provide partial protection against thermal and oxidative degradation of sulfur-containing metabolites. These findings indicate that the choice of cooking oil plays a critical role in modulating the biochemical quality of stir-fried *Allium* vegetables, beyond the effects of temperature alone. One-way ANOVA revealed a statistically significant effect of oil type on pyruvic acid content across all cultivars ($p < 0.05$), with sesame oil treatments showing significantly higher retention compared to sunflower and olive oil groups.

Table 1. Pyruvic acid content in *A. sativum* and *A. ampeloprasum* cultivars of stir-frying in sesame, refined sunflower, and olive oils

Cultivar	Oil	Pyruvic Acid (μmolg^{-1})
AS1	Sesame	17.81±0.1^{a}
	Refined sunflower	6.34±1.2^{c}
	Olive	14.45±0.07^{b}
AS2	Sesame	11.3±0.07^{a}
	Refined sunflower	7.44±0.1^{c}
	Olive	9.13±0.03^{b}
AA1	Sesame	12.30±0.1^{a}
	Refined sunflower	4.61±0.02^{c}
	Olive	5.42±1.2^{b}
AA2	Sesame	9.6±1.2^{a}
	Refined sunflower	3.74±0.07^{c}
	Olive	6.83±2.3^{b}

Values are expressed as mean ± SD (n = 3). Different superscript letters (a–c) within each cultivar indicate statistically significant differences ($p < 0.05$) based on one-way ANOVA followed by Tukey's post-hoc test.

One-way ANOVA analysis revealed a statistically significant effect of oil type on pyruvic acid content across all cultivars ($p < 0.05$). Tukey's post-hoc test indicated that sesame oil treatments (group 'a') retained significantly higher pyruvic acid compared to olive oil (group 'b') and sunflower oil (group 'c'), demonstrating the superior protective effect of sesame oil against thermal degradation. The quantification of pyruvic acid serves as a reliable indirect metric for assessing the integrity of the alliinase enzyme and the subsequent formation of organosulfur compounds, which are primary contributors to the pungency and therapeutic value of *Allium* species. In this study, a drastic reduction in pyruvic acid levels was observed across all cultivars compared to typical values found in raw garlic (approximately 117.92 μmol g^{-1}). This decline is primarily attributed to the thermal denaturation of alliinase, which is highly heat-labile and known to lose significant activity at temperatures exceeding 60°C[1,11]. A standout finding was the superior retention of pyruvic acid in cultivars stir-fried in sesame oil, despite it being heated to the highest temperature (200°C). This phenomenon can be attributed to the unique chemical composition of sesame oil. Unlike sunflower and olive oils, sesame oil contains specialised lignans such as sesamin and sesamolin, which, upon thermal treatment, can transform into sesamol, a potent antioxidant[7]. These components likely provide a protective antioxidant shield, mitigating the oxidative degradation of both the alliinase enzyme and its enzymatic products.In contrast, refined sunflower oil exhibited the lowest pyruvic acid retention. This is likely due to its high concentration of Polyunsaturated Fatty Acids (PUFAs), which are highly susceptible to lipid peroxidation at high temperatures[4]. The resulting lipid peroxides and free radicals create an aggressive oxidative environment that accelerates the degradation of sulfur-containing intermediates. Olive oil, characterised by its Monounsaturated Fatty Acid (MUFA) profile and polyphenols, showed moderate retention, performing better than sunflower oil but lacking the specialised protective efficacy of sesame oil's lignans. These results underscore that the choice

of cooking oil is not merely a medium for heat transfer but a critical factor in determining the biochemical stability of stir-fried vegetables.

3.2 Qualitative Phytochemical Profile of Stir-fried *Allium* Cultivars

Qualitative phytochemical screening was performed to evaluate the influence of oil-mediated stir-frying and solvent polarity on the retention of primary and secondary metabolites in *A. sativum* (AS1, AS2) and *A. ampeloprasum* (AA1, AA2) cultivars (Tables 2-8). Extracts prepared using polar, mid-polar, and non-polar solvents revealed distinct variations in phytoconstituent profiles depending on the cooking oil employed. Across all cultivars and oils, reducing sugars were consistently detected in all solvent extracts, indicating their relative thermal stability during stir-frying. In contrast, amino acids, alkaloids, flavonoids, phenols, glycosides, terpenoids, and phytosterols exhibited selective retention, strongly influenced by both oil type and solvent polarity.

Notably, non-polar solvents (petroleum ether and hexane) demonstrated superior extraction efficiency for flavonoids, phenols, terpenoids, and phytosterols, particularly in sesame oil–processed samples. This trend was consistently observed in both *A. sativum* and *A. ampeloprasum* cultivars, suggesting that stir-frying promoted the partitioning of thermally stable phytoconstituents into the lipid phase, thereby enhancing their recovery in non-polar extracts. Among the three oils tested, sesame oil–stir-fried cultivars exhibited the richest and most diverse phytochemical profile, followed by olive oil, while refined sunflower oil showed the poorest retention of secondary metabolites. The reduced phytoconstituent diversity in sunflower oil–processed samples may be attributed to enhanced oxidative degradation under high-temperature conditions, consistent with previous reports on sunflower oil–mediated thermal instability of phenolic compounds. The presence of flavonoids and phenols predominantly in non-polar extracts indicates possible structural modification or lipid association

Table 2. Qualitative phytochemical profile of *A. sativum* cultivars stir-fried in sesame oil and extracted using solvents

Cultivar	Phytoconstituent	Sesame Oil Extracts						
		Me	Et	Ac	Ch	Aq	Pe	He
AS1	Reducing sugars	+	+	+	+	+	+	+
	Amino acids	+	-	-	+	-	+	+
	Alkaloids	-	-	-	+	-	-	-
	Flavonoids	-	-	+	-	-	-	+
	Phenols	-	-	+	-	-	-	+
	Saponins	-	-	-	-	-	-	-
	Glycosides	-	-	-	-	-	-	-
	Tannins	-	-	-	-	-	-	-
	Terpenoids	-	-	-	+	-	+	+
	Phytosterols	-	-	-	+	-	+	+
AS2	Reducing sugars	+	+	+	+	+	+	+
	Amino acids	+	-	+	-	-	+	+
	Alkaloids	-	-	+	-	-	-	+
	Flavonoids	-	-	-	-	-	-	+
	Phenols	-	-	+	+	-	+	+
	Saponins	-	-	-	-	-	-	-
	Glycosides	-	-	-	-	-	+	+
	Tannins	-	-	-	-	-	-	-
	Terpenoids	-	-	+	-	-	+	+
	Phytosterols	-	-	+	-	-	+	+

Table 3. Qualitative phytochemical profile of *A. sativum* cultivars stir-fried in refined sunflower oil

Cultivar	Phytoconstituent	Refined Sunflower Oil Extracts						
		Me	Et	Ac	Ch	Aq	Pe	He
AS1	Reducing sugars	+	+	+	+	+	+	+
	Amino acids	-	-	-	-	-	+	+
	Alkaloids	-	-	-	-	-	-	-
	Flavonoids	-	-	-	-	-	-	+
	Phenols	-	-	-	-	-	-	+
	Saponins	-	-	-	-	-	-	-
	Glycosides	-	-	-	+	-	+	+
	Tannins	-	-	-	-	-	-	-
	Terpenoids	+	+	+	-	-	+	+
	Phytosterols	-	-	-	-	-	-	+
AS2	Reducing sugars	+	+	+	+	+	+	+
	Amino acids	+	+	+	+	+	+	+
	Alkaloids	-	-	+	-	+	-	-
	Flavonoids	+	+	+	-	+	+	+
	Phenols	+	+	+	+	+	-	+
	Saponins	+	-	+	-	+	+	+
	Glycosides	+	-	-	-	+	-	-
	Tannins	-	-	-	-	-	-	-
	Terpenoids	-	-	-	-	-	-	-
	Phytosterols	-	-	-	-	-	-	+

of these compounds during stir-frying, which may alter their solubility characteristics. Additionally, the sporadic detection of sulfur-related phytoconstituents and terpenoids in sesame oil–processed samples suggests partial preservation of heat-sensitive compounds, potentially mediated by the antioxidant lignans naturally present in sesame oil. Comparatively, *A. sativum* cultivars retained a broader range of phytoconstituents than *A. ampeloprasum*, particularly with respect to phenols and flavonoids, indicating species-specific resilience to thermal processing. These findings collectively demonstrate that oil composition plays a decisive role in determining phytochemical retention during stir-frying, with sesame oil providing a comparatively protective processing environment.

The qualitative screening revealed that the phytochemical landscape of stir-fried *Allium* bulbs is significantly shaped by the interplay between the cooking oil and the extraction solvent. The consistent detection of reducing sugars across all treatments highlights their relative thermal stability compared to secondary metabolites like alkaloids, flavonoids, and phenol[3]. The superior diversity of phytochemicals observed in sesame oil-stir-fried samples suggests a dual role of the oil: as a stabilising medium and as a partitioning phase. During stir-frying, high temperatures and mechanical stirring disrupt the cellular matrix of the bulbs, facilitating the migration of lipophilic and mid-polar phytochemicals into the lipid phase[17,18]. The fact that non-polar solvents (hexane and petroleum ether) recovered the broadest range of these compounds confirms this partitioning. Furthermore, the presence of sesame oil's native antioxidants likely prevents the "co-oxidation" of these partitioned phytochemicals, which is a common occurrence in PUFA-rich oils like sunflower oil.

The species-specific differences were also notable, with *Allium sativum* (garlic) cultivars (AS1 and AS2) generally retaining a richer phytochemical profile than *Allium ampeloprasum* (AA1 and AA2). This disparity can be attributed to the inherent differences in their metabolic profiles and cellular architecture. Garlic

Table 4. Qualitative phytochemical profile of *A. sativum* cultivars stir-fried in olive oil

Cultivar	Phytoconstituent	Olive Oil Extracts						
		Me	Et	Ac	Ch	Aq	Pe	He
AS1	Reducing sugars	+	+	+	+	+	+	+
	Amino acids	+	-	+	-	+	+	+
	Alkaloids	+	-	-	+	-	-	-
	Flavonoids	-	-	-	-	-	+	+
	Phenols	-	-	-	+	-	-	+
	Saponins	-	-	-	-	-	-	-
	Glycosides	-	-	-	-	-	-	-
	Tannins	-	-	-	-	-	-	-
	Terpenoids	+	+	+	-	+	-	+
	Phytosterols	-	-	+	+	+	-	+
AS2	Reducing sugars	+	+	+	+	+	+	+
	Amino acids	+	-	+	-	-	+	+
	Alkaloids	-	-	-	+	-	-	-
	Flavonoids	-	-	-	-	-	+	+
	Phenols	-	-	-	-	-	-	+
	Saponins	-	-	-	-	-	-	+
	Glycosides	+	-	-	-	-	-	+
	Tannins	-	-	-	-	-	-	-
	Terpenoids	-	-	+	-	-	-	-
	Phytosterols	-	-	-	-	-	-	+

bulbs are traditionally richer in organosulfur precursors and specialised phenolic acids compared to the larger, often milder *A. ampeloprasum* cultivars[5]. The higher density of bioactive compounds in garlic may provide a "buffering effect" against thermal degradation, allowing for a higher residual concentration after processing. These findings suggest that for maximum phytochemical retention during high-heat cooking, using *A. sativum* in a sesame oil medium is the most effective approach.

3.3 Effect of Oil-Mediated Stir-Frying on Total Phenolic and Flavonoid Content

The impact of oil-mediated stir-frying on the retention of total phenolic and flavonoid compounds in *A. sativum* (AS1, AS2) and *A. ampeloprasum* (AA1, AA2) cultivars was quantitatively evaluated using petroleum ether and hexane extracts, as these solvents demonstrated selective recovery of phenolic and flavonoid constituents during preliminary qualitative screening. The results are summarised in Table 8. A substantial reduction in both total phenolic and flavonoid contents was observed across all cultivars following stir-frying, confirming the susceptibility of these bioactive compounds to high-temperature processing. Among the three cooking oils examined, sesame oil consistently enabled greater retention of phenolic and flavonoid compounds, followed by olive oil, while refined sunflower oil resulted in the greatest losses. Hexane extracts of sesame oil processed *A. sativum* cultivars exhibited the highest phenolic and flavonoid contents, with AS1 showing maximum values of 3.1 ± 0.2 µg GAE mg^{-1} and 6.12 ± 0.2 µg QE mg^{1}, respectively. In contrast, sunflower oil–stir-fried samples displayed markedly lower levels, particularly in AA2, where phenolic content decreased to as low as 0.03 ± 0.2 µg GAE mg^{-1}. These findings indicate that sunflower oil promotes extensive degradation of polyphenolic compounds during stir-frying, likely due to enhanced oxidative reactions at elevated temperatures. Comparatively, olive oil–processed samples retained moderate levels of phenols and flavonoids; however, these values remained

Table 5. Qualitative phytochemical profile of *A. ampeloprasum* cultivars stir-fried in sesame oil

Cultivar	Phytoconstituent	Sesame oil extracts						
		Me	Et	Ac	Ch	Aq	Pe	He
AA1	Reducing sugars	+	+	+	+	+	+	+
	Amino acids	+	-	+	+	-	+	+
	Alkaloids	-	-	-	-	-	+	+
	Flavonoids	+	+	-	-	-	+	+
	Phenols	+-	-	-	-	-	-	+
	Saponins	-	-	-	-	-	-	-
	Glycosides	-	-	-	-	-	+	+
	Tannins	-	-	-	-	-	-	-
	Terpenoids	-	-	-	-	-	-	+
	Phytosterols	-	-	-	-	-	-	+
AA2	Reducing sugars	+	+	+	+	+	+	+
	Amino acids	+	-	-	+	-	+	+
	Alkaloids	-	-	+	-	-	-	-
	Flavonoids	-	-	-	-	-	+	+
	Phenols	-	-	+	-	-	-	+
	Saponins	-	-	-	-	-	-	+
	Glycosides	-	-	-	-	-	-	-
	Tannins	-	-	-	-	-	-	-
	Terpenoids	-	-	-	-	-	-	+
	Phytosterols	-	-	+	-	-	+	+

inferior to those obtained using sesame oil. The superior performance of sesame oil may be attributed to its inherent antioxidant constituents, including lignans such as sesamin and sesamol, which are known to mitigate thermal and oxidative degradation of polyphenolic compounds. This protective effect appears to stabilise phenolic structures during short-duration high-temperature processing.

Species-specific differences were also evident, with *A. sativum* cultivars demonstrating greater retention of phenolic and flavonoid compounds than *A. ampeloprasum* across all oil treatments. This variation may be linked to inherent differences in phytochemical composition, cellular architecture, and matrix interactions within the two species. Thermal degradation of phenolic compounds during stir-frying is further exacerbated by cell wall disruption, which exposes phenolics to oxidative enzymes and promotes their conversion into less active or polymerised forms. The observed decline in flavonoid content is particularly significant, as flavonoids contribute substantially to the antioxidant capacity of *Allium* vegetables. Previous studies have reported a direct correlation between flavonoid loss and reduced free radical scavenging activity following thermal processing, supporting the trends observed in the present investigation. Overall, the quantitative findings demonstrate that stir-frying significantly alters the polyphenolic profile of *Allium* vegetables, with the extent of loss being strongly influenced by the type of cooking oil employed. Among the oils tested, sesame oil provided a comparatively protective processing medium, preserving higher levels of phenolic and flavonoid compounds and thereby maintaining superior phytochemical quality.

The results of this study demonstrate that stir-frying significantly influences the phytochemical profile of both *A. sativum* and *A. ampeloprasum*, leading to a general reduction in Total Phenolic Content (TPC) and Total Flavonoid Content (TFC). This decrease is primarily attributed to the high-temperature thermal degradation (oxidation and hydrolysis) of these

Table 6. Qualitative phytochemical profile of *A. ampeloprasum* cultivars stir-fried in refined sunflower oil

Cultivar	Phytoconstituent	Refined Sunflower oil extracts						
		Me	Et	Ac	Ch	Aq	Pe	He
AA1	Reducing sugars	+	+	+	+	+	+	+
	Amino acids	+	+	+	+	-	+	+
	Alkaloids	-	-	-	-	-	-	-
	Flavonoids	-	-	-	-	-	+	+
	Phenols	-	-	+	-	-	-	+
	Saponins	-	-	-	-	-	-	-
	Glycosides	-	-	-	-	-	-	-
	Tannins	-	-	-	-	-	-	-
	Terpenoids	-	-	-	-	-	-	+
	Phytosterols	-	-	-	-	-	-	+
AA2	Reducing sugars	+	+	+	+	+	+	+
	Amino acids	-	+	-	-	-	+	+
	Alkaloids	-	-	-	-	-	-	-
	Flavonoids	-	-	-	-	-	+	+
	Phenols	-	-	-	-	-	+	+
	Saponins	-	-	-	-	-	-	-
	Glycosides	-	-	-	-	-	-	+
	Tannins	-	-	-	-	-	-	-
	Terpenoids	-	-	-	-	-	-	-
	Phytosterols	-	-	-	-	-	+	+

bioactive compounds during the stir-frying process. Similar findings have been reported in the literature, where pan-frying and deep-frying garlic were found to cause more substantial losses in antioxidant activity compared to milder methods like steaming or boiling[2,4]. A key observation in this study is the varying degree of protection offered by different cooking oils. Sesame oil exhibited a significantly higher protective effect on TPC and TFC compared to sunflower and olive oils. This superior performance can be linked to the unique chemical composition and high Oxidative Stability Index (OSI) of sesame oil. Unlike many other vegetable oils, sesame oil contains a specialised group of lignans, including sesamin, sesamolin, and sesamol. During the stir-frying process, sesamolin undergoes thermal conversion into sesamol, a potent antioxidant with exceptional radical-scavenging capacity at high temperatures (90–180 °C)[6,18]. These lignans create a stable reductive environment in the cooking medium, effectively mitigating the oxidative stress on the *Allium* phytochemicals and preventing their extensive degradation. In contrast, sunflower and olive oils, while containing vitamin E and other phenolics, lack these specific heat-activated lignans, making them more susceptible to oxidative breakdown at stir-frying temperatures, which in turn accelerates the loss of phenolics from the vegetable matrix[8].

Furthermore, the higher retention of bioactives in *A. sativum* (AS1, AS2) compared to *A. ampeloprasum* (AA1, AA2) may be attributed to differences in the baseline phytochemical concentration and the nature of the plant matrix. *A. sativum* is known to possess a higher initial density of organosulfur and phenolic compounds, which may provide a greater «buffer» against thermal loss compared to the leek-like matrix of *A. ampeloprasum*[10]. Statistical analysis confirmed that total phenolic and flavonoid contents differed significantly among oil treatments ($p < 0.05$), with sesame oil showing the highest retention, followed by olive oil and sunflower oil.

Table 7. Qualitative phytochemical profile of *A. ampeloprasum* cultivars stir-fried in olive oil

Cultivar	Phytoconstituent	Olive oil extracts						
		Me	Et	Ac	Ch	Aq	Pe	He
AA1	Reducing sugars	+	+	+	+	+	+	+
	Amino acids	+	-	-	+	-	+	+
	Alkaloids	-	-	+	+	-	-	-
	Flavonoids	-	-	+	-	-	-	+
	Phenols	-	+	-	-	-	-	+
	Saponins	-	-	-	-	-	-	-
	Glycosides	-	-	-	-	-	-	+
	Tannins	-	-	-	-	-	-	-
	Terpenoids	-	-	-	-	-	+	+
	Phytosterols	-	-	-	-	-	-	+
AA2	Reducing sugars	+	+	+	+	+	+	+
	Amino acids	-	-	-	+	-	+	+
	Alkaloids	-	-	-	-	-	-	+
	Flavonoids	-	-	-	-	-	+	+
	Phenols	-	-	-	-	-	-	+
	Saponins	-	-	-	-	-	-	-
	Glycosides	-	-	-	-	-	+	+
	Tannins	-	-	-	-	-	-	-
	Terpenoids	-	-	-	-	-	-	+
	Phytosterols	-	-	-	-	-	+	+

Table 8. Total phenolic and total flavonoid content in petroleum ether (Pe) and hexane (He) extracts of stir-fried *A. sativum* and *A. ampeloprasum* cultivars

Oil	Cultivar	Total Phenols (µg GAEmg^{-1})		Total Flavonoids (µg QEmg^{-1})	
		Pe	He	Pe	He
Sesame Oil	AS1	2.3 ±0.07^{a}	3.1 ±0.2^{a}	5.1 ±0.09^{a}	6.12 ±0.2^{a}
	AS2	1.81 ±0.2^{b}	1.41 ±0.07^{b}	3.23 ±2.1^{b}	3.41 ±1.2^{b}
	AA1	1.43 ±0.02^{c}	2.16 ±2.1^{b}	2.14 ±1.2^{c}	3.32 ±0.2^{b}
	AA2	1.56 ±0.09^{c}	0.41 ±1.2^{c}	2.21 ±2.1^{c}	2.55 ±0.09^{c}
Refined Sunflower Oil	AS1	0.21 ±0.03^{a}	1.3 ±0.2^{a}	1.41 ±0.09^{a}	2.36 ±0.03^{a}
	AS2	0.16 ±0.07^{a}	0.76 ±0.07^{b}	0.87 ±0.2^{b}	2.16 ±2.1^{a}
	AA1	0.14 ±1.2^{a}	0.45 ±0.02^{b}	0.96 ±0.03^{b}	1.41 ±0.09^{b}
	AA2	0.03 ±0.2^{b}	0.14 ±0.09^{c}	0.87 ±0.02^{b}	1.16 ±1.2^{c}
Olive Oil	AS1	1.47 ±2.1^{a}	2.42 ±1.2^{a}	3.41 ±0.07^{a}	3.97 ±0.03^{a}
	AS2	1.31 ±1.2^{a}	1.14 ±0.09^{b}	2.16 ±0.03^{b}	3.22 ±0.02^{b}
	AA1	1.41 ±2.1^{a}	1.03 ±2.1^{b}	1.11 ±0.2^{c}	2.46 ±0.03^{c}
	AA2	0.88 ±0.09^{b}	0.91 ±0.03^{b}	1.49 ±0.03^{c}	3.1 ±0.07^{b}

Abbreviations: Me – Methanol; Et – Ethanol; Ac – Acetone; Ch – Chloroform; Aq – Aqueous; Pe – Petroleum ether; He – Hexane. Values are expressed as mean ± SD (n = 3). Different superscript letters (a–c) within each column indicate statistically significant differences ($p < 0.05$) based on one-way ANOVA followed by Tukey's post-hoc test.

3.4 FTIR Analysis of Stir-Fried *Allium* Cultivars

Fourier Transform Infrared (FTIR) spectroscopy was employed to elucidate the functional group alterations induced by oil-mediated stir-frying in *A. sativum* (AS1, AS2) and *A. ampeloprasum* (AA1, AA2) cultivars. Based on qualitative and quantitative phytochemical outcomes, hexane extracts of sesame oil–stir-fried samples were selected for FTIR analysis to obtain insights into the structural integrity of retained bioactive constituents. The FTIR spectra and corresponding functional group assignments are presented in Figure 1 and Table 9, respectively. The spectra represent characteristic functional groups associated with phytochemical constituents, indicating variations in compound stability and retention under different oil-mediated thermal treatments. The FTIR spectra of all cultivars revealed prominent absorption bands corresponding to hydroxyl, amine, carbonyl, carboxyl, ether, ester, and sulfur-containing functional groups, indicating the presence of diverse phytochemical classes even after thermal processing. Broad absorption peaks observed between 3413–3436 cm^{-1} across all samples corresponded to O–H stretching vibrations, suggesting the retention of hydroxyl groups commonly associated with phenolic compounds. These findings corroborate the quantitative detection of phenols and flavonoids in sesame oil–processed samples. Absorption bands near 2920–2928 cm^{1} were attributed to N–H stretching vibrations, indicative of amino acid residues or nitrogen-containing compounds that remained stable under stir-frying conditions. The presence of peaks in the range of 1641–1644 cm^{-1} corresponded to C=O stretching vibrations, signifying carbonyl-containing compounds such as aldehydes, ketones, and carboxylic acids, which are often generated or modified during thermal processing.

Distinct absorption peaks between 1420–1439 $cm\text{-}^{1}$ were assigned to carboxyl functional groups, further supporting the formation or retention of organic acids and oxidised phenolic derivatives. Additionally, peaks observed around 1038–1158 cm^{-1} were characteristic of ether and ester linkages, suggesting lipid–phytochemical interactions and possible esterification events occurring during oil-mediated stir-frying. Importantly, weak absorption bands detected in the range of 710–714 cm^{-1} in selected cultivars indicated the presence of sulfur-containing functional groups. However, these peaks were less prominent, reflecting a partial loss or structural modification of sulfur-based compounds, which aligns with the reduced pyruvic acid content and the known thermal sensitivity of organosulfur metabolites in *Allium* species. The observed FTIR profiles demonstrate that stir-frying induces measurable alterations in the functional group composition of *Allium* vegetables, driven by high-temperature oil-mediated reactions such as oxidation, hydrolysis, and polymerisation. The comparatively

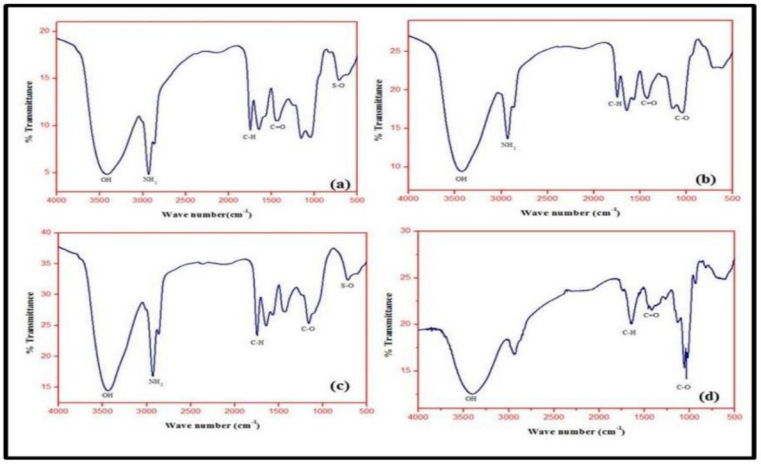


Figure 1. FTIR spectra of hexane extracts of stir-fried *Allium sativum* (AS1, AS2) and *Allium ampeloprasum* (AA1, AA2) cultivars processed using sesame, refined sunflower, and olive oils.

richer and more defined functional group patterns observed in sesame oil–processed samples suggest a protective influence of sesame oil constituents, potentially mitigating excessive oxidative degradation during cooking. Overall, FTIR analysis provided complementary structural evidence supporting the phytochemical and quantitative findings, confirming that the choice of cooking oil significantly influences the biochemical integrity of stir-fried *Allium* vegetables. The retention of hydroxyl and carbonyl functionalities, alongside partial preservation of sulfur-containing groups, underscores the role of sesame oil as a comparatively favourable medium for maintaining phytochemical quality during stir-frying.

The FTIR spectra provided structural confirmation of the phytochemical changes and interactions occurring during the oil-mediated stir-frying process. The broad absorption bands at 3413–3436 cm^{-1} (O–H stretching) in the sesame oil-processed samples correlate with the higher quantitative retention of phenolics and flavonoids discussed in section 3.3. These hydroxyl groups are characteristic markers for the aromatic rings of phenolic compounds, and their prominence in sesame oil extracts underscores the oil›s protective role[1,2]. The absorption peaks in the range of 1038–1158 cm^{-1} (fingerprint region) are particularly significant. These bands correspond to C–O stretching vibrations in ether and ester linkages.

Table 9. Comparative assessment of phytochemical profiles (TPC, TFC) and antioxidant capacities of *A. sativum* and *A. ampeloprasum*

S. No	Species and Variety	Reported TPC	Reported TFC	Antioxidant Assays and Results
1.	*A. sativum* (fresh garlic, aqueous and ethanolic extracts)	Aqueous: 303.07 ± 6.58 mg GAE/100 g; Ethanolic: 638.96 ± 15.30 mg GAE/100 g	Aqueous: 109.78 ± 6.78 mg QE/100 g; Ethanolic: 258.47 ± 12.37 mg QE/100 g	Total *in vitro* antioxidant activity measured; cooking temperature significantly affected antioxidant outcomes (DPPH/ABTS/FRAP not reported in abstract)[19].
2.	*A. sativum* processed products: white garlic (WG), green garlic (GG), Laba garlic (LAG), black garlic (BG)	Not presented as single TPC value in the abstract; antioxidant index correlated with phenol content	Flavonoid content correlated with antioxidant indices; BG had the highest activity among products	DPPH IC50 for black garlic (BG): 0.63 ± 0.02 mg/mL; hydroxyl radical scavenging IC50 (BG): 0.80 ± 0.01 mg/mL[20].
3.	*A. sativum* (raw, heated, aged garlic extracts)	Agedgarlic extract (AGE) TPC: 562.6 ± 1.92 mg/100 g GAE (higher than raw or heated extracts)	TFC was not numerically reported in the abstract; SODlike activity and other measures were reported qualitatively	DPPH SC50: heated garlic extract (HGE) had the highest SC50 (worst) at 2.1 mg/mL; SODlike activity order: RGE (raw) > AGE > HGE[21].
4.	*A. sativum* leaves (ultrasoundassisted extraction)	Optimised/predicted TPC 9.9 mg GAE/g (i.e., 990 mg GAE/100 g) under optimised UAE conditions	Optimised/predicted TFC 6.8 mg QE/g (i.e., 680 mg QE/100 g) under optimised UAE	Antioxidant activity predicted ~58% (assay reported as % in abstract, assay type not specified)[22].
5.	*A. sativum* (processing: pickling, frying, freezing, drying)	Processing reduced TPC in all treated samples versus fresh; freezing best preserved phenolics (no absolute values in abstract)	Processing reduced TFC in all treated samples versus fresh; freezing preserved flavonoids best	The reducing power of fresh garlic is highest; processed samples have lower reducing power than fresh[23].
6.	*A. sativum* HG17	Higher phenolic content in dry methanolic extract (DgM) compared with other HG17 forms; (numeric TPC not reported in abstract)	Higher flavonoid content in DgM versus other HG17 extracts	DPPH and ABTS: HG17 > Snow Mountain garlic (SMG); DgM exhibited maximum radical scavenging among HG17 extracts
7.	*A. ampeloprasum* Snow Mountain garlic (SMG)	Lower TPC in SMG versus HG17 under study conditions	Lower TFC in SMG versus HG17 extracts	DPPH and ABTS: SMG < HG17 in reported assays

In the context of stir-frying, these peaks likely signify lipid-phytochemical interactions, where the fatty acids from the cooking oil form ester or ether complexes with the *Allium* phenolics. Such interactions can effectively «trap» the bioactive compounds within the oil phase, reducing their volatility and susceptibility to thermal oxidation[1,2](1,2). The presence of these defined peaks in sesame oil-treated samples suggests a more robust formation of these protective complexes.The absorption bands at 2920–2928 cm^{-1} (N–H stretching) and 1641–1644 cm^{-1} (C=O stretching) reflect the presence of amino acid residues and carbonyl-containing products (such as organic acids or Maillard reaction intermediates), respectively. These functional groups remain relatively stable under the tested stir-frying conditions, contributing to the overall phytochemical diversity of the cooked product.

Finally, the weak absorption bands at 710–714 cm^{-1} are characteristic of C–S and S–S stretching vibrations associated with sulfur-containing functional groups. The reduced prominence of these peaks across all stir-fried samples provides spectroscopic evidence for the thermal degradation of allicin and other volatile organosulfur compounds. High heat triggers the breakdown of allicin into diallyl sulfides, disulfides, and other more stable but less FTIR-active derivatives, which is consistent with the significant reduction in pyruvic acid content (a marker for allicin potency) typically observed after frying[4,9]. Therefore, the combined quantitative and spectroscopic data suggest that sesame oil acts as a superior medium for stir-frying *Allium* vegetables, not only by providing a more stable antioxidant environment but also by potentially stabilising bioactives through lipid-phytochemical complexation. HG17 (*A. sativum*) showed higher DPPH and ABTS antioxidant activity than Snow Mountain garlic, with its dry methanolic extract richest in phenolics/flavonoids and containing unique polyphenols. Cooking and extraction methods strongly alter TPC, TFC, and antioxidant metrics across studies.This table compares reported TPC, TFC, antioxidant assay results, processing/extraction conditions, key phytochemicals, and main findings from studies on *A.sativum* and *A. ampeloprasum*, with Monika *et al.* (HG17) included for direct comparison. Numeric values are shown when reported in the source; otherwise, relative or qualitative outcomes are summarized with the supporting study cited.

4. Conclusion

This study demonstrates that the choice of cooking oil significantly dictates the phytochemical integrity and antioxidant stability of stir-fried *Allium* vegetables. While thermal processing induces structural modifications such as oxidation and the degradation of volatile organosulfur compounds, sesame oil serves as a superior medium for maintaining quality. FTIR analysis reveals that sesame oil facilitates protective lipid-phytochemical complexation, effectively stabilising bioactive hydroxyl and carbonyl functional groups. Consequently, stir-frying in sesame oil mitigates excessive oxidative damage compared to other methods, offering a more robust retention of health-promoting phenolics and flavonoids in processed garlic and leek cultivars.

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