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Using of Lemon Peels (*Citrus lemon*) in Production of Safety Foods for Cancer Patients

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ABSTRACT

This study aimed to use lemon peel in production of safety foods for cancer patients. Lemon peels were dried, milled and used in manufacture laboratory of gummy candy and herbal tea. Where, adding 0.5%, 1%, 2% lemon peel powder (LPP) to gummy candy and 40% , 50%, 70% to herbal tea. Gummy candy and lemon herbal tea were investigated for crude fiber, ash, total phenol content, phenols and flavonoids compounds identification and minerals composition. Moreover, cytotoxicity of LPP and sensory evaluation of gummy candy and lemon herbal tea samples were evaluated. The results showed that the LPP has a very good content of crude fibre, ash, total phenol, calcium, manganese and magnesium. In HepG2 cells, LPP showed dose dependent cytotoxicity with cell viability at doses of 62.5, 125, 250, 500 and 1000 µg/ml of LPP being 81.80, 65.77, 45.52, 45.29 and 2.11%, respectively and the IC50 value being 238.81 µg/ml in HepG2 cells. The usage of LPP caused enhancement in crude fibre, ash, total phenol, calcium, manganese and magnesium contents, improvement in phenolic and flavonoids compounds of the gummy candy and lemon herbal tea samples. Moreover, its overall acceptability had good score. Overall, the study demonstrates that lemon peel powder can be successfully utilized as a sustainable and value-added ingredient for developing functional food products with enhanced nutritional and phytochemical properties while contributing to the reduction of citrus-processing waste and supporting circular economy approaches.

Keywords: Lemon peel powder, anticancer, cytotoxicity, total phenols, gummy candy, lemon peel herbale tea, sustainability.

1. Introduction

Cancer is a globally meaningful death cause. drug expansion for cancer treatment has always been associated with side effects and a lot of limitations in applications. On the other hand, citrus peels that are in general discarded as waste to the environment can play as potential therapeutic resources add to their low-cost and available. Citrus fruit which are highly consumption worldwide belonging to the family *Rutaceae* and their peels have many health-properties such as antitumor, anti-inflammatory, antiproliferative and anticarcinogenic which have been related with many active compounds. Phenols and Flavonoids are bioactive substances in the citrus peel that are greatly related to anticancer potential, the flavonoid derivatives particularly polymethoxy flavones and flavone glycosides have potential anticancer effects including apoptosis, metastasis, angiogenesis, cell proliferation and cell cycle regulation. So, these bioactive rich citrus extracts can be utilize as a chemotherapeutic agent against the growth of different cancer cells such as breast cancer, colon cancer, prostate cancer, and others (Kawaii *et al*., 2000; Lario *et al*., 2004; Kosseva, 2013 and Mohd *et al*., 2024).

Lemon (*Citrus limon* L.) is one of the most widely cultivated citrus fruits worldwide and is extensively consumed in fresh and processed forms. The citrus-processing industry generates substantial quantities of by-products, particularly peels, which may constitute approximately 40–50% of the whole fruit weight. These by-products are frequently discarded as waste, causing environmental and economic concerns despite being rich sources of valuable bioactive compounds. Recent research

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has highlighted the importance of utilizing citrus by-products as sustainable functional ingredients in food systems and as part of circular economy strategies (Sharma *et al*., 2017; Mahato *et al*., 2021).

Lemon is the third most important in citrus After orange and tangerine. Annually, a third of the food produced (1.3 billion tons) of food is lost worldwide (Trigo *et al*., 2020). Lemon is a wealthy source of vitamin C, which plays as a water-soluble antioxidant, also, lemon peels rich in phenols and flavonoids it consider biologica activity and functional food (Rhodes, 2000; Aronson, 2001; Mohammadi & Mortazavian, 2011; Albishi *et al*., 2013; Nahed and Naeem., 2021; Abd-Alzahra and Makki, 2025). Lemon peel is divided into two different tissue types, flavido and albedo (Agust, 2003). Flavido is the outer layer of the peel and this is rich in essential oils, and its color is between green to yellow (Brat *et al*., 2001), which has been used since ancient times in the manufacture of flavors and perfumes (Vekiari *et al*., 2002). The main component of lemon peel is albedo (a spongy and cellulosic layer placed under the flavido), its thickness varies depending on the type and degree of maturity. Its high content of dietary fiber, when added to foods, yields healthy new products (Trumbo *et al*., 2002; Aleson-Carbonell *et al*., 2003). Finally, The use of lemon peel waste can help in the continuous feeding system, which increasing as a result of the continuous increase in the population and solutions to meet food needs, at the same time, it consider biological activity and functional foods (Sahar, 2022).

Lemon peels contain considerable amounts of dietary fiber, phenolic acids, flavonoids, essential oils, vitamins, and minerals. The major bioactive compounds identified in lemon peel include hesperidin, eriocitrin, rutin, quercetin, diosmin, kaempferol, chlorogenic acid, ferulic acid, gallic acid, and *p*-coumaric acid. These compounds have been associated with antioxidant, antimicrobial, anti-inflammatory, and potential health-promoting properties. Moreover, studies have demonstrated that citrus peels often contain higher concentrations of phenolic compounds and antioxidant constituents than the edible portions of the fruit (Ghasemi *et al*., 2009; Ferreira *et al*., 2022).

Gummy Candy is very popular with the public especially chledren and elderly people. It can be used as a snack because its sweety taste and refreshing. It is easy to carry anywhere due to its small size. As well, simple to manufacture by the home industry. It was produced from a mixture of hydrocolloids (gelling agents including gelatin) (Ciriminnaei *et al*., 2017), sugar syrup and citric acid. The addition of citric acid in the production of gummy candies leads to the desired elastic texture as it hydrolyses the gelatin (Ge *et al*., 2021; Mohd *et al*., 2024). Therefore, the present study was conducted to investigate the feasibility of incorporating lemon peel powder into gummy candy and herbal tea formulations and to evaluate their nutritional, phytochemical, antioxidant, sensory, and in vitro cytotoxic properties.

2. Materials and Methods

2.1. Materials

Lemon, gelatin, honey, lemon oil (LO), ginger, cinnamon, dry mint from local market. Other chemical ingredients used in the experimental analysis were of analytical grade (Al-Gomhorya Company for Chemicals, Cairo, Egypt).

2.2. Methods

2.2.1. Preparation of lemon powder (LPP)

Three kg Lemon from local market were prepared according to the method of Rahman *et al*. (2024) with some modifications. Lemon fruits were cleaned with tap water, the skin was manually peeled off and cut into pieces, then was dried at 50°C in a cabinet dryer for 42 h, milled into a fine powder using an electric grinder stainless steel (made in france; LM240 6A06 495 (b), Powder was sived (60 mesh), packed and stored at 4 °C.

2.2.2. Formulation of lemon peel powder herbal tea

Lemon peel powder herbal tea formulations were prepared according to method described by Ubbor *et al*., (2022) with slight modifications. Dried ginger powder (G), cinnamon powder (C), mint powder (M) and lemon peel powders (LPP) were blended in different proportions to produce five herbal tea formulations. Tea1 (T1) served as the ginger-based control formulation and consisted of 50% ginger, 25% cinnamon, and 25% mint. Tea 2 (T2) contained 100% lemon peel powder and served as the lemon peel control. The remaining formulations were prepared by partially replacing the ginger-based formula with lemon peel powder at levels of 40%, 50%, and 70%, designated as T3, T4, and T5, respectively. The composition of the herbal tea formulations is presented in Table 1.

Table 1: Formulation of lemon peel powder herbal Tea samples (%)

Ingredient (%)	Samples				
	T1	T2	T3	T4	T5
Lemon peel powder (LPP)	-	100	40	50	70
Ginger powder (G)	50	-	30	25	15
Cinnamon powder (C)	25	-	15	12.5	7.5
Mint powder (M)	25	-	15	12.5	7.5
Total	100	100	100	100	100

T1 = 50% Ginger+25% Cinnamon+ 25% Mint; T2 = 100% lemon peel powder; T3 = 40% LPP + 30% ginger+15% Cinnamon +15% Mint ; T4 = 50% LPP + 25% ginger+12.5% Cinnamon +12.5% Mint; T5 = 70% LPP + 15% ginger+7.5% Cinnamon +7.5% Mint.

2.2.3. Preparation of lemon peel powder gummy candy

Gummy candy samples were prepared according to the method of Mohd *et al*., (2024) with slight modifications. The formulations used for gummy candy preparation are presented in Table 2. Gelatin solution was prepared by dispersing gelatin in warm water and allowing it to bloom for 10 minutes. Honey, sugar and citric acid were dissolved in the remaining water and heated to 70˚C with continuous stirring. The mixture was heated until a temperature of 116˚C was reached. The syrup was then cooled to approximately 60°C, after which LPP and lemon oil (LO) were added and thoroughly mixed. The bloomed gelatin was subsequently incorporated into the mixture and stirred until a homogeneous gel-like consistency was obtained. Air bubbles were removed and the mixture was poured into silicone moulds. The molded samples were refrigerated at 4˚C for 24 h to allow complete gel formation. After setting, the gummy candies were demoulded and stored in airtight polypropylene containers at 25˚C until further analysis.

Table 2: Formulation of lemon peel powder gummy candy samples (%)

Ingredients %	Samples			
	GC1	GC2	GC3	GC4
Water	60.90	60.40	59.85	58.8
Honey	20.00	20.00	20.00	20.00
Sugar	5.00	5.00	5.00	5.00
Gelatin	12.00	12.00	12.00	12.00
Citric acid	2.00	2.00	2.00	2.00
Lemon peel powder (LPP)	0.00	0.5	1.00	2.00
Lemon oil (LO)	0.10	0.10	0.15	0.20

GC1 = Control gummy candy; GC2 = gummy candy containing 0.5% LPP; GC3 = gummy candy containing 1.0% LPP; GC4 = gummy candy containing 2.0% LPP.

2.2.4. Sensory evaluation

The Sensory evaluation of gummy candies and tea samples were conducted according to the method described by Said *et al*., (2019) with slight modifications. A panel of ten trained assessors evaluated the sensory characteristics of the gummy candies and tea samples. The evaluated attributes included appearance, taste, texture, aroma and overall acceptability. whereas every quality received a score ranging from 1 (poor) to 10 (great).

2.3. Analytical Methods

2.3.1. Cytotoxicity determination by Sulforhodamine B (SRB) assay for LPP

The cytotoxicity effect of LPP was performed in Nawah Scientific Inc., (Mokatam, Cairo, Egypt), which detected against HepG2: Hepatocellular carcinoma according to Allam et al., 2018 and Skehan et al., 1990. Cells were maintained in DMEM media supplemented with 100 mg/mL of streptomycin, 100 units/mL of penicillin and 10% of heat inactivated fetal bovine serum in humidified, 5% (v/v) CO2 atmosphere at 37 °C. Cell viability was assessed by SRB assay. Aliquots of 100 µL cell suspension (5x10^3 cells) were in 96-well plates and incubated in complete media for 24 h. Cells were treated with another aliquot of 100 µL media containing drugs at various concentrations. After 72 h of drug exposure, cells were fixed by replacing media with 150 µL of 10% TCA and incubated at 4 °C for 1 h. The TCA solution was removed, and the cells were washed 5 times with distilled water. Aliquots of 70 µL SRB solution (0.4% w/v) were added and incubated in a dark place at room temperature for 10 min. Plates were washed 3 times with 1% acetic acid and allowed to air-dry overnight. Then, 150 µL of TRIS (10 mM) was added to dissolve protein-bound SRB stain; the absorbance was measured at 540 nm using a BMG LABTECH®- FLUOstar Omega microplate reader (Ortenberg, Germany).

2.3.2. Chemical composition

Crud fiber and ash of LPP, LPP herbal tea, LPP gummuy candy were estimated according to A.O.A.C. (2007).

2.3.3. Minerals composition:

LPP, herbal tea and gummy candy samples were determined for minerals composition in terms of Ca, Fe, Mg, Mn, Cu, Zn according to AOAC (2007) by Desert Research Centre, Cairo, Egypt. Minerals concentration was indicated as the average value (mg/100mg of dry weight).

2.3.4. Total phenols

The prepared extracts of LPP and gummy candy& LPP Tea were carried out according to Carciochi *et al*. (2014) with some modification:

- Two grams of powder were homogenized with 20 mL of 80% ethanol. The mixture was kept in the dark at room temperature overnight, filtered (0.45 µm) and stored at -18°C until determination.
- Total phenols were determined according to the methodology described by Renata *et al.* (2012). One milliliter of alcoholic extract was added to 1 mL 95% ethanol, 5 mL distilled water and 0.5 mL 1N Folin-Ciocalteu reagent. After 5 min, 1 mL 5% Na2CO3 was added, and the reagent mixture was kept for60 min at room temperature. The quantification of phenolic compounds was performed spectrophotometrically by measuring the absorbance in UV-VIS spectrophotometer Shimadzu 1240, at 725 nm, and a gallic acid (10-100 µg/mL) in 95% ethanol was used for obtaining a standard curve.

2.3.5. Antioxidant activity

Antioxidant activity of LPP, herbal tea and gummy candy were evaluated by determine the DPPH free radical scavenging of all samples under study according to Shekhar and Anju, (2014).

2.3.6. Phenolic compounds identification

Phenolic and flavonoid compounds of LPP and gummy candy& LPP Tea samples were identified by using high performance liquid chromatography (HPLC) analysis according to Biswas *et al*. (2013) in Desert Research Center laboratories, Cairo, Egypt. The instrument Condition was: system Thermo (Ultimate 3000) consisted of: pump, automatic sample injector and DELL-compatible computer supported with Cromelion7 interpretation program. A diode array detector DAD-3000 was used. The Thermohypersil reversed phase C18 column 2.5× 30 cm was operated at 25º C. Mobile phase consists of 0.05% Trifluoroacetic acid/Acetonitrile (solvent A) and distilled water (solvent B). The UV absorption spectra of both standards and samples were registered in range of 230–400 nm. Samples, standards solutions and the mobile phase were degassed then purified by using 0.45 µm membrane filter (Millipore). Sample preparation :0.1 gm of sample dissolved in 10 ml methanol, in vortex for 10 minutes, then filtered and stocked under cooling conditions (4°C). Identification of the compounds was done by comparison of their retention's time and UV absorption spectrum with those of the standards.

2.4. Statistical Analysis

Statistical Analysis All experiments in this study were reported as means of triplicate determinations. One way analysis of variance were carried out using the Statistical Product of Service Solution (SPSS) version 20 to compare between the mean values while treatment means were separated using Duncan multiple range test at 95 % confidence level ($p<0.05$) (Ubbor *et al*., 2022).

3. Results and Discussion

3.1. Cytotoxicity determination by Sulforhodamine B (SRB) assay for lemon peel powder (LPP):

The Sulforhodamine B (SRB) assay is a widely used colorimetric method for evaluating cytotoxicity by measuring cell viability and cellular protein content (Vichai and Kirtikara, 2006). The cytotoxic activity of lemon peel powder (LPP) extract against HepG2 cells (human hepatocellular carcinoma cell line) is presented in Figure 1.

The results demonstrated a dose-dependent cytotoxic effect of LPP extract on HepG2 cells after 72 h of exposure. Cell viability decreased progressively with increasing concentrations of the extract. The percentages of viable HepG2 cells at LPP extract concentrations of 62.5, 125, 250, 500, and 1000 µg/mL were 81.80%, 65.77%, 45.52%, 45.29%, and 2.11%, respectively. The IC_{50} value was calculated to be 238.81 µg/mL, indicating moderate cytotoxic activity against HepG2 cells. These findings suggest that increasing the concentration of LPP extract significantly reduces cell viability, reflecting its potential antiproliferative effect.

The observed cytotoxic activity may be attributed to the high content of bioactive phytochemicals present in lemon peels, particularly flavonoids, phenolic compounds, polymethoxyflavones, and other antioxidant constituents. These compounds have been reported to exhibit anticancer properties through several mechanisms, including inhibition of cell proliferation, suppression of inflammation and angiogenesis, and induction of apoptosis in cancer cells.

The present results are in agreement with those reported by Kumar *et al*. (2012); Rawson *et al*. (2014) and Diab *et al*. (2015), who demonstrated that citrus peel extracts possess significant antitumor activities against various cancer types, including skin, colon, prostate, lung, and liver cancers. Furthermore, Diab (2016) and Selim *et al*. (2019) reported that lemon peel extracts exhibited pronounced cytotoxic effects against liver cancer cells, which were largely attributed to their rich flavonoid and phenolic profiles. Therefore, the cytotoxic activity observed in the present study highlights the potential of lemon peel powder as a natural source of bioactive compounds with promising anticancer properties.

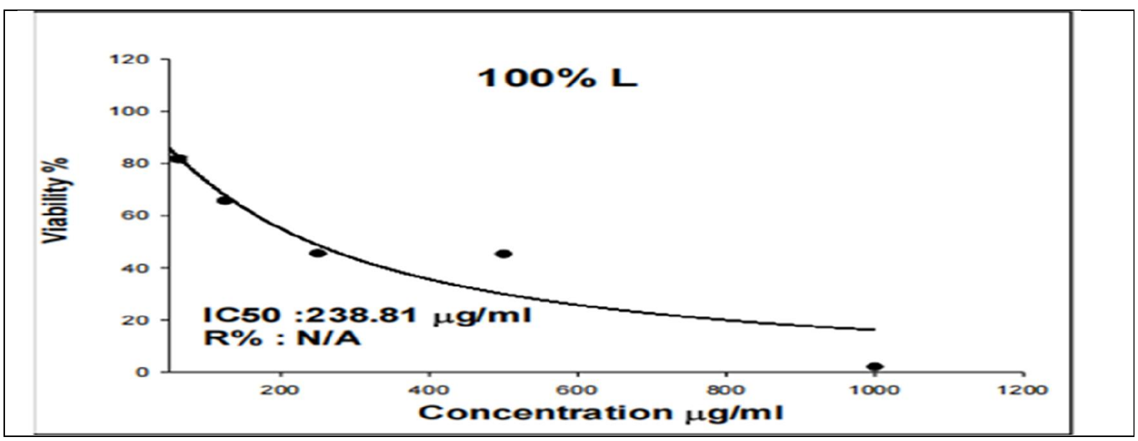

Fig. 1. Cytotoxic activity of lemon peel powder (LPP) extract against HepG2 cells determined by the Sulforhodamine B (SRB) assay after 72 h of incubation. Values are expressed as percentage cell viability relative to the untreated control. The IC_{50} value was calculated as 238.81 µg/mL.

3.2. Sensory evaluation of gummy candies:

Sensory evaluation is essential for determining the consumer acceptability of food products. The sensory attributes of gummy candies fortified with lemon peel powder (LPP) are presented in Table 3. The results showed no significant differences ($p > 0.05$) among all samples in terms of appearance and aroma, indicating that the incorporation of LPP up to 2% did not adversely affect these attributes.

Regarding taste and texture, significant differences ($p < 0.05$) were observed among the treatments. The control sample (GC1) and the gummy candy containing 0.5% LPP (GC2) achieved the highest scores and did not differ significantly from each other. In contrast, samples containing higher levels of LPP exhibited lower sensory scores. GC3 (1% LPP) and GC4 (2% LPP) recorded taste scores of 9.25 and 8.75, respectively, while texture scores were 9.50 and 8.50, respectively.

A similar trend was observed for overall acceptability. GC1 and GC2 received the highest overall acceptability scores (10.00 and 9.75, respectively), followed by GC3 (9.17) and GC4 (8.92). These findings indicate that the incorporation of LPP at low levels (0.5%) can maintain desirable sensory characteristics, whereas higher concentrations may negatively affect consumer preference.

The present results are consistent with those reported by Nikita *et al*. (2016), who found that gummies containing 5% lemon peel powder received higher scores for appearance, taste, texture, aroma, and overall acceptability than samples containing 15% lemon peel powder. The reduction in sensory scores at higher LPP levels may be attributed to the increased dietary fiber content and the development of a slightly bitter taste associated with citrus peel components, which can adversely affect texture and palatability. Similar observations were reported by Chandra and Priyanti (2024), who noted that increasing the levels of psyllium husk, chia seeds, and tamarind ingredients rich in dietary fiber resulted in lower texture and overall acceptability scores in gummy candy formulations.

Table 3: Sensory evaluation of gummy candies supplemented with lemon peel powder (LPP)

Samples	Appearance (10)	Taste (10)	Aroma (10)	Texture (10)	Overall acceptability (10)
GC1	10±0^{a}	10±00000^{a}	10±0^{a}	10±0000^{a}	10±00000^{a}
GC2	10±0^{a}	10±00000^{a}	10±0^{a}	10±0000^{a}	9.75±0.42^{a}
GC3	10±0^{a}	9.25±0.27^{b}	10±0^{a}	9.5±0.45^{b}	9.17±0.26^{bc}
GC4	10±0^{a}	8.75±0.27^{c}	10±0^{a}	8.5±0.55^{c}	8.92±0.23^{c}

GC1 = Control (without LPP); GC2 = 0.5% LPP; GC3 = 1% LPP; GC4 = 2% LPP. Values are expressed as mean ± SD (n = 3). Means within the same column followed by different letters are significantly different at $p < 0.05$.

3.3. Sensory evaluation of lemon peel powder herbal tea.

The sensory evaluation of herbal tea samples containing different proportions of ginger formula (GF) and lemon peel powder (LPP) is presented in Table 4. The results showed no significant differences among the samples (T1, T2, T3, T4, and T5) in terms of appearance, aroma, and texture, indicating that the incorporation of LPP did not adversely affect these sensory attributes.

However, significant differences ($p < 0.05$) were observed in taste and overall acceptability. The highest taste scores were recorded for T1 (100% ginger formula), T3 (60% GF : 40% LPP), and T4 (50% GF : 50% LPP), with values of 9.67, 9.67, and 9.25, respectively. These samples also exhibited the highest overall acceptability scores, with T1, T3, and T4 each receiving a score of 10.00. In contrast, T5 (30% GF : 70% LPP) and T2 (100% LPP) recorded significantly lower taste scores of 8.08 and 7.92, respectively, as well as lower overall acceptability scores of 9.33 and 7.92, respectively.

The decline in taste and overall acceptability observed at higher levels of LPP may be attributed to the bitter and astringent compounds naturally present in citrus peels, which can negatively affect flavor perception and consumer preference. Nevertheless, the incorporation of moderate levels of LPP improved the sensory quality of the herbal tea while providing additional nutritional and functional benefits.

These findings are consistent with those reported by Ubbor *et al*. (2022), who demonstrated that herbal teas produced from moringa leaves, lemon peel powder, and their blends possess valuable nutritional and therapeutic properties due to their rich chemical and phytochemical composition.

Furthermore, the utilization of lemon peel powder in herbal tea production adds value to an agricultural by-product and contributes to waste reduction. However, excessive inclusion of lemon peel powder may increase bitterness and astringency, thereby reducing taste scores and overall consumer acceptability. So, some drops of lemon oil were added to lemon peel powder tea to improve the bitter taste with high percent.

Table 4: Sensory evaluation of lemon peel powder herbal tea (T)

Samples	Appearance (10)	Taste (10)	Aroma (10)	Texture (10)	Overall acceptability (10)
T1	10±0^{a}	9.67±0.41^{a}	10±00000^{a}	10±0^{a}	10±00000^{a}
T2	10±0^{a}	7.92±0.58^{c}	9.58±0.38^{a}	10±0^{a}	7.92±0.38^{c}
T3	10±0^{a}	9.67±0.52^{a}	10±0000^{a}	10±0^{a}	10±00000^{a}
T4	10±0^{a}	9.25±0.27^{a}	10±0000^{a}	10±0^{a}	10±00000^{a}
T5	10±0^{a}	8.08±0.58^{b}	9.55±0.92^{a}	10±0^{a}	9.33±0.52^{b}

T1 = Control 1 (100% ginger formula, GF); T2 = Control 2 (100% lemon peel powder, LPP); T3 = 60% GF : 40% LPP; T4 = 50% GF : 50% LPP; T5 = 30% GF : 70% LPP. Values are expressed as mean ± SD (n = 3). Means within the same column followed by different letters are significantly different at $p < 0.05$.

3.4. Fiber, ash, and total phenolic content of lemon peel powder gummy candy

The fiber, ash, and total phenolic contents of gummy candies supplemented with lemon peel powder (LPP) are presented in Table 5. The results showed that the incorporation of LPP significantly increased ($p < 0.05$) the fiber, ash, and total phenolic contents of the gummy candy samples compared with the control (GC1).

Among all treatments, GC4 (2% LPP) exhibited the highest fiber content (1.25%), followed by GC3 (1% LPP) and GC2 (0.5% LPP), with values of 0.62 % and 0.32%, respectively, whereas the control sample (GC1) contained no detectable fiber (0.00%). A similar trend was observed for ash content, where GC4 recorded the highest value (0.14 ± 0.01%), followed by GC3 (0.06%) and GC2 (0.03 %), while GC1 showed no detectable ash content.

Table 5: Fiber, ash, and total phenolic contents of gummy candies supplemented with lemon peel powder (LPP)

Parameters %	Samples			
	GC1	GC2	GC3	GC4
Fiber (%)	0±0^{d}	0.32±0.010^{c}	0.62±0.01^{b}	1.25±0.01a
Ash (%)	0±0^{d}	0.03±0.001^{c}	0.06±0.02^{b}	0.14±0.01a
Total phenols mg/g	0.74±0.01^{d}	0.75±0.020^{c}	0.79±0.02^{b}	0.83±0.3a

GC1 = Control (without LPP); GC2 = 0.5% LPP; GC3 = 1% LPP; GC4 = 2% LPP. Values are expressed as mean ± SD (n = 3). Means within the same row followed by different letters are significantly different at $p < 0.05$.

Regarding total phenolic content, GC4 also exhibited the highest value (0.83 mg/g), followed by GC3 (0.79 mg/g) and GC2 (0.75 mg/g), whereas the control sample recorded the lowest value (0.74 mg/g). These results indicate that increasing the level of LPP in the gummy candy formulation enhanced its functional and nutritional properties.

The observed increases in fiber, ash, and total phenolic contents can be attributed to the naturally high concentrations of these components in lemon peel powder, which contains approximately 63 g/100 g dietary fiber, 6.7 g/100 g ash, and 15.48 mg/g total phenolic compounds. Similar findings were reported by Daniela *et al*. (2025), who demonstrated that lemon peel powder is an excellent source of dietary fiber, containing approximately 85 g/100 g. Furthermore, Abdel Wahab *et al*. (2018) reported ash contents of 7.92 g/100 g and 7.72 g/100 g in sun-dried and oven-dried lemon peel powder, respectively. The present findings are also consistent with those of Durmuş *et al*. (2023), who reported that lemon peel powder contains 16.7 mg/g total phenolic compounds on a dry matter basis. Therefore, the enrichment of gummy candies with LPP can improve their nutritional quality and increase their content of bioactive compounds with potential health-promoting properties.

3.5. Fiber, ash, and total phenolic content of lemon peel powder herbal tea

The fiber, ash, and total phenolic contents of herbal tea formulations containing different proportions of ginger formula (GF) and lemon peel powder (LPP) are presented in Table 6. The results showed significant differences ($p < 0.05$) among the tested formulations, indicating that the incorporation of LPP markedly influenced the nutritional and functional properties of the herbal tea blends.

The highest fiber content was recorded in T2 (100% LPP), with a value of 63.02 %, followed by T5 (30% GF : 70% LPP), T3 (60% GF : 40% LPP), and T4 (50% GF : 50% LPP), with values of 50.77 %, 46.72 %, and 42.62 %, respectively. In contrast, T1 (100% GF) exhibited the lowest fiber content (22.30 %).

Regarding ash content, T2 also recorded the highest value (6.71 %), followed by T3 and T5 (6.63 % for both samples), while T4 contained 6.58 %. The lowest ash content was observed in T1 (6.18 %). Similarly, total phenolic content increased with increasing levels of LPP in the formulation. T2 (100% LPP) showed the highest total phenolic content (15.48 mg/g), followed by T5 (13.02 mg/g), T3 (11.88 mg/g), and T4 (11.33 mg/g), whereas T1 (100% GF) recorded the lowest value (7.25 mg/g).

The enhancement in fiber, ash, and total phenolic contents observed in the LPP-containing formulations can be attributed to the naturally high concentrations of these constituents in lemon peel powder. Lemon peel is recognized as a rich source of dietary fiber, minerals, and phenolic compounds, which contribute to its nutritional and antioxidant potential. Similar findings were reported by Daniela *et al*. (2025), who found that lemon peel powder contains approximately 85 g/100 g dietary fiber. Furthermore, Abdel Wahab *et al*. (2018) reported ash contents of 7.92% and 7.72% in sun-dried and oven-dried lemon peel powder, respectively. The present results are also in agreement with those of Durmuş *et al*. (2023, 2024), who reported that lemon peel powder contains approximately 16.7 mg/g total phenolic compounds on a dry matter basis. Therefore, the incorporation of LPP into herbal tea formulations can significantly improve their nutritional value and enrich them with bioactive compounds possessing potential health-promoting and antioxidant properties.

Table 6: Fiber, ash, and total phenolic contents of herbal tea formulations supplemented with lemon peel powder (LPP)

Parameters	Samples				
	T1	T2	T3	T4	T5
Fiber (%)	22.3 ± 0.05^{f}	63.02 ± 0.17^{a}	46.72 ± 0.08^{c}	42.62 ± 0.01^{d}	50.77 ± 0.02^{b}
Ash (%)	6.18 ± 0.03^{c}	6.71 ± 0.26^{a}	6.63 ± 0.01^{ab}	6.58 ± 0.000^{b}	6.63 ± 0.01^{ab}
Total phenols mg/g	7.25 ± 0.05^{e}	15.48 ± 0.1^{a}	11.88 ± 0.25^{c}	11.33 ± 0.07^{d}	13.02 ± 0.01^{b}

T1 = Control 1 (100% ginger formula, GF); T2 = Control 2 (100% lemon peel powder, LPP); T3 = 60% GF : 40% LPP; T4 = 50% GF : 50% LPP; T5 = 30% GF : 70% LPP. Values are expressed as mean ± SD (n = 3). Means within the same row followed by different letters are significantly different at $p < 0.05$.

3.6. Antioxidant activity of lemon peel powder gummy candy and herbal tea

Phenolic compounds present in citrus peels are recognized for their strong antioxidant properties and their potential role in preventing oxidative stress-related disorders. Individual phenolic compounds and their mixtures extracted from citrus peels have been reported to exhibit significant antioxidant activity due to their ability to scavenge free radicals and inhibit oxidative reactions (Durmuş *et al*., 2024).

The antioxidant activity of gummy candies supplemented with lemon peel powder (LPP) is presented in Figure 2. The results showed that antioxidant activity, expressed as DPPH radical scavenging activity, increased significantly with increasing levels of LPP in the formulation. The highest DPPH value was observed in GC4 (2% LPP) (29.41 %), followed by GC3 (1% LPP) (25.43 %)

and GC2 (0.5% LPP) (23.65 %). In contrast, the control sample GC1 (without LPP) recorded the lowest antioxidant activity (22.92 %). These findings indicate that the addition of LPP enhanced the antioxidant capacity of gummy candies owing to its high content of phenolic compounds and other bioactive constituents.

The antioxidant activity of herbal tea formulations containing different proportions of ginger formula (GF) and LPP is shown in Figure 3. Among all samples, T2 (100% LPP) exhibited the highest DPPH radical scavenging activity (93.00 %), followed by T5 (30% GF : 70% LPP), T3 (60% GF : 40% LPP), and T4 (50% GF : 50% LPP), with values of 90.91 %, 90.31 %, and 89.92 %, respectively. The lowest antioxidant activity was recorded in T1 (100% GF), with a value of 88.69 %.

The observed increase in antioxidant activity with increasing levels of LPP may be attributed to the high concentration of phenolic compounds, flavonoids, vitamin C, and other antioxidant constituents naturally present in lemon peel. The strong positive relationship between total phenolic content and antioxidant activity observed in the present study suggests that phenolic compounds are major contributors to the free radical scavenging capacity of the tested products.

These findings are consistent with those reported by Durmuş *et al*. (2024), who demonstrated that lemon peel powder contains considerable amounts of phenolic compounds that contribute significantly to its antioxidant potential. Similarly, Daniela *et al.* (2025) reported that lemon peel dietary fiber and its associated bioactive components, including phenolic compounds and essential oils, exhibit strong antioxidant activity. Therefore, the incorporation of lemon peel powder into gummy candy and herbal tea formulations can enhance their functional value by increasing their antioxidant capacity and providing additional health-promoting benefits.

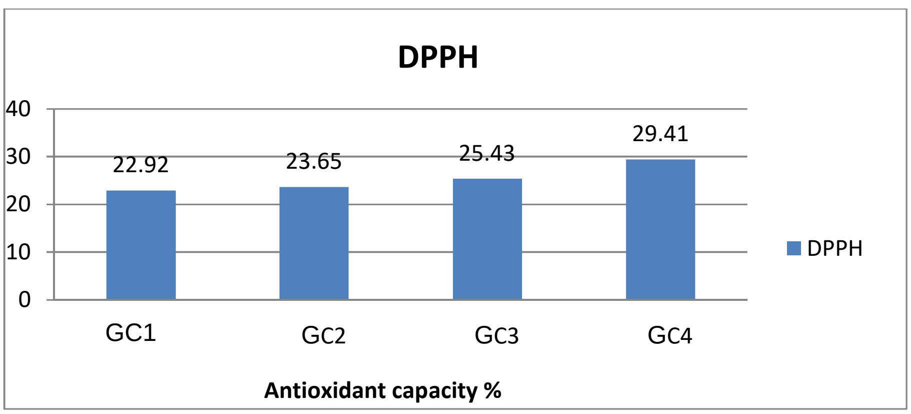

Fig. 2. DPPH radical scavenging activity (%) of gummy candies supplemented with different levels of lemon peel powder (LPP).

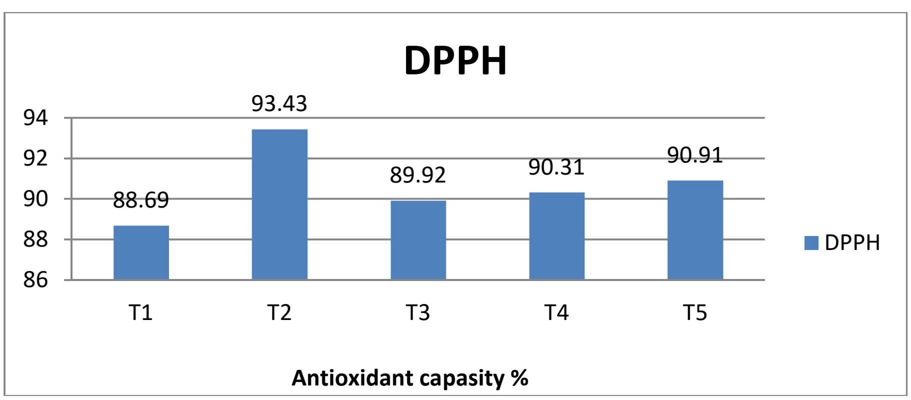

Fig. 3: DPPH radical scavenging activity (%) of herbal tea formulations containing different proportions of ginger formula (GF) and lemon peel powder (LPP).

3.7. Identification of phenolic and flavonoid compounds in lemon peel powder gummy candy

Phenolic compounds and flavonoids extracted from citrus peels possess numerous biological activities, particularly antioxidant properties. These compounds contribute significantly to the health-promoting potential of citrus by-products and are relatively stable during processing and drying. Flavonoids exert their antioxidant effects through free radical scavenging, enhancement of antioxidant enzyme activities, and inhibition of oxidative enzymes (Durmuş *et al*., 2024).

The identified phenolic compounds in gummy candies supplemented with lemon peel powder (LPP) are presented in Table 7. The results showed that the concentrations of all identified phenolic compounds increased with increasing levels of LPP in the formulation. Among the tested samples, GC4 (2% LPP) exhibited the highest concentrations of quinic acid, gallic acid, chlorogenic acid, resorcinol, pyrocatechol, vanillic acid, p-coumaric acid, ellagic acid, ferulic acid, and cinnamic acid, with values of 12.57, 12.35, 11.03, 6.29, 51.18, 2.94, 1.49, 2.35, 5.30, and 9.22 mg/100 g, respectively. In contrast, the control sample (GC1) recorded the lowest concentrations of these compounds, with values of 0.10, 0.10, 0.20, 0.01, 0.025, 0.01, 0.02, 0.01, 0.01, and 0.20 mg/100 g, respectively.

Table 7: Identification of phenolic and flavonoid compounds in gummy candies supplemented with lemon peel powder (LPP) (mg/100 g).

	Samples			
	GC 1	**GC 2**	**GC 3**	**GC 4**
Phenols				
Quinic	0.10	3.45	6.25	12.57
Galic acid	0.10	3.52	6.89	12.35
Choloroginic	0.20	2.63	5.01	11.03
Resorcinol	0.01	1.78	3.55	6.29
Pyrocatechol	0.02	12.21	25.72	51.18
Vailinic	0.01	0.47	1.89	2.49
Coumaric	0.02	0.38	0.79	1.49
Ellagic	0.01	0.69	1.21	2.35
Ferulic	0.01	1.47	2.90	5.30
Cinnamic	0.20	2.47	4.85	9.22
Flavonoid				
Apeginin	0.07	18.99	38.70	76.40
Diosmin	0.01	0.06	0.14	0.30
Rutin	0.10	0.19	0.21	0.36
Hisperidin	0.03	0.53	1.13	2.22
Kamperol	0.03	0.33	0.69	1.37
Qurecetin	0.02	0.79	1.61	3.07

GC1 = Control (without LPP); GC2 = 0.5% LPP; GC3 = 1% LPP; GC4 = 2% LPP. Values are expressed as mg/100 g of sample.

The progressive increase in phenolic compounds with increasing LPP incorporation can be attributed to the naturally high phenolic content of lemon peel powder. These findings are in agreement with Bao *et al*. (2020) and Durmuş and Kılıç-Akyılmaz (2023), who reported that lemon peel powder is a rich source of phenolic acids, particularly gallic, p-coumaric, and ferulic acids.

Regarding flavonoid compounds, a similar trend was observed. GC4 (2% LPP) contained the highest concentrations of apigenin, diosmin, rutin, hesperidin, kaempferol, and quercetin, recording values of 76.40, 0.30, 0.36, 2.22, 1.37, and 3.07 mg/100 g, respectively. Conversely, the control sample (GC1) showed the lowest concentrations, with values of 0.07, 0.01, 0.10, 0.025, 0.03, and 0.02 mg/100 g, respectively.

The substantial increase in flavonoid content in LPP-enriched gummy candies reflects the richness of lemon peel in bioactive flavonoids. These compounds are known for their antioxidant, anti-inflammatory, and health-promoting effects. The present findings are consistent with those reported by

Bao *et al*. (2020) and Durmuş and Kılıç-Akyılmaz (2023), who identified rutin, hesperidin, kaempferol, and quercetin as major flavonoids present in lemon peel powder. Therefore, the incorporation of LPP into gummy candy formulations significantly enhances their phytochemical profile and functional properties through enrichment with valuable phenolic and flavonoid compounds.

3.8. Identification of phenolic and flavonoid compounds in lemon peel powder herbal tea

The identification and quantification of phenolic and flavonoid compounds in herbal tea formulations containing different proportions of ginger formula (GF) and lemon peel powder (LPP) are presented in Table 8. Phenolic compounds are among the most important bioactive constituents of citrus peels and contribute significantly to their antioxidant, anti-inflammatory, and potential anticancer activities.

The results showed that T2 (100% LPP) contained the highest concentrations of most identified phenolic compounds, including quinic acid, gallic acid, chlorogenic acid, resorcinol, pyrocatechol, vanillic acid, ellagic acid, and ferulic acid, with values of 553.00, 587.00, 498.00, 1170.00, 1989.00, 68.88, 224.25, and 417.25 mg/100 g, respectively. In contrast, T1 (100% GF) exhibited the lowest concentrations of these compounds, recording values of 323.63, 105.75, 255.00, 540.75, 1088.88, 9.00, 94.50, and 169.88 mg/100 g, respectively. However, T1 showed the highest concentrations of p-coumaric acid and cinnamic acid, with values of 186.75 and 362.63 mg/100 g, respectively, compared with the other formulations.

Table 8. Identification of phenolic and flavonoid compounds in herbal tea formulations supplemented with lemon peel powder (LPP) (mg/100 g)

	Samples				
	T1	**T2**	**T3**	**T4**	**T5**
Phenols					
Quinic	323.36	553.00	335.22	341.00	451.66
Galic acid	105.75	587.00	180.21	196.88	313.88
Choloroginic	255.00	498.00	237.13	243.55	342.55
Resorcinol	540.75	1170.00	495.43	521.13	755.47
Pyrocatechol	1088.88	1989.00	112.56	957.50	1344.35
Vailinic	9.00	68.88	29.61	35.25	49.52
Coumaric	186.75	11.13	69.88	88.13	75.64
Ellagic	94.50	224.25	102.34	111.88	155.88
Ferulic	169.88	417.25	199.66	218.88	301.88
Cinnamic	362.63	299.38	203.14	213.00	271.12
Flavonoid					
Apeginin	3887.85	4991.01	4235.21	4285.23	4293.21
Diosmin	0.62	2.76	2.74	2.74	2.75
Rutin	8.99	24.03	21.43	20.68	22.35
Hisperidin	91.03	171.53	137.66	146.56	152.99
Kamperol	32.22	77.84	29.99	35.35	55.11
Qurecetin	105.80	241.73	193.45	184.87	210.31

T1 = Control 1 (100% ginger formula, GF); T2 = Control 2 (100% lemon peel powder, LPP); T3 = 60% GF: 40% LPP; T4 = 50% GF: 50% LPP; T5 = 30% GF: 70% LPP. Values are expressed as mg/100 g of sample.

The elevated levels of phenolic compounds in T2 can be attributed to the high phenolic content of lemon peel powder, which was previously determined to contain 15.48 mg/g total phenolic compounds. Furthermore, increasing the proportion of LPP in the herbal tea formulations generally resulted in higher concentrations of most phenolic compounds, indicating that LPP is a major contributor to the phenolic profile of the blends.

A similar trend was observed for flavonoid compounds. T2 (100% LPP) recorded the highest concentrations of apigenin, diosmin, rutin, hesperidin, kaempferol, and quercetin, with values of

4991.01, 2.76, 24.03, 171.53, 77.84, and 241.73 mg/100 g, respectively. Conversely, T1 (100% GF) contained the lowest concentrations of these flavonoids, recording values of 3887.85, 0.62, 8.99, 91.03, 32.22, and 105.80 mg/100 g, respectively. The intermediate formulations (T3, T4, and T5) exhibited flavonoid concentrations proportional to their LPP content.

The high concentrations of phenolic and flavonoid compounds detected in the LPP-containing formulations are of particular interest because these compounds are recognized for their potent antioxidant and health-promoting activities. Numerous studies have demonstrated that citrus peel extracts exhibit significant antitumor effects against several cancer cell lines, including liver, colon, and breast cancers. Kumar *et al*. (2012), Diab *et al*. (2015), Diab (2016), Selim *et al*. (2019), and El Sheikh *et al*. (2022) attributed the anticancer activity of lemon peel extracts largely to their rich content of phenolic acids and flavonoids. These compounds contribute to the cytotoxic and antioxidant properties of citrus peel extracts and are believed to play a major role in their reported low IC_{50} values against cancer cells. Therefore, the enrichment of herbal tea with lemon peel powder enhances its phytochemical composition and may increase its potential health benefits through the incorporation of valuable phenolic and flavonoid compounds.

3.9. Mineral composition of lemon peel powder gummy candy and herbal tea

The mineral composition of gummy candies and herbal tea formulations supplemented with lemon peel powder (LPP) is presented in Table 9. Minerals are essential nutrients that play important roles in numerous physiological functions, including bone formation, enzymatic activity, antioxidant defense, and maintenance of cellular homeostasis. For gummy candy samples, the results showed that increasing the level of LPP significantly increased ($p < 0.05$) the concentrations of most minerals. GC4 (2% LPP) recorded the highest values of calcium (Ca), iron (Fe), manganese (Mn), magnesium (Mg), copper (Cu), and zinc (Zn), with values of 540.25, 2.88,0. 22, 28.25, 4.89, and 1.18 mg/100 g, respectively. In contrast, the control sample (GC1) exhibited the lowest mineral contents, recording 444.88, 2.50, 0.11, 18.0, 4.75, and 0.125 mg/100 g for Ca, Fe, Mn, Mg, Cu, and Zn, respectively. The increase in mineral content with increasing LPP levels can be attributed to the naturally high mineral and ash contents of lemon peel powder, which contained 6.71% ash in the present study.

Table 9. Mineral composition of gummy candies and herbal tea formulations supplemented with lemon peel powder (LPP) (mg/100 g)

Samples	Lemon peel powder gummy candy					
	Ca	Fe	Mn	Mg	Cu	Zn
GC1	444.88±0.01^d	2.500±0.2^d	0.11000±0.01^d	18.00±0.0^d	4.750±0.01^d	0.125±0.1^c
GC2	471.63±0.1^c	2.63±0.0^c	0.14000±0.30^c	20.63±0.3^c	4.763±0.20^c	0.127±0.2^b
GC3	499.0±0.30^b	2.75±0.10^b	0.15000±0.01^b	23.13±0.2^b	4.875±0.10^b	1.163±0.01^a
GC4	540.25±0.1^a	2.88±0.0^a	0.2200±.0.01^a	28.25±0.0^a	4.89±0.03^a	1.180±0.10^a
	Lemon peel powder herbal tea					
T1	910.0±0.01^e	91.01±0.01^a	20.43±0.10^a	85.29±0.1^e	8.75±0.030^a	3.00±0.20^b
T2	5412.5±0.1^a	23.75±0.10^e	4.38±0.002^e	513.75±0.2^a	5.710±0.04^e	3.13±0.01^a
T3	3062.5±0.3^d	82.75±0.0^b	18.13±0.01^c	287.25±0.2^d	6.0±0.00^b	1.80±0.02^c
T4	3602.5±0.1^c	79.38±0.01^c	18.25±0.02^b	337.13±0.1^c	5.900±0.01^c	1.48±0.01^e
T5	4637.5±0.1^b	74.88±0.01^d	16.75±0.01^d	438.88±0.3^b	5.790±0.01^d	1.51±0.01^d

GC1 = Control (without LPP); GC2 = 0.5% LPP; GC3 = 1% LPP; GC4 = 2% LPP. T1 = Control 1 (100% ginger formula, GF); T2 = Control 2 (100% LPP); T3 = 60% GF : 40% LPP; T4 = 50% GF : 50% LPP; T5 = 30% GF : 70% LPP. Values are expressed as mean ± SD (n = 3). Means within the same column followed by different letters are significantly different at $p < 0.05$.

Regarding herbal tea formulations, T2 (100% LPP) exhibited the highest concentrations of calcium, magnesium, and zinc, with values of 5412.5, 513.75, and 3.13 mg/100 g, respectively, followed by T5 (30% GF: 70% LPP), which contained 4637.5 mg/100 g calcium and 438.88 mg/100 g magnesium. The elevated levels of these minerals in T2 and T5 are attributable to the high mineral content of lemon peel powder. In contrast, T1 (100% ginger formula) recorded the lowest calcium and magnesium values (910.0 and 85.29 mg/100 g, respectively).

Interestingly, T1 exhibited the highest concentrations of iron, manganese, and copper (91.01±0.01, 20.43±0.1, and 8.75±0.03 mg/100 g, respectively), suggesting that the ginger formula, consisting of ginger, cinnamon, and mint, is also a valuable source of certain trace minerals. The relatively high ash content of the ginger formula (6.18%) may have contributed to these mineral levels.

The present findings are consistent with those reported by Lario *et al*. (2004); El Sheikh *et al*. (2022) and Daniela *et al*. (2025), who demonstrated that lemon peel powder is not only rich in dietary fiber but also contains considerable amounts of essential minerals, including calcium, potassium, phosphorus, manganese and magnesium. These minerals contribute to the nutritional value of LPP and enhance its potential as a functional food ingredient. Therefore, the incorporation of lemon peel powder into gummy candy and herbal tea formulations can improve their mineral composition and nutritional quality while providing additional health benefits.

4. Conclusion

Lemon peel powder (LPP) exhibited dose-dependent cytotoxic activity against HepG2 liver cancer cells, with an IC_{50} value of 238.81 µg/mL. LPP was also found to be a rich source of dietary fiber, phenolic compounds, flavonoids, and essential minerals, particularly calcium, magnesium, and manganese. The incorporation of LPP into gummy candy and herbal tea significantly enhanced their nutritional value, phytochemical composition, and antioxidant activity. Moreover, the developed products showed good sensory acceptability, especially at moderate levels of LPP supplementation. Therefore, lemon peel powder can be considered a promising, low-cost functional ingredient for the development of sustainable food products with potential health-promoting properties.

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