Combination of green tea catechins, polysaccharides, and flavonols against urban fine dust particle-induced bronchial damage mediated by modulation of inflammation factors and airway cilia

Juewon Kim (✉ jwkim@amorepacific.com)

Amorepacific R&D center <https://orcid.org/0000-0002-0975-7873>

Hyunjung Choi

Amorepacific R&D center

Dong-Hwa Choi

GyeongGi Bio Center

Kyuhee Park

GyeongGi Bio Center

Hyung-June Kim

Amorepacific R&D center

Miyoung Park (✉ mypark@amorepacific.com)

Amorepacific R&D center

Research

Keywords: Urban fine dust, Green tea, Green tea flavonols, Green tea polysaccharides, Cilia, Bronchial

Posted Date: April 10th, 2020

DOI: <https://doi.org/10.21203/rs.3.rs-21543/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Abstract

Background Many studies have reported that environmental pollution has become a serious public health issue. Airborne fine dust particles (FDPs) have been identified as major toxins in air pollution that threaten human respiratory health. Developing strategies for defense against FDPs is one of the primary goals of air pollution research. **Results** While searching for an anti-FDP reagent, we found that green tea extract (GTE) and green tea fractions rich in flavonol glycosides (FLGs) and crude green tea polysaccharides (CTPs) had protective effects against FDP-stimulated cellular damage in the BEAS-2B airway epithelial cell line. The results demonstrated that GTE, FLGs, and CTPs significantly increased viability and lowered oxidative stress levels in FDP-treated cells. Major catechin and flavonol compounds increased cell survival, and (-)-epigallocatechin gallate (EGCG) and myricetin exerted synergistic effects on cell survival under FDP stimulation. Combined treatment with GTE, FLGs, and CTPs also exerted synergistic protective effects on cells, and the green tea components attenuated FDP-induced elevations in inflammatory gene expression. Moreover, the green tea components increased the proportion of ciliated cells and upregulated ciliogenesis in the airway in FDP-stimulated BEAS-2B cells. **Conclusions** Our findings provide insights into how natural phytochemicals protect the airway and suggest that green tea could be used to reduce FDP-induced airway damage as an individual therapeutic agent or as an ingredient in pharmaceutical and cosmeceutical products.

Background

Ambient air pollution is composed of gaseous constituents and particulate matter (PM). PM can be classified on the basis of the particle size, also known as the aerodynamic equivalent diameter, as PM₁₀, PM_{2.5}, or ultrafine PM [1]. PM₁₀ reaches the lower airways and accumulates in the more proximal conducting airways [2, 3]. PM is naturally inhaled as a particulate suspension in the air and is deposited in the airway as it passes through the respiratory tract, after which it interacts with airway cells. Human bronchial epithelia are invariably exposed to toxic factors such as ambient fine dust particles (FDPs), which can cause acute and chronic pulmonary infections and respiratory diseases [4, 5]. In addition, toxic pollutants induce oxidative stress and imbalance between reactive oxygen species (ROS) production and scavenging [6, 7]. Elevated oxidative stress causes airway epithelial barrier dysfunction, airway inflammation, infection, and mitochondrial dysfunction [8, 9, 10]. Airway defense strategies include coughing, anatomical barrier-mediated blockade, immune mechanisms, and primary defense via mucociliary clearance (MCC). MCC enables the efficient clearance of inhaled particles, and in human studies, MCC has been found to remove inhaled particles larger than 6 μm from the airway within 24 h [11, 12, 13]. Because of the toxic effects of FDPs, removal of air pollutants via activation of MCC and attenuation of FDP-induced oxidative stress in airway cells via ROS scavenging are important. Moreover, FDP-generated ROS cause airway cilia dysfunction [14], and applied ROS scavengers may show positive effects in reducing oxidative stress and activating MCC.

In this study, we focused on the potent activities of natural phytochemicals in green tea. Green tea is an important dietary product that contains antioxidative molecules with cytoprotective and anti-

inflammatory activities that protect cells from oxidative stress-induced apoptosis [15, 16, 17]. Catechin compounds, such as (-)-epigallocatechin-3-gallate (EGCG), act as radical scavengers and metal-chelating agents and play roles in various cellular processes; for example, they exert neuroprotective functions, regulate blood pressure, and protect against cardiovascular disease [18, 19, 20]. Previous studies have reported the protective effects of plant extracts and phenolic compounds against oxidative stress and inflammation induced by FDPs [21, 22, 23, 24], and we hypothesized that green tea components could exert potent protective effects against FDP-induced toxicity. Similar to N-acetyl cysteine [25], EGCG exhibits scavenging efficacy against FDP-induced ROS [26]. EGCG also reduces skin inflammation and asthma in rats caused by FDP stimulation [26, 27, 28]. However, the studies that have revealed these findings have concentrated only on active EGCG. In addition to catechins, green tea also contains significant amounts of flavonols and polysaccharides [29, 30]. Plant flavonols exhibit anticancer, proapoptotic, antioxidant, antibacterial, and antifibrotic effects [31, 32, 33, 34, 35]. Additionally, polysaccharides exert several health-promoting effects, such as antibacterial, antitumor, antioxidant, and anti-inflammatory effects [36, 37, 38, 39, 40, 41, 42]. Despite exerting these positive effects, green tea flavonols and polysaccharides, unlike catechins, have received little attention with respect to their use and functionality.

In the present study, we investigated the protective effects of green tea catechins, flavonols, and polysaccharides against FDP-induced airway cellular toxicity, oxidative stress, and cilia dysfunction using human bronchial epithelial cells (BEAS-2B cells) as an experimental model.

Results

FDPs induce oxidative damage and cell death in airway/lung cells

Following inhalation, the primary sites of air pollution exposure are respiratory tract cells, including bronchial and lung cells. Inhaled FDPs can interact with the epithelial cells lining the airway and with lung cells. Since FDPs are known to cause toxicity in various individual cell types [43, 44], we attempted to identify the cellular toxicity and oxidative stress levels in airway and lung cells exposed to FDPs. We evaluated cell survival rates and intracellular ROS levels under FDP treatment to examine the cellular damage induced by FDPs. We first performed the experiments using the bronchial epithelial cell line BEAS-2B, the lung fibroblast line IMR90, and the adenocarcinomic alveolar epithelial cell line A549 to assess the toxicity of FDPs on the overall respiratory tract. Treatment with FDPs at concentrations in the range of 1-100 $\mu\text{g/ml}$ resulted in significant concentration-dependent reductions in the survival rates of the cells (Fig. 1a) and increases in the cellular ROS levels (Fig. 1b). The morphology of individual cells was also examined (Fig. 1c). The viability of cells treated with 100 $\mu\text{g/ml}$ FDPs was lower than 50%, and the ROS levels in these cells were nearly 2-fold those in the control cells. As the damaging effects of FDPs on viability and ROS levels were similar among the tested respiratory tract cell lines, we proceeded to perform further experiments using BEAS-2B cells, the first airway cells exposed to air pollution.

Protective effects of the green tea components against FDP-induced damage

Recently, we isolated GTE, fractions rich in FLGs, and CTPs from green tea leaves as bioactive ingredients [45, 46]. Because phenolic compounds from various plants have been shown to exert protective effects against FDP-induced oxidative stress and inflammation in skin cells [47, 48, 49] and because green tea polysaccharides exhibit beneficial antioxidant [50], antitumor [36], and antiaging properties [51], we hypothesized that green tea polyphenols and polysaccharides could also ameliorate FDP-induced cellular damage in the airway. Our results revealed that GTE, FLGs, and CTPs attenuated the cellular toxicity induced by FDPs in BEAS-2B cells in a concentration range of 10–50 ppm (Fig. 2a). These bioactive green tea ingredients also lowered oxidative stress levels in FDP-treated cells (Fig. 2b).

The chemical properties of GTE, FLGs, and CTPs were investigated. As shown in Table 1, the total catechins in GTE amounted to $36.52 \pm 1.6\%$ of the dry matter and included EGCG ($16.8 \pm 0.8\%$), EGC ($11.8 \pm 2.0\%$), EC ($3.68 \pm 0.8\%$), and ECG ($2.94 \pm 0.2\%$). On the other hand, catechins, a major group of phenolics in green tea, were not detected, and the FLGs quercetin, kaempferol, and myricetin were contained mainly in the FLG fraction [46]. In addition, the CTPs included mainly pectic substances and glucosidic macromolecules found in unlignified cell walls, major components of the middle lamellae in plants [45]; these pectic polysaccharides have various pharmacological properties [30, 52, 53]. We next examined the effects of higher levels of GTE and FLGs on FDP-induced cellular toxicity in BEAS-2B cells. The epicatechins EGCG, EGC, EC, and ECG effectively reduced FDP-induced cytotoxicity when applied at concentrations ranging from 1–10 μM (Fig. 2c). The flavonols quercetin, kaempferol, and myricetin also showed protective effects on cell viability in the 1–100 μM concentration range (Fig. 2d). Among these active compounds, EGCG and myricetin, which were found in the GTE and FLGs, respectively, showed the most potent protective efficacy against FDP.

Combined effects of the green tea components on FDP-induced cellular damage

According to the cell survival rates under FDP treatment, the catechin EGCG and the flavonol myricetin exhibited potent and concentration-dependent protective effects against FDP-induced toxicity (Fig. 2c-d). EGCG (Fig. 3a) was the most abundant catechin in GTE and is commonly used in cosmetics, functional foods, and dietary supplements due to its health benefits [54, 55]. EGCG has also been shown to reduce FDP-induced skin inflammation in epidermal keratinocytes and dermal fibroblasts [26, 28]. Myricetin (Fig. 3b) is a flavonol that is present in vegetables, fruits, nuts, berries, and tea. Like many other flavonols, myricetin shows antioxidant, antiviral, and anti-inflammatory effects [21, 31, 56]. Interestingly, among polyphenolic compounds, myricetin and EGCG have been shown to exhibit inhibitory effects against house dust-induced allergic reactions [57]. According to a previous report, among polyphenols (including catechins and flavonols), myricetin and EGCG effectively inhibit the release of kinin by house dust mites.

We tested the effects of EGCG and myricetin on cellular toxicity and ROS levels to investigate whether these active compounds in green tea have synergistic effects. Administration of 10 μ M EGCG or myricetin reduced toxicity and intracellular ROS levels in cells under FDP treatment (Fig. 3c-d). Surprisingly, co-treatment with 5 μ M EGCG and myricetin exhibited synergistic effects, enhancing cell viability and attenuating oxidative stress levels in FDP-treated cells (Fig. 3c-d). The effects of representative catechins and flavonols on FDP-induced morphological changes are depicted in Fig. 3e. We next tested the combined preventative effects of GTE and the FLG and CTP green tea fractions against FDP-induced cellular damage. Combined treatment with the green tea components was more effective than GTE treatment alone in preventing FDP-induced cell survival impairment and oxidative stress (Fig. 4a-c). Taken together, these data suggest that supplementation with whole green tea rather than with a specific fraction may enable useful synergy between catechins and flavonols to combat FDP-induced cellular damage.

Protective effects of the green tea components against the FDP-induced immune response

Following inhalation, the primary site of exposure to FDPs is the airway tract. Inhaled PM directly affects the immune processes of airway epithelial cells, which can be stimulated by airborne materials in the environment. FDP-stimulated airway cells act as components of multicellular immune responses and trigger cellular signaling pathways. Because improper and excessive immune reactions can result in serious infections, malignancies, and autoimmune conditions, proper regulation of the effects of air pollution on the immune system is important [44, 58]. The proinflammatory cytokine milieu in the airway that develops after inhalation of FDPs disrupts immune modulation. To determine whether green tea and the combination of GTE, FLGs, and CTPs attenuated FDP-induced effects on the airway immune system, we investigated the expression of known bronchial inflammatory genes. Upon sensing of toxic particles, bronchial epithelial cells produce many proinflammatory cytokines [59, 60]. These molecules are well known asthma and chronic obstructive pulmonary disease (COPD) markers [61, 62]. Treatment with 100 μ g/ml FDPs greatly increased the expression of the inflammatory marker genes IL-4, IL-13, IL-17A, CCL-11, CCL-17, and MMP-12. Combined treatment with GTE, FLGs, and CTPs largely reduced this hyperimmune response to a greater extent than treatment with GTE alone (Fig. 5). This pollution-induced cytokine response is clinically relevant [63], and as IL-17A is also known as a COPD marker, the green tea components exhibit potential for the prevention of airway disease. Moreover, given that IL-4, IL-13, CCL-11, and CCL-17 regulate lung cell tight junctions, these results suggest that the green tea components can be used for lung health applications.

Protective effects of the green tea components on airway cilia

Bronchial epithelial cells create a physical barrier at the airway lumen, form the mucous lining of the respiratory tract, sense toxic biological and anthropogenic PM accumulation on the airway wall and help to remove PM from the airway via ciliary action. MCC plays a crucial role in the airway defense machinery, as it involves secretion of antimicrobials, fluids, and anti-inflammatory proteins [64]. The mucociliary system removes PM and pathogens mechanically via the actions of cilia and coughing [65]. MCC abnormalities related to ciliary dysfunction can result in chronic pulmonary disorders, including asthma and COPD. In patients with primary ciliary dyskinesia, airway clearance of particles is impaired and prolonged, which allows longer residence times for bacteria, viruses, and toxins in the airway [66]. Disruption of ciliated cell functions has been detected in many chronic lung diseases and contributes to morbidity, mortality, and infection in individuals with these disorders [67, 68, 69, 70].

To determine the effects of the green tea components on ciliogenesis in bronchial epithelial cells, we treated FDP-treated BEAS-2B cells with GTE or with GTE, FLGs, and CTPs. FDP treatment greatly suppressed cilium formation (Fig. 6a-b) and cilium length (Fig. 6c). Cilia are specialized microtubule-based cellular organelles that beat in metachronal waves to facilitate the expulsion of inhaled particles and pathogens trapped in the mucus layer from the airway [71]. To detect cilia, immunofluorescence was performed for acetylated α -tubulin and the ARL13B protein [72, 73]. Ciliated cells are defined by their multiple motile apical cilia and by the presence of motor proteins that mediate directional beating, which is critical for MCC [74]. Although the biomechanical actions of cilia in epithelial cells are well identified as essential building blocks of MCC [66], recent studies have revealed that airway ciliated cells sense and respond to mechanical and irritant stimulation [13, 74]. In our study, we found that GTE increased the proportion of ciliated cells by approximately 3-fold under FDP treatment conditions; moreover, the combined green tea components increased the ciliated cell proportion by over 4-fold (Fig. 6a-b). Additionally, GTE, FLG, and CTP application protected cilia against FDP-induced declines in length (Fig. 6c), indicating that these green tea components activate airway cilia and can upregulate MCC of inhaled pollutants such as FDPs.

Discussion

We depicted here the protective effects of green tea catechins, polysaccharides, and flavonols against airborne particles. Compared to green tea catechins, flavonols and polysaccharides from green tea have received little attention. Green tea contains a many of polyphenols, especially monomeric flavonols [75, 76]. Since there are very limited studies for investigating protective effects of green tea polyphenols against particulate pollutants [77, 78], we examined green tea flavonols rich fraction FLGs and its representative compounds, quercetin, kaempferol, and myricetin for damage attenuation by FDP. Among these compounds, myricetin have shown potent positive effects of cell survival under FDP-stimulation dose-dependent manner (Fig. 2d). Moreover, myricetin represented synergetic effects against FDP with EGCG. Combination of myricetin with EGCG effectively lowered cellular ROS level and increased cell survival under FDP treatment (Fig. 3c-d).

Along with green tea catechins and flavonols, polysaccharides are also gaining attention due to their health benefits, especially immune response [40, 79]. Air pollution has increased concern about its inhalation toxicity. Inadequate or excessive immune reactions by FDP could result in serious infection, metastatic malignancies, and auto-immune state. FDP stimulates cells through ROS sensing pathways and activate pro-inflammatory signaling cascades such as MAPK pathways [80, 81]. The affection of FDP to stimulate cells may due to the particles containing microbial molecules and also pollutants inducing host-derived molecules production. FDP could stimulate airway epithelial cells and generate ROS in cellular and acellular systems [82, 83]. FDP also cause oxidative stress by both the heavy metal and organic compounds and can directly reduce endogenous antioxidants [84, 85]. In our results, combination of green tea components effectively inhibited hyper-immune responses by FDP-stimulation (Fig. 5). These pro-inflammatory cytokine milieus after ambient pollutant inhalation may be important for perturbing immune regulation and actually closely related with airway and pulmonary dysfunction, such as asthma and COPD. Treatment of whole green tea component could be more promising application to attenuate immune dysfunction more than green tea catechin only. Although in vitro experiments are important for understanding the toxicity of air pollution and its therapeutic treatment, pollution exposure in cell culture system has limitation of actual inhalation. However, relationship between airway defenses and epithelial cells gives a clue to protect airway against FDP.

FDP is naturally inhaled as a particulate matter in the air, deposit in the airway, passing through respiratory tract before interacting with airway cells. The bronchial airway cells form a physical barrier, sense dangerous biological and toxic particles, and deposit on the airway wall by ciliary action to clear particles from the airway. The airway cilia are an organelle producing from the cell body that senses external stimulations and removes harmful particles by its movements. Mucociliary clearance is an integral part of airway-lung defense methods, enabling efficient clearance of inhaled particles from the respiratory tract [4, 12]. The activity and efficacy of clearance closely related with ciliated cells proportion and ciliogenesis in airway epithelial cells [13, 71]. As shown in our results, application of green tea component enhanced the ciliated cells rate of BEAS-2B cell and also showed increased cilia length against FDP treatment. These ciliogenesis activation was more remarkable in combined treatment of green tea component and it could be upregulate MCC actions against pollutant inhalation.

Conclusion

In this study, we investigated FDP-induced cellular toxicity and oxidative stress in bronchial epithelial cells and examined the protective effects of green tea components against FDP-induced cytotoxicity and declines in ciliogenesis. Our results demonstrated that FDPs induced cytotoxicity by increasing intracellular oxidative stress levels, reducing cell viability, increasing inflammatory gene expression, and attenuating airway ciliogenesis in BEAS-2B cells. Green tea components including catechins, flavonols, and polysaccharides exerted protective effects individually and in combination against FDP-induced cellular damage. Specifically, GTE, FLGs, and CTPs lowered intracellular ROS levels, attenuated the hyperimmune response and increased ciliated cell beating rates and ciliogenesis. Amelioration of acute oxidative stress, proper modulation of the immune response and activation of MCC are critical strategies

for protection against air pollution-induced airway/lung damage. Based on these results, we suggest that green tea catechins, flavonols, and polysaccharides are promising reagents for protection against FDP-induced airway damage and are candidates for use in the pharmaceutical and cosmeceutical fields.

Methods

Chemicals and reagents

The airborne PM reference material ERM-CZ100 (PM10-like) and the pure catechin compounds EGCG, epigallocatechin (EGC), epicatechin (EC), and epicatechin gallate (ECG) were purchased from Sigma-Aldrich (St. Louis, MO, USA). Phenolic compounds, quercetin, kaempferol, and myricetin were also obtained from Sigma-Aldrich. An alcoholic water extract and crude tea polysaccharides from green tea leaves were prepared according to previously described methods [45]. All other chemicals used in this study were of analytical grade.

ERM-CZ100 was suspended in serum-free DMEM and homogenized by sonication to make a 10 mg/ml stock solution. Phosphate-buffered saline (PBS), dimethyl sulfoxide (DMSO), and the fluorescent probe 2',7'-dichlorodihydrofluorescein diacetate (DCFH-DA) were purchased from Sigma-Aldrich. MitoSOX Red (M36008) was obtained from Thermo Fisher Scientific (Indianapolis, IN, USA), and an MTT assay kit and a Cell Counting Kit-8 were purchased from Dojindo (Kumamoto, Japan).

Preparation of GTE, purified flavonol glycosides (FLGs), and CTPs from green tea leaves

Dried green tea leaves (Osulloc Farm, Jeju Island, Korea) were obtained, extracted, and purified for the preparation of GTE, FLGs, and CTPs as previously described [45, 46]. Briefly, dried green tea leaves were soaked in 70% (v/v) aqueous ethanol at 70 °C for 1 h. The ethanol in the extract was removed by an evaporator (Hei-VAP, Heidolph Instruments, Schwabach, Germany), and the remaining material was filtered using a 20 mm filter (Pall Corp., Port Washington, NY, USA) and solidified with a KL-8 spray dryer (Seogang Engineering, Cheonan, Korea) to obtain the GTE. To obtain purified FLGs, GTE aqueous solution (1% w/v, pH 5.0) was reacted with 1% (v/v) tannase (500 units/ml) in a thermoshaker (Eppendorf, Hamburg, Germany) for 14 h at 40 °C. The enzymatic reaction was stopped by heating at 90 °C for 20 min. The remaining residues after GTE extraction were extracted with water at 90 °C for 3 h and filtered to remove insoluble residue. The clear supernatant was concentrated to 1:150 (v/v) in a vacuum evaporator and precipitated by supplementation with 4 volumes of 95% cold ethanol to obtain crude polysaccharides. Then, the precipitates were dissolved in a small amount of water and spray-dried to produce the CTP fraction.

Cell culture

The human bronchial epithelial cell line BEAS-2B (CRL-9609), the human fibroblast cell line IMR90 (CCL-186), and the human lung adenocarcinoma cell line A549 (CCL-185) were purchased from the American Type Culture Collection (ATCC, Manassas, VA, USA). The BEAS-2B cells were cultured in 25 mM HEPES-buffered M199 medium containing 10% FBS, 2 mM L-glutamine, 100 U/ml penicillin, 100 mg/ml streptomycin supplemented with 2.5 mg/ml insulin, 361 ng/ml hydrocortisone, 2.5 mg/ml apotransferrin, and 20 ng/ml EGF [86]. The IMR90 cells were maintained in Eagle's MEM (EMEM, Lonza 125F) supplemented with 2 mM L-glutamine, 10% FBS and 1 mM sodium pyruvate with 100 U/ml penicillin and 100 mg/ml streptomycin. A549 cells were cultured in DMEM supplemented with 10% FBS, 100 mg/ml streptomycin and 100 U/ml penicillin. The cell lines were cultured at 37 °C in a humidified atmosphere with 5% CO₂.

Determination of the effects of the reagents on cell survival after exposure to fine dust

Cells were incubated in a 12-well plate for 24 h and then treated with different reagents. After 2 days of treatment, FDPs (100 mg/ml) were added to the cells. After 24 h of incubation, MTT solution (2 mg/mL) was added to each well, and the cells were further incubated for 1 h. The cell viability was determined by MTT assay [87] with a microplate reader (SPECTROstar Nano, BMG Labtech, Ortenberg, Germany).

Determination of intracellular ROS levels

Cells were seeded in 24-well plates for 24 h and then treated with various reagents. After 6 h of incubation, FDPs (100 mg/ml) were added to the cells. The intracellular ROS levels were measured by 2',7'-dichlorofluorescein diacetate (DCF-DA) assay (excitation: 485 nm; emission: 535 nm) with a microplate reader (SPECTROstar Nano, BMG Labtech, Ortenberg, Germany) [88].

RNA extraction and quantitative real-time PCR

Total RNA from BEAS-2B cells was prepared with an RNeasy Mini Kit (#74106, Qiagen, Hilden, Germany). Reverse transcription was performed on 4 mg of total RNA using an iScript cDNA Synthesis Kit (#170-8891, Bio-Rad, CA, USA). Quantitative PCR was performed using an ABI 7500 Fast Real-Time PCR System with TaqMan Universal Master Mix II and TaqMan site-specific primers and probes (Applied Biosystems, CA, USA). All reactions were performed in triplicate, and the amounts of mRNA were calculated by the comparative cycle threshold (CT) method.

Immunofluorescence labeling of cilia

BEAS-2B cells were treated with each reagent, washed with PBS, fixed for 30 min in 4% paraformaldehyde, washed again, and incubated for 10 min in 0.1% Triton X-100. The cells were washed three times in PBS and incubated with anti-acetylated tubulin antibodies (1:1000 dilution, Sigma-Aldrich, MO, USA) and anti-ARL13B antibodies (1:200 dilution, Proteintech, IL, USA) diluted in Hank's solution (0.44 mM KH_2PO_4 , 5.37 mM KCl, 0.34 mM Na_2HPO_4 , 136.89 mM NaCl, and 5.55 mM D-glucose) at 4 °C overnight. The cells were then incubated with goat anti-rabbit or goat anti-mouse Alexa Fluor 555- or Alexa Fluor 488-conjugated secondary antibodies for 1 h at room temperature. After washing, the coverslips were mounted onto glass slides and visualized using a confocal laser scanning microscope (LSM800, Carl Zeiss, Germany). DAPI was used to counterstain the cell nuclei. The acquired images were analyzed using ZEN software (Carl Zeiss).

Statistical analysis

The data are expressed as the mean $\pm$ SD. The normality of the data was analyzed using the Shapiro-Wilk test, and the results between different groups were compared using one-way ANOVA (followed by Dunnett's post hoc test) or Student's t-test. All statistical tests were two-sided, with the level of significance established at $p < 0.05$. SPSS software (ver. 21, SAS Institute, NC, USA) was used for statistical analyses.

Abbreviations

FDPs: Airborne fine dust particles; GTE: green tea extract; FLGs: fractions rich in flavonol glycosides; CTPs: crude green tea polysaccharides; EGCG: (-)-epigallocatechin gallate; EGC: epigallocatechin; EC: epicatechin; ECG: epicatechin gallate; PM: particulate matter; ROS: reactive oxygen species; MCC: mucociliary clearance; BEAS-2B: human bronchial epithelial cells; COPD: chronic obstructive pulmonary disease; DCF-DA: 2',7'-dichlorofluorescein diacetate

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and materials

The raw data used and/or analyzed in current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare no conflicts of interest.

Funding

This research was part of a basic bioscience research project funded by the Amorepacific R&D Center.

Authors' contributions

J. K., H. C., and M. P. have full access to all data from the study and take responsibility for the integrity of the data as well as for the manuscript. J. K., H. C., H. K., and M. P. conceived, designed and performed most of the experiments and data analyses and prepared the manuscript. D. C. and K. P. performed the immunofluorescence assay. J.K., H.K., and M.P. conceived and designed the research, analyzed and interpreted data, wrote the manuscript, and administered the project.

Acknowledgments

We thank to Dr. Jin-Oh Chung and Chan-Su Rha for supplementation of green tea flavonols and polysaccharides.

References

1. Kim KH, Kabir E, Kabir S. A review on the human health impact of airborne particulate matter. *Environment international*. 2015;74:136–43. doi:.
2. Jiang SY, Ma A, Ramachandran S. Negative Air Ions and Their Effects on Human Health and Air Quality Improvement. *Int J Mol Sci*. 2018;19 10; doi:.
3. Oberdorster G, Oberdorster E, Oberdorster J. Nanotoxicology: an emerging discipline evolving from studies of ultrafine particles. *Environmental health perspectives*. 2005;113 7:823–39. doi:.
4. Glencross DA, Ho TR, Camina N, Hawrylowicz CM, Pfeffer PE. Air pollution and its effects on the immune system. *Free Radic Biol Med*. 2020. doi:.
5. Sicard P, Khaniabadi YO, Perez S, Gualtieri M, De Marco A. Effect of O₃, PM₁₀ and PM_{2.5} on cardiovascular and respiratory diseases in cities of France, Iran and Italy. *Environmental science and pollution research international*. 2019;26 31:32645–65; doi: .
6. Chen J, Zhao Q, Liu BB, Wang J, Xu HB, Zhang Y, et al. [Airway oxidative stress and inflammation markers in chronic obstructive pulmonary diseases(COPD) patients are linked with exposure to traffic-related air pollution: a panel study]. *Zhonghua yu fang yi xue za zhi [Chinese journal of preventive medicine]*. 2016;50 5:411–7; doi: .
7. Usemann J, Roth M, Bisig C, Comte P, Czerwinski J, Mayer ACR, et al. Gasoline particle filter reduces oxidative DNA damage in bronchial epithelial cells after whole gasoline exhaust exposure in vitro. *Sci Rep*. 2018;8 1:2297; doi:.

8. Xian Z, Choi YH, Zheng M, Jiang J, Zhao Y, Wang C, et al. Imperatorin alleviates ROS-mediated airway remodeling by targeting the Nrf2/HO-1 signaling pathway. *Bioscience, biotechnology, and biochemistry*. 2020;1–13; doi: .
9. Wu G, Yang L, Xu Y, Jiang X, Jiang X, Huang L, et al. FABP4 induces asthmatic airway epithelial barrier dysfunction via ROS-activated FoxM1. *Biochemical and biophysical research communications*. 2018;4951:1432–9; doi: .
10. Weng CM, Lee MJ, He JR, Chao MW, Wang CH, Kuo HP. Diesel exhaust particles up-regulate interleukin-17A expression via ROS/NF-kappaB in airway epithelium. *Biochem Pharmacol*. 2018;151:1–8. doi:.
11. Scheuch G, Philipson K, Falk R, Anderson M, Svartengren M, Stahlhofen W, et al. Retention of particles inhaled in bolus with and without induced bronchoconstriction. *Experimental lung research*. 1995;21 6:901–16. doi:.
12. Kolanjiyil AV, Kleinstreuer C, Kleinstreuer NC, Pham W, Sadikot RT. Mice-to-men comparison of inhaled drug-aerosol deposition and clearance. *Respiratory physiology & neurobiology*. 2019;260:82–94; doi: .
13. Whitsett JA. Airway Epithelial Differentiation and Mucociliary Clearance. *Annals of the American Thoracic Society*. 2018;15Suppl 3:S143-s8; doi: .
14. Price ME, Pavlik JA, Liu M, Ding SJ, Wyatt TA, Sisson JH. Alcohol drives S-nitrosylation and redox activation of protein phosphatase 1, causing bovine airway cilia dysfunction. *American journal of physiology Lung cellular molecular physiology*. 2017;312(3):L432-l9. doi:.
15. Keske MA, Ng HL, Premilovac D, Rattigan S, Kim JA, Munir K, et al. Vascular and metabolic actions of the green tea polyphenol epigallocatechin gallate. *Curr Med Chem*. 2015;22 1:59–69. doi:.
16. Legeay S, Rodier M, Fillon L, Faure S, Clere N. Epigallocatechin Gallate: A Review of Its Beneficial Properties to Prevent Metabolic Syndrome. *Nutrients*. 2015;7 7:5443–68. doi:.
17. Oliveira MR, Nabavi SF, Daglia M, Rastrelli L, Nabavi SM. Epigallocatechin gallate and mitochondria-A story of life and death. *Pharmacological research*. 2016;104:70–85. doi:.
18. Oak MH, Auger C, Belcastro E, Park SH, Lee HH, Schini-Kerth VB. Potential mechanisms underlying cardiovascular protection by polyphenols: Role of the endothelium. *Free Radic Biol Med*. 2018;122:161–70. doi:.
19. Pawlowska E, Szczepanska J, Koskela A, Kaarniranta K, Blasiak J. Dietary Polyphenols in Age-Related Macular Degeneration: Protection against Oxidative Stress and Beyond. *Oxidative medicine and cellular longevity*. 2019;2019:9682318; doi: .
20. Ohishi T, Goto S, Monira P, Isemura M, Nakamura Y. Anti-inflammatory Action of Green Tea. *Anti-inflammatory & anti-allergy agents in medicinal chemistry*. 2016;15 2:74–90; doi: .
21. Knickle A, Fernando W, Greenshields AL, Rupasinghe HPV, Hoskin DW. Myricetin-induced apoptosis of triple-negative breast cancer cells is mediated by the iron-dependent generation of reactive oxygen species from hydrogen peroxide. *Food chemical toxicology: an international journal published for the British Industrial Biological Research Association*. 2018;118:154–67. doi:.

22. Jayawardena TU, Asanka Sanjeewa KK, Shanura Fernando IP, Ryu BM, Kang MC, Jee Y, et al. *Sargassum horneri* (Turner) C. Agardh ethanol extract inhibits the fine dust inflammation response via activating Nrf2/HO-1 signaling in RAW 264.7 cells. *BMC complementary and alternative medicine*. 2018;181:249; doi: .
23. de Paula PH, Mateus VL, Araripe DR, Duyck CB, Saint'Pierre TD, Gioda A. Biomonitoring of metals for air pollution assessment using a hemiepiphyte herb (*Struthanthus flexicaulis*). *Chemosphere*. 2015;138:429–37. doi:.
24. Ping F, Li Z, Zhang F, Li D, Han S. Effects of Lianhua Qingwen on Pulmonary Oxidative Lesions Induced by Fine Particulates (PM_{2.5}) in Rats. *Chinese medical sciences journal = Chung-kuo i hsueh k'o hsueh tsa chih*. 2016;31 4:233–8; doi: .
25. Meng ZQ, Zhang QX. [Effects of dust storm fine particles instillation on oxidative damage in hearts, livers, lungs of rats]. *Wei sheng yan jiu = Journal of hygiene research*. 2006;35 6:690–3.
26. Wang L, Lee W, Cui YR, Ahn G, Jeon YJ. Protective effect of green tea catechin against urban fine dust particle-induced skin aging by regulation of NF-kappaB, AP-1, and MAPKs signaling pathways. *Environmental pollution (Barking, Essex: 1987)*. 2019;252 Pt B:1318-24; doi: .
27. Li Y, Chen L, Guo F, Cao Y, Hu W, Shi Y, et al. Effects of epigallocatechin-3-gallate on the HMGB1/RAGE pathway in PM_{2.5}-exposed asthmatic rats. *Biochem Biophys Res Commun*. 2019;513 4:898–903. doi:.
28. Seok JK, Lee JW, Kim YM, Boo YC. Punicalagin and (-)-Epigallocatechin-3-Gallate Rescue Cell Viability and Attenuate Inflammatory Responses of Human Epidermal Keratinocytes Exposed to Airborne Particulate Matter PM₁₀. *Skin pharmacology and physiology*. 2018;313:134–43; doi: .
29. Jiang H, Engelhardt UH, Thrane C, Maiwald B, Stark J. Determination of flavonol glycosides in green tea, oolong tea and black tea by UHPLC compared to HPLC. *Food Chem*. 2015;183:30–5. doi:.
30. Yan Y, Ren Y, Li X, Zhang X, Guo H, Han Y, et al. A polysaccharide from green tea (*Camellia sinensis* L.) protects human retinal endothelial cells against hydrogen peroxide-induced oxidative injury and apoptosis. *Int J Biol Macromol*. 2018;115:600–7. doi:.
31. Li X, Ouyang X, Liang M, Chen D. Comparative Analysis of Radical Adduct Formation (RAF) Products and Antioxidant Pathways between Myricetin-3-O-Galactoside and Myricetin Aglycone. *Molecules*. 2019;24:15. doi:.
32. Brunetti C, Sebastiani F, Tattini M. Review. ABA, flavonols, and the evolvability of land plants. *Plant science: an international journal of experimental plant biology*. 2019;280:448–54. doi:.
33. Huang S, Wu R, Gao F, Li C, Zhou X. Two flavonol glycosides from *Liparis bootanensis*. *Journal of natural medicines*. 2018;72 3:768–73. doi:.
34. Nawwar M, Ayoub N, El-Raey M, Zaghloul S, Hashem A, Mostafa E, et al. Acylated flavonol diglucosides from *Ammania auriculata*. *Zeitschrift fur Naturforschung C. Journal of biosciences*. 2015;70(1–2):39–43. doi:.
35. Lea MA. Flavonol regulation in tumor cells. *Journal of cellular biochemistry*. 2015;116 7:1190–4. doi:.

36. Yang K, Gao ZY, Li TQ, Song W, Xiao W, Zheng J, et al. Anti-tumor activity and the mechanism of a green tea (*Camellia sinensis*) polysaccharide on prostate cancer. *Int J Biol Macromol*. 2019;122:95–103. doi:.
37. Fiorito S, Epifano F, Preziuso F, Taddeo VA, Genovese S. Selenylated plant polysaccharides: A survey of their chemical and pharmacological properties. *Phytochemistry*. 2018;153:1–10. doi:.
38. Ulvskov P, Harholt J. A New Polysaccharide with a Long Evolutionary History. *The Plant cell*. 2018;30 6:1165–6; doi: .
39. Liu Y, Sun Y, Huang G. Preparation and antioxidant activities of important traditional plant polysaccharides. *Int J Biol Macromol*. 2018;111:780–6. doi:.
40. Huang G, Mei X, Hu J. The Antioxidant Activities of Natural Polysaccharides. *Curr Drug Targets*. 2017;18 11:1296–300. doi:.
41. Pauly M, Keegstra K. Biosynthesis of the Plant Cell Wall Matrix Polysaccharide Xyloglucan. *Annual review of plant biology*. 2016;67:235–59. doi:.
42. Larskaya IA, Gorshkova TA. Plant oligosaccharides - outsiders among elicitors? *Biochemistry Biokhimiia*. 2015;80 7:881–900. doi:.
43. Sanchez-Soberon F, Cuykx M, Serra N, Linares V, Belles M, Covaci A, et al. In-vitro metabolomics to evaluate toxicity of particulate matter under environmentally realistic conditions. *Chemosphere*. 2018;209:137–46. doi:.
44. Gerlofs-Nijland ME, Bokkers BGH, Sachse H, Reijnders JJE, Gustafsson M, Boere AJF, et al. Inhalation toxicity profiles of particulate matter: a comparison between brake wear with other sources of emission. *Inhalation toxicology*. 2019;31 3:89–98. doi:.
45. Chung JO, Yoo SH, Lee YE, Shin KS, Yoo SJ, Park SH, et al. Hypoglycemic potential of whole green tea: water-soluble green tea polysaccharides combined with green tea extract delays digestibility and intestinal glucose transport of rice starch. *Food function*. 2019;10(2):746–53. doi:.
46. Rha CS, Jeong HW, Park S, Lee S, Jung YS, Kim DO. Antioxidative, Anti-Inflammatory, and Anticancer Effects of Purified Flavonol Glycosides and Aglycones in Green Tea. *Antioxidants* (Basel, Switzerland). 2019;8 8; doi: .
47. Huang PH, Tseng CH, Lin CY, Lee CW, Yen FL. Preparation, characterizations and anti-pollutant activity of 7,3',4'-trihydroxyisoflavone nanoparticles in particulate matter-induced HaCaT keratinocytes. *Int J Nanomed*. 2018;13:3279–93. doi:.
48. Tsai MH, Hsu LF, Lee CW, Chiang YC, Lee MH, How JM, et al. Resveratrol inhibits urban particulate matter-induced COX-2/PGE2 release in human fibroblast-like synoviocytes via the inhibition of activation of NADPH oxidase/ROS/NF-kappaB. *Int J Biochem Cell Biol*. 2017;88:113–23. doi:.
49. Li Y, Qian W, Wang D, Meng Y, Wang X, Chen Y, et al. Resveratrol relieves particulate matter (mean diameter < 2.5 μm)-induced oxidative injury of lung cells through attenuation of autophagy deregulation. *Journal of applied toxicology: JAT*. 2018;38 9:1251–61. doi:.
50. Sun XY, Wang JM, Ouyang JM, Kuang L. Antioxidant Activities and Repair Effects on Oxidatively Damaged HK-2 Cells of Tea Polysaccharides with Different Molecular Weights. *Oxidative medicine*

- and cellular longevity. 2018;2018:5297539; doi: .
51. Skovgaard GR, Jensen AS, Sigler ML. Effect of a novel dietary supplement on skin aging in post-menopausal women. *Eur J Clin Nutr.* 2006;60 10:1201–6. doi:.
 52. Nakamura M, Miura S, Takagaki A, Nanjo F. Hypolipidemic effects of crude green tea polysaccharide on rats, and structural features of tea polysaccharides isolated from the crude polysaccharide. *Int J Food Sci Nutr.* 2017;68(3):321–30. doi:.
 53. 10.1016/j.ijbiomac.2016.09.036
Wu S, Lai M, Luo J, Pan J, Zhang LM, Yang L. Interactions between alpha-amylase and an acidic branched polysaccharide from green tea. *International journal of biological macromolecules.* 2017;94 Pt A:669 – 78; doi: .
 54. Ikeda A, Iso H, Yamagishi K, Iwasaki M, Yamaji T, Miura T, et al. Plasma tea catechins and risk of cardiovascular disease in middle-aged Japanese subjects: The JPHC study. *Atherosclerosis.* 2018;277:90–7. doi:.
 55. Franks M, Lawrence P, Abbaspourrad A, Dando R. The Influence of Water Composition on Flavor and Nutrient Extraction in Green and Black Tea. *Nutrients* 2019;11 1; doi:.
 56. Gupta SC, Kunnumakkara AB, Aggarwal S, Aggarwal BB. Inflammation, a Double-Edge Sword for Cancer and Other Age-Related Diseases. *Frontiers in immunology.* 2018;9:2160. doi:.
 57. Noguchi Y, Fukuda K, Matsushima A, Haishi D, Hiroto M, Kodera Y, et al. Inhibition of Df-protease associated with allergic diseases by polyphenol. *J Agric Food Chem.* 1999;47 8:2969–72. doi:.
 58. Zhao CN, Xu Z, Wu GC, Mao YM, Liu LN, Qian W, et al. Emerging role of air pollution in autoimmune diseases. *Autoimmun rev.* 2019;18 6:607–14. doi:.
 59. Boonpiyathad T, Sozener ZC, Satitsuksanoa P, Akdis CA. Immunologic mechanisms in asthma. *Seminars in immunology.* 2019;46:101333. doi:.
 60. Leclercq B, Kluza J, Antherieu S, Sotty J, Alleman LY, Perdrix E, et al. Air pollution-derived PM2.5 impairs mitochondrial function in healthy and chronic obstructive pulmonary diseased human bronchial epithelial cells. *Environmental pollution (Barking, Essex: 1987).* 2018;243 Pt B:1434-49; doi: .
 61. Frossing L, Kjaersgaard Klein D, Backer V, Baines KJ, Porsbjerg C. The six-gene expression signature in whole sampled sputum provides clinically feasible inflammatory phenotyping of asthma. *ERJ open research.* 2020;6 1; doi:.
 62. Sam A, Kraft M. Asthma/COPD Overlap: A Gene by Environment Interaction? *Chest.* 2018;154 6:1270–1; doi: .
 63. Rich DQ, Thurston SW, Balmes JR, Bromberg PA, Arjomandi M, Hazucha MJ, et al. Does Ambient Ozone or Other Pollutants Modify Effects of Controlled Ozone Exposure on Pulmonary Function? *Annals of the American Thoracic Society.* 2020. doi:.
 64. Bustamante-Marin XM, Ostrowski LE. Cilia and Mucociliary Clearance. *Cold Spring Harbor perspectives in biology* 2017;9 4; doi:.

65. Loxham M, Morgan-Walsh RJ, Cooper MJ, Blume C, Swindle EJ, Dennison PW, et al. The effects on bronchial epithelial mucociliary cultures of coarse, fine, and ultrafine particulate matter from an underground railway station. *Toxicol Sci.* 2015;145 1:98–107. doi:.
66. Moller W, Haussinger K, Ziegler-Heitbrock L, Heyder J. Mucociliary and long-term particle clearance in airways of patients with immotile cilia. *Respiratory research.* 2006;7:10. doi:.
67. Tu C, Nie H, Meng L, Wang W, Li H, Yuan S, et al. Novel mutations in SPEF2 causing different defects between flagella and cilia bridge: the phenotypic link between MMAF and PCD. *Human genetics.* 2020;139(2):257–71. doi:.
68. Shapiro A, Davis S, Manion M, Briones K. Primary Ciliary Dyskinesia (PCD). *American journal of respiratory and critical care medicine.* 2018;1982:P3-p4; doi: .
69. Butterfield R. Primary Ciliary Dyskinesia. *Pediatrics in review.* 2017;38 3:145–6; doi: .
70. Fitzgerald DA, Shapiro AJ. Primary Ciliary Dyskinesia. *Paediatric respiratory reviews.* 2016;18:1–2; doi: .
71. Holmes SMV, Saha D, Chen SC, Brown J, Jayathilake RJ. PG. Muco-ciliary clearance: A review of modelling techniques. *Journal of biomechanics.* 2020;99:109578. doi:.
72. Soares H, Carmona B, Nolasco S, Viseu Melo L, Goncalves J. Cilia Distal Domain: Diversity in Evolutionarily Conserved Structures. *Cells* 2019;8 2; doi:.
73. Lauring MC, Zhu T, Luo W, Wu W, Yu F, Toomre D. New software for automated cilia detection in cells (ACDC). *Cilia.* 2019;8:1. doi:.
74. 10.1242/jcs.066308
Bloodgood RA. Sensory reception is an attribute of both primary cilia and motile cilia. *Journal of cell science.* 2010;123 Pt 4:505-9; doi: .
75. Latos-Brozio M, Masek A. Structure-Activity Relationships Analysis of Monomeric and Polymeric Polyphenols (Quercetin, Rutin and Catechin) Obtained by Various Polymerization Methods. *Chem Biodivers.* 2019;16 12:e1900426. doi:.
76. Song BJ, Manganais C, Ferruzzi MG. Thermal degradation of green tea flavan-3-ols and formation of hetero- and homocatechin dimers in model dairy beverages. *Food Chem.* 2015;173:305–12. doi:.
77. Rudolphi-Skorska E, Dyba B, Kreczmer B, Filek M. Impact of polyphenol-rich green tea extracts on the protection of DOPC monolayer against damage caused by ozone induced lipid oxidation. *Acta Biochim Pol.* 2018;65 2:193–7. doi:.
78. Chen L, Mo H, Zhao L, Gao W, Wang S, Cromie MM, et al. Therapeutic properties of green tea against environmental insults. *J Nutr Biochem.* 2017;40:1–13. doi:.
79. Monobe M, Ema K, Kato F, Maeda-Yamamoto M. Immunostimulating activity of a crude polysaccharide derived from green tea (*Camellia sinensis*) extract. *J Agric Food Chem.* 2008;56 4:1423–7. doi:.
80. Santos J, Foster R, Jonckheere AC, Rossi M, Luna Junior LA, Katekaru CM, et al. Outdoor Endurance Training with Air Pollutant Exposure Versus Sedentary Lifestyle: A Comparison of Airway Immune

- Responses. *Int J Environ Res Public Health*. 2019;16 22; doi:.
81. Puttur F, Gregory LG, Lloyd CM. Airway macrophages as the guardians of tissue repair in the lung. *Immunol Cell Biol*. 2019;97 3:246–57. doi:.
 82. Kaur R, Kaur J, Mahajan J, Kumar R, Arora S. Oxidative stress–implications, source and its prevention. *Environ Sci Pollut Res Int*. 2014;21 3:1599–613. doi:.
 83. Valavanidis A, Vlachogianni T, Fiotakis K, Loridas S. Pulmonary oxidative stress, inflammation and cancer: respirable particulate matter, fibrous dusts and ozone as major causes of lung carcinogenesis through reactive oxygen species mechanisms. *Int J Environ Res Public Health*. 2013;10 9:3886–907. doi:.
 84. Eftekhari A, Dizaj SM, Chodari L, Sunar S, Hasanzadeh A, Ahmadian E, et al. The promising future of nano-antioxidant therapy against environmental pollutants induced-toxicities. *Biomedicine pharmacotherapy = Biomedecine pharmacotherapie*. 2018;103:1018–27. doi:.
 85. Gupta P, Thompson BL, Wahlang B, Jordan CT, Zach Hilt J, Hennig B, et al. The environmental pollutant, polychlorinated biphenyls, and cardiovascular disease: a potential target for antioxidant nanotherapeutics. *Drug delivery and translational research*. 2018;83:740–59; doi: .
 86. Divya P, Puthusseri B, Manual DJK, Savanur MA. Epigallocatechin gallate protects BEAS-2B cells from lipopolysaccharide-induced apoptosis through upregulation of gastrin-releasing peptide. *Molecular cellular biochemistry*. 2017;434(1–2):105–11. doi:.
 87. Hansen MB, Nielsen SE, Berg K. Re-examination and further development of a precise and rapid dye method for measuring cell growth/cell kill. *J Immunol Methods*. 1989;119(2):203–10. doi:.
 88. Kim J, Cho SY, Kim SH, Cho D, Kim S, Park CW, et al. Effects of Korean ginseng berry on skin antipigmentation and antiaging via FoxO3a activation. *J Ginseng Res*. 2017;41(3):277–83. doi:.

Tables

Table 1. Chemical properties and identification of catechins in green tea extract (GTE) prepared from the leaves of green tea

Chemical constituent	Amount in GTE (w/w) (%)
Epigallocatechin	11.8 ± 2.0
Gallocatechin	0.56 ± 0.26
Epicatechin	3.68 ± 0.8
Catechin	0.21 ± 0.06
Epigallocatechin gallate	16.8 ± 0.8
Gallocatechin gallate	0.53 ± 0.4
Epicatechin gallate	2.94 ± 0.2
Total catechin	36.52 ± 1.6
Caffeine	3.3 ± 0.5

Percentage (%) in dry matter. The data are presented as the mean ± SE (N = 5).

Figures

Figure 1

Effects of FDPs on airway and lung cells. (a) Cytotoxicity of FDPs toward BEAS-2B, IMR90, and A549 cells. (b) Intracellular ROS levels in FDP-stimulated BEAS-2B, IMR90, and A549 cells. (c) Cell morphology of FDP-treated cells. Cell viability was estimated by MTT assay, and intracellular ROS levels were determined by DCF-DA assay. The data are presented as the mean $\pm$ SD. (N = 3). * $p < 0.001$ compared to the control group. Scale bars, 200 μ m.

Figure 2

Protective effects of GTE, FLGs, and CTPs and their bioactive components against FDP-induced damage. (a) Protective effects of GTE, FLGs, and CTPs against FDP-induced cell death. (b) Relative ROS levels in FDP-stimulated cells treated with GTE, FLGs, and CTPs. (c) Protective effects of green tea catechins against FDP-induced cytotoxicity. (d) Effects of green tea flavonols on the relative survival rates of FDP-treated cells. Cell viability was measured by MTT assay, and intracellular ROS levels were investigated by DCF-DA assay. All results are expressed as the means $\pm$ SDs of the values obtained in 3 independent experiments. * $p < 0.05$ and ** $p < 0.001$ compared to the FDP-treated group; # $p < 0.001$ compared to the vehicle-control group.

Figure 3

Synergistic effects of EGCG and myricetin against FDP-induced cellular damage. (a) Molecular structure of (-)-epigallocatechin gallate. (b) Molecular structure of myricetin. (c) Synergistic protective effects of EGCG and myricetin on cell survival under FDP treatment. (d) Synergistic ROS-scavenging effects of EGCG and myricetin in FDP-stimulated BEAS-2B cells. (e) Effects of green tea catechins and flavonols on the morphology of FDP-treated cells. The results are shown as the means $\pm$ SDs of the values obtained in 3 independent experiments. * $p < 0.05$ and ** $p < 0.001$ compared to the FDP-treated group; # $p < 0.001$ compared to the vehicle control group. Scale bars, 200 µm.

Figure 4

Synergistic protective effects of GTE, FLGs, and CTPs against FDP-elicited cellular damage. (a) Synergistic effects of GTE, FLGs, and CTPs on cell survival in FDP-stimulated BEAS-2B cells. (b) Synergetic ROS-scavenging effects of GTE, FLGs, and CTPs against FDP-induced oxidative stress. (c) Effects of GTE, FLGs, and CTPs on the morphology of FDP-treated BEAS-2B cells. The data are presented as the mean $\pm$ SD (N = 3). * $p < 0.05$ and ** $p < 0.001$ compared to the FDP-treated group; # $p < 0.001$ compared to the vehicle control group. Scale bars, 200 μ m.

Figure 5

Inhibitory effects of GTE or GTE, FLGs, and CTPs against FDP-induced inflammatory response elevation. The synergistic effects of GTE, FLGs, and CTPs on the expression levels of the airway inflammatory genes (a) IL-4, (b) IL-13, (c) IL-17A, (d) CCL-11, (e) CCL-17, and (f) MMP12 were measured in FDP-stimulated BEAS-2B cells. All results are either representative results or are expressed as the means $\pm$ SDs of the values obtained in three independent experiments. * $p < 0.05$ and ** $p < 0.001$ compared to the FDP-treated group; # $p < 0.001$ compared to the vehicle control group.

Figure 6

Ameliorative effects of GTE, FLGs, and CTPs on FDP-induced ciliogenesis suppression in BEAS-2B cells. (a) Immunostaining of cilia in FDP-stimulated BEAS-2B cells. (b) Ciliated cells were counted, and the results are presented as the proportions of ciliated cells among all cells. (c) Activation of ciliogenesis by GTE, FLG, and CTP treatment. The data are presented as the mean $\pm$ SD (N = 3). * p < 0.05 and ** p < 0.001 compared to the FDP-treated group; # p < 0.001 compared to the vehicle control group. The ciliated cells were immunostained for ARL13B (red) and acetylated- α -tubulin (green), and merged fluorescence is indicated with DAPI (blue). Scale bars, 20 μ m in A and 5 μ m in C.