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IN-VITRO ANTIOXIDANT AND NEUROPROTECTIVE POTENTIAL OF *MUSA PARADISIACA* FRUIT PEEL EXTRACT IN SH-SY5Y HUMAN NEUROBLASTOMA CELLS

Sumithira George[1*], Abitha Sri Ramamurthy[1], Ragul Ravi[1], Abirami Gopi[1], Abarna Shanmugam[1], Chandru Elumalai[1], Raguraman ponraj[1], Krishnamoorthy Balakrishnan[2] Suresh Ratinasamy[3]

[1]Department of Pharmacology, The Erode College of Pharmacy and Research Institute, Erode – 638112, Tamil Nadu, India. (Affiliated to The Tamil Nadu Dr MGR Medical University Chennai).
[2] Department of pharmaceutics, Sanjivani College of pharmaceutical Sciences, Khetri-333503, Rajasthan. India (Affiliated to Rajasthan university of Health Sciences, Jaipur)
[3]Department of pharmacology, Greensmed Labs, Chennai– 600097, Tamil Nadu, India.

Corresponding Author: Dr. G. Sumithira,
[*]Professor, Department of Pharmacology, The Erode College of Pharmacy and Research Institute, Erode – 638112, ORCID ID: 0000-0002-0181-3201, Email: georgesumithira@gmail.com

Abstract:
Aim and Objective: Parkinson's disease (PD) is the second most prevalent neurodegenerative disorder after Alzheimer's marked by dopaminergic neuronal loss linked to oxidative stress. The aim of present study was to investigate the *in-vitro* antioxidant and neuroprotective potential of the ethanolic extract of *Musa paradisiaca* fruit peel (*EEMP*) and its cytoprotective efficacy in SH-SY5Y human neuroblastoma cells.
Methods and Materials: Fruit peels of *Musa paradisiaca* were shade-dried, extracted with ethanol, and analyzed for physicochemical and phytochemical properties. Total phenolics, flavonoids, vitamin C, and vitamin E were quantified. Anti-oxidant activity was determined by the DPPH assay, and neuroprotective effects were assessed by the MTT assay on SH-SY5Y cells.
Results & Discussion: Quantitative analysis of *EEMP* revealed the presence of a significant amount of phenols, flavonoids, vitamin C and E. EEMP showed moderate antioxidant activity with IC_{50} of 80.65 µg/mL and concentration-dependent cytotoxicity (IC_{50} = 70.13 µg/mL) against SH-SY5Y cells, with morphological evidence of apoptosis at higher concentrations. The potent antioxidant and neuroprotective effects of *EEMP* may be attributed to its rich phenolic and vitamin content, which effectively counteracts oxidative stress and helps maintain neuronal integrity. *Musa paradisiaca* fruit peel may serve as a promising natural therapeutic candidate for the prevention and management of oxidative stress–related neurodegenerative disorders, such as Parkinson's disease.

Keywords: *Musa paradisiaca*, Anti-oxidant, SH-SY5Y cells, Neuroprotection, Parkinson's disease.

1. Introduction

Parkinson's disease (PD) is the second most prevalent neurodegenerative disorder after Alzheimer's disease. It is a chronic, progressive condition characterized by the selective degeneration of dopaminergic neurons in the substantia nigra pars compacta, leading to a marked reduction in striatal

dopamine levels. This dopaminergic deficit manifests clinically as bradykinesia, rigidity, resting tremor, and postural instability—the cardinal motor symptoms of PD [1,2]. The prevalence of PD increases with age, affecting approximately 1% of individuals over 60 years and up to 4% of those over 80 years [3]. The average age of onset is around 60 years, although about 10% of cases occur before age 50 and are classified as young-onset PD, potentially representing a distinct subtype. The disease is more common in men than women, possibly due to the neuroprotective effects of oestrogen [4].

The pathogenesis of PD is multifactorial and incompletely understood, involving a complex interplay between genetic susceptibility, environmental factors, mitochondrial dysfunction, oxidative stress, and neuroinflammation. Among these, the abnormal aggregation of α-synuclein (α-syn) into Lewy bodies is a key pathological hallmark contributing to neuronal toxicity and cell death [5]. Age-related mitochondrial impairment, increased oxidative stress, and accumulation of misfolded α-synuclein further accelerate dopaminergic neurodegeneration [6]. Oxidative stress is a central mechanism underlying PD pathology. Excessive generation of reactive oxygen species (ROS), arising from dopamine metabolism, mitochondrial dysfunction, and iron accumulation, overwhelms endogenous antioxidant defences such as superoxide dismutase and catalase. This imbalance triggers oxidative damage to lipids, proteins, and DNA, leading to neuronal apoptosis and progressive motor impairment [6]. Therefore, therapeutic strategies aimed at restoring redox homeostasis and preventing oxidative neuronal injury hold promise in PD management. Currently available pharmacological agents, including carbidopa/levodopa, amantadine, and rasagiline, offer only symptomatic relief and do not halt disease progression. Moreover, long-term use is associated with adverse effects such as dyskinesia and motor fluctuations [7]. Consequently, there is a growing interest in exploring plant-derived bioactive compounds as safer, multifunctional alternatives due to their antioxidant, anti-inflammatory, and neuroprotective properties [8].

Musa paradisiaca (banana), belonging to the family *Musaceae*, is widely cultivated across tropical regions and is rich in phytoconstituents such as phenolics, flavonoids, alkaloids, vitamin C, and vitamin E. These compounds possess potent antioxidant and free-radical scavenging properties that may protect dopaminergic neurons from oxidative stress and apoptosis [9–11]. The fruit peel, often regarded as agricultural waste, contains high concentrations of polyphenols and vitamins with proven antioxidant and cytoprotective potential [7]. Previous studies have reported diverse pharmacological effects of *Musa* species, including anti-diabetic, anti-ulcer, anti-inflammatory, hepatoprotective, wound-healing, and memory-enhancing activities [10–13]. Despite this wide range of biological properties, no systematic study has yet evaluated the anti-Parkinson's potential of *Musa paradisiaca* fruit peel. Therefore, the present study was designed to investigate the *in vitro* anti-Parkinson's activity of the ethanolic extract of *Musa paradisiaca* fruit peel (*EEMP*) using the MTT assay on SH-SY5Y human neuroblastoma cells, along with assessment of its antioxidant potential through the DPPH free radical scavenging assay. These investigations aim to provide scientific evidence supporting the neuroprotective potential of *Musa paradisiaca* fruit peel extract against oxidative stress–induced neuronal injury.

2. Methods and Materials:

2.1. Chemicals and Reagents

Folin–Ciocalteu reagent, gallic acid (standard), sodium carbonate (Na_2CO_3, 7.5%), aluminium chloride ($AlCl_3$, 10%), sodium nitrite ($NaNO_2$, 5%), sodium hydroxide (NaOH, 1 M), quercetin (standard), 2,6-dichlorophenol indophenol (DCPIP), ascorbic acid (standard), 2,2-diphenyl-1-picrylhydrazyl (DPPH), and MTT [3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyl tetrazolium bromide)] were procured from SRL Chemicals (Mumbai, India). α-Tocopherol was obtained from PCI (Mumbai, India), and Isopulegol was purchased from Sigma-Aldrich (USA). SH-SY5Y human neuroblastoma cell line was obtained from the National Centre for Cell Science (NCCS), Pune, India.

2.2. Collection, Authentication, and Preparation of Extract

Fresh fruits of *Musa paradisiaca* were collected in January and authenticated by Dr. S. S. Hameed, Scientist 'F' and Head, Botanical Survey of India (BSI), Coimbatore. A voucher specimen was deposited in the BSI herbarium for future reference. The fruit peels were separated, washed thoroughly with distilled water, shade-dried at room temperature, and pulverized to a coarse powder. The powder was passed through a No. 40 mesh sieve and stored in airtight containers until extraction. Approximately 50 g of powdered peel was extracted using ethanol in a Soxhlet apparatus for 72 h. The solvent was evaporated under reduced pressure using a rotary evaporator to obtain a concentrated ethanolic extract (*EEMP*), which was dried and stored at 4 °C until further use [14,15].

2.3. Physicochemical Parameters

Physicochemical parameters were determined according to the methods described in the Indian Pharmacopoeia [16].

2.3.1 Ash Values

2.3.1.1 Total Ash: Two grams of air-dried powder were incinerated in a silica crucible at 500–600 °C until white ash was obtained. Total ash values were determined by using the formula.

$$Total\ Ash\ (\%\ w/w) = \frac{(Weight\ of\ total\ ash\ (gm))}{Weight\ of\ airdried\ sample\ (gm)}\ X\ 100$$

2.3.1.2 Acid-Insoluble Ash: The total ash was boiled with 25 mL of dilute hydrochloric acid, filtered, and ignited to constant weight. Acid-Insoluble ash values were calculated using following formula.

$$Acid - Insoluble\ Ash\ (\%\ w/w) = \frac{(Weight\ of\ acid - insoluble\ residue\ (gm))}{Weight\ of\ airdried\ sample\ (gm)}\ X\ 100$$

2.3.1.3 Water-Soluble Ash: The total ash was boiled with 25 mL of distilled water, filtered, and ignited to obtain the residue. Water-Soluble ash values were calculated using following formula.

$$Water - Soluble\ Ash\ (\%\ w/w) = \frac{(Weight\ of\ water - Soluble\ ash\ (gm))}{Weight\ of\ airdried\ sample\ (gm)}\ X\ 100$$

2.3.2 Moisture Content

One gram of air-dried powder was heated in a hot-air oven at 105 °C until a constant weight was obtained. The moisture content was expressed as the percentage loss in weight. Moisture content was estimated by using the formula.

$$Moisture\ Content\ (\%\ w/w) = \frac{(Loss\ of\ weifht\ after\ drying\ (gm))}{Weight\ of\ sample\ before\ drying\ (gm)}\ X\ 100$$

2.4 Preliminary Phytochemical Evaluation

Phytochemical screening was performed to identify and estimate major bioactive constituents.

2.4.1 Qualitative Analysis

Qualitative analysis for phytochemical groups such as alkaloids, phenolics, flavonoids, carbohydrates, and tannins were performed using standard methods [17].

2.4.2 Quantitative Analysis

2.4.2.1 Total Phenolic Content (TPC):

Determined using the Folin–Ciocalteu method according to Oracz J *et al.,* and expressed as mg gallic acid equivalents (GAE) [18].

2.4.2.2 Total Flavonoid Content (TFC):
Estimated by the aluminium chloride colorimetric method according to Shraim AM *et al*., and expressed as mg quercetin equivalents (QE) [19].

2.4.2.3 Vitamin C (Ascorbic Acid) Content:
Determined by the 2,6-dichlorophenol indophenol (DCPIP) titration method Zainal Abidin NN and expressed as mg ascorbic acid equivalents (AAE) per 100 gm of dry powder [20].

2.4.2.4 Vitamin E (Tocopherol) Content:
Determined by the Emmerie–Engel method Emmerie A and expressed as mg α-tocopherol equivalents per gram of extract [21].

2.5 *In Vitro* Studies
In vitro assays were conducted to evaluate the antioxidant potential and neuroprotective activity of *Musa paradisiaca* peel extract.

2.5.1 Antioxidant Activity (DPPH Radical Scavenging Assay)
The antioxidant potential of *EEMP* was assessed using the DPPH radical scavenging assay as described earlier [22]. One mL of 0.1 mM DPPH solution in methanol was mixed with 1 mL of extract (25–200 µg/mL). After 30 min of incubation in the dark, absorbance was measured at 517 nm. Radical scavenging activity and IC_{50} values were calculated from the dose–response curve. The % DPPH Inhibition was calculated by using formula;

$$\%\ DPPH\ Inhibition = \frac{OD\ of\ control - OD\ of\ test}{OD\ of\ control} X\ 100$$

2.5.2 Anti-Parkinson Activity (MTT Assay on SH-SY5Y Cells)
The cytoprotective potential of *EEMP* was evaluated using the MTT assay on SH-SY5Y neuroblastoma cells [23]. Cells (5×10^3 cells/well) were seeded in 96-well plates and incubated for 48 h. They were treated with varying concentrations of EEMP (6.25–100 µg/mL) for 24 h in a CO_2 incubator. After treatment, MTT solution (0.5 mg/mL) was added and incubated for 3 h. The resulting formazan crystals were dissolved in DMSO, and absorbance was measured at 570 nm. Cell viability was calculated relative to untreated control cells.

3 Statistical Analysis
All experiments were performed in triplicate, and the results were expressed as mean ± Standard deviation (SD). Statistical analysis and graphical representations were carried out using GraphPad Prism Software (10.6.0).

4. Results:
4.1 Appearance and Percentage yield of *EMPP*
The Appearance of extract and percentage yield are summarized in Table-1.

Table: 1: - Appearance and Percentage Yield of *EMPP*

Drug	*Musa Paradisiaca* fruit peel
Solvent	Ethanol
Colour	Yellowish Dark Brown
Consistency	Semisolid
Percentage yield	40.55%w/w

4.2 Physical Parameters of *Musa Paradisiaca* Fruit
The general physical parameters of *Musa Paradisiaca* fruit, obtained value and typical range are present in Table-2. *Musa Paradisiaca* banana variety weighed between 144.7-151.3 gm with the fruit

length of 18-20 cm and the fruit circumference of 10.9-12.1 cm. The pulp weight varied between 102.1-107.02 gm whereas the peel weighed in the range of 42.6-45.27 gm. The peel to pulp ratio was 2.31-2.41.

Table: 2: - Physical parameters of *Musa Paradisiaca* fruit

Parameters	Values	Typical Range [25]
Fruit Weight (gm)	144.70 – 151.33	100 – 220
Fruit Length (cm)	18 – 20	15 – 25
Fruit Circumference (cm)	10.91 – 12.15	10 – 14
Pulp Weight (gm)	102.10 – 107.02	70 – 160
Peel Weight (gm)	42.65 – 45.27	30 – 60
Pulp to Peel Ratio	2.31 – 2.41	2.0 – 4.50

4.3 Physicochemical Parameters of *Musa Paradisiaca* Fruit Peel:

Physicochemical characterization was conducted on powdered *Musa Paradisiaca* Fruit Peel. The physicochemical evaluation of *Musa Paradisiaca* Fruit Peel revealed a total ash content of 10% w/w, acid-insoluble ash of 7.5% w/w, water-soluble ash of 10.5% w/w, and a moisture content (loss on drying) of 9.3% w/w that are summarized in Table-3.

Table:3: - Physicochemical parameters of *Musa Paradisiaca* fruit peel

Parameter	**Percentage**
Total Ash	10 % w/w
Water Soluble	10.50 % w/w
Acid Insoluble	7.50 % w/w
Moisture Content	9.30 % w/w

4.4 Phytochemical Analysis

4.4.1 Qualitative Analysis

Preliminary phytochemical screening shows the *EEMP* extract revealed the presence of alkaloids, flavonoids, phenolic compounds and vitamin E that are summarized in table-4.

Table: 4: - Preliminary Phytochemical Screening of *EEMP*

S.no	**Phytochemical Constituents**	**Results**
1.	Alkaloids	+
2.	Carbohydrates	-
3.	Flavonoids	+
4.	Tannins	-
5.	Phenolic compounds	+
6.	Vitamin E	+

[Note: (+) indicates the present (-) indicates the absences]

4.4.2 Quantitative Analysis:

The quantitative estimation of major antioxidant constituents in the ethanolic extract of Musa paradisiaca fruit peel (EEMP) revealed appreciable levels of phenolic compounds, flavonoids, and vitamins C and E (Table 5). The total phenolic content of EEMP was 67.40 mg gallic acid equivalents (GAE) per 100 gm of extract, indicating a rich reservoir of polyphenolic compounds responsible for free-radical scavenging activity. The total flavonoid content was 38.51 mg quercetin equivalents (QE) per 100 gm, supporting the presence of potent flavonoid antioxidants. In addition, the extract contained 13.16 mg ascorbic acid equivalents (AAE) per 100 gm of vitamin C and 79.65 mg

tocopherol equivalents (TE) per gm of vitamin E, both of which contribute to redox homeostasis and membrane protection.

Table:5: - Quantitative analysis of *EEMP* extract

Plant Extract	Total Phenolic content (mg GAE/100gm)	Total Flavonoid content (mg QE/100gm)	Total Vitamin C content (mg AAE/100gm)	Total Vitamin E content (mg TE/gm)
EEMP	67.40	38.51	13.16	79.65

4.5 *In-vitro* Studies:

4.5.1 *In-vitro* Anti-oxidant Activity (DPPH Assay):

The DPPH radical scavenging assay demonstrated significant antioxidant potential of *EEMP* with an IC_{50} value of 80.65 µg/mL, compared to 13.25 µg/mL for ascorbic acid (Table-6, Fig-1).

Table:6: - DPPH Radical scavenging activity of *EEMP* extract

Concentration (µg/ml)	Ascorbic Acid (% inhibition ± SD)	EEMP (% inhibition ± SD)
5	0.00 ± 0.00	0.00 ± 0.00
10	0.00 ± 0.00	0.00 ± 0.00
50	23.72 ± 1.12	84.91 ± 1.64
100	47.59 ± 1.58	88.84 ± 1.02
150	58.30 ± 1.25	94.09 ± 0.88
200	64.86 ± 1.46	95.55 ± 0.74
250	70.35 ± 1.35	96.96 ± 0.63
IC_{50}	**13.25 µg/mL**	**80.65 µg/mL**

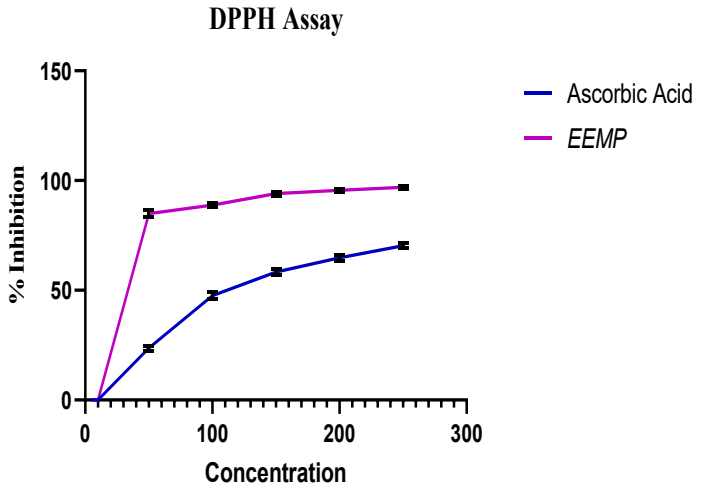

Figure-1: Antioxidant Activity of ethanolic extract of *Musa Paradisiaca* fruit peel

4.5.2 *In-vitro* MTT^{+} Assay:

The MTT assay revealed that *EEMP* exhibited a concentration-dependent cytotoxic effect on SH-SY5Y cells. Cell viability was 93.07% at 6.25 µg/mL and progressively decreased to 30.90% at 100 µg/mL, indicating a significant reduction in cell survival at higher concentrations and IC_{50} values also mentioned (Table: 6).

The bar graph displays the percentage of viable SH-SY5Y cells after exposure to various concentrations of *EEMP*, showing a dose-dependent decrease in cell viability mentioned in (Fig-2).

Microscopic images illustrating morphological changes in SH-SY5Y cells after treatment with varying concentrations of *EEMP*, showing dose-dependent cytotoxic and apoptotic effects compared to untreated control cells mentioned in (Fig-3)

Table:7: - Cytotoxicity of *EEMP* against SH-SY5Y cells

Concentration (µg/ml)	% Cytotoxicity (Mean ± SD)	IC_{50}
6.25	6.92±0.63	70.13 µg/mL
12.5	9.00±0.92	
25	16.74±0.76	
50	29.14±2.33	
100	69.09±3.47	

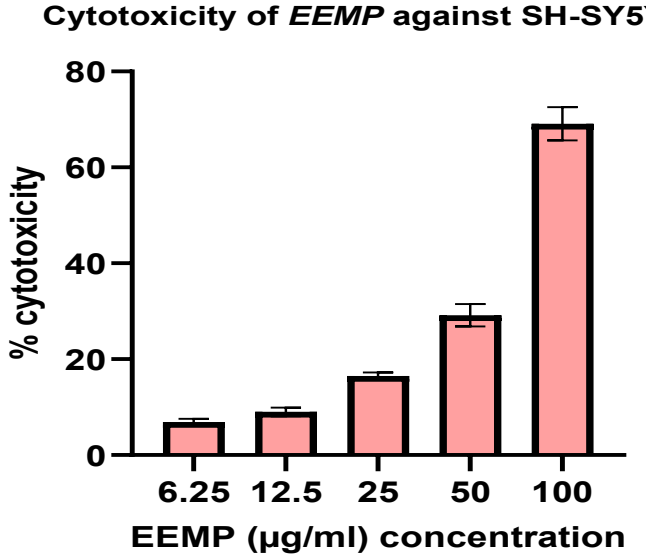

Figure-2: Anti-Parkinson Activity of *EEMP* in MTT^+ Assay with SHSY5Y Cell

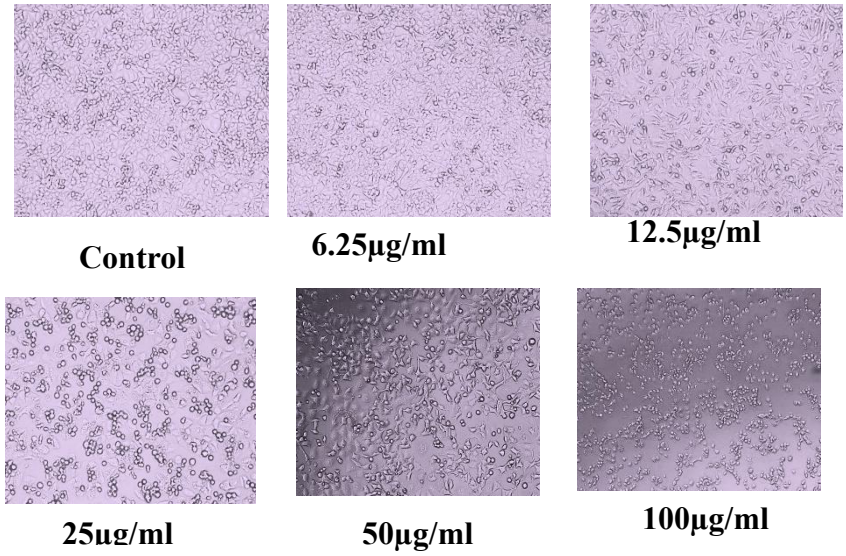

Figure-3: Cytotoxicity of *EEMP* against SH-SY5Y cells

5. DISCUSSION:

5.1 Appearance, Physical parameters and Phytochemical Evaluation:

Parkinson's disease (PD) is a progressive neurodegenerative disorder marked by dopaminergic neuronal loss in the substantia nigra and corpus striatum, causing motor and cognitive deficits. Its pathogenesis involves genetic mutations (e.g., α-synuclein, parkin), environmental toxins, oxidative stress, ROS generation, and neuroinflammation. All therapies provide symptomatic relief but do not slow the progression of neurodegeneration. *Musa paradisiaca* fruit has phytoconstituents, particularly phenolics and flavonoids, vitamin C and vitamin E show promise in reducing oxidative stress, mitigating neuroinflammation, and potentially slowing PD progression.

Extraction of dried *Musa paradisiaca* fruit peel was carried out to isolate bioactive constituents, particularly alkaloids, flavonoids, and other secondary metabolites [25]. The ethanolic extract (*EEMP*) yield value is 40.55% w/w and appeared dark brown in colour. Studying banana's physical parameters is vital for assessing quality, maturity, and uses [26]. Size, shape, edible yield, and pulp-to-peel ratio indicate maturity and quality [27]. In our study, *Musa paradisiaca* fruits showed typical values, reflecting good quality and high nutritional value. Physicochemical analysis of *Musa paradisiaca* fruit peel revealed total ash (10% w/w), water-soluble ash (10.5% w/w), and acid-insoluble ash (7.5% w/w), indicating low contamination and good purity. Moisture content (9.3% w/w) was within acceptable limits, ensuring stability and suitability for further pharmacological and formulation studies.

5.2 Phytochemical Analysis of Total Phenolic, Flavonoids, Vitamin-C, Vitamin-E Content:

The phytochemical characterization of *EEMP* was foundational compounds of this study. In Qualitative analysis confirmed that presence of secondary metabolites including Flavonoids, Phenolic compounds, Alkaloids, Vitamin C and Vitamin E. These findings are the agreement with previous reports that have documented similar phytochemical profiles in *Musa Paradisiaca* fruit peel [28]. These metabolites are recognized for their significant biologic activities such as scavenging of free radicals and also for neurodegeneration disorders. Quantitative analysis further reveals that total phenolics (69.40 mg GAE/100gm), flavonoids (38.51 mg QE/100gm) confirming the presence of key antioxidant compounds, vitamin C (13.52 mg AAE/100gm) plays a crucial in water-soluble antioxidant that maintains redox balance, supports neurotransmitter synthesis, and protects neurons by reducing oxidative stress and excitotoxicity, helping prevent neurodegenerative diseases such as Parkinson's and Alzheimer' [29] and vitamin E (79.65 mg TE/100gm). Additionally, vitamin E content further supports its therapeutic potential to cross blood brain barriers for neurodegenerative disease management. These findings justify relevance of phytoconstituents profiling in establishing a mechanistic understanding of the extract pharmacological actions [28].

5.3 *In-vitro* DPPH Assay:

In Parkinson's disease (PD), excess production of reactive oxygen species (ROS) impairs the brain's antioxidant defences—such as superoxide dismutase and catalase—leading to oxidative stress, mitochondrial dysfunction, and loss of dopaminergic neurons in the substantia nigra [30]. Oxidative stress is a key driver of PD pathology, associated with α-synuclein aggregation, neuroinflammation, and disrupted dopaminergic signalling [31].

Plant-derived antioxidants have demonstrated neuroprotective effects in PD models by scavenging free radicals, reducing lipid peroxidation, and restoring redox balance [32] The DPPH radical scavenging assay is widely used to evaluate such antioxidant potential in phytochemicals [32].

In our study, the ethanolic extract of *Musa paradisiaca* demonstrated a dose-dependent DPPH radical scavenging activity, showing 59.69% inhibition at 50 µg/ml, increasing to 70.54% inhibition at 250 µg/ml, with an IC_{50} of 80.65 µg/ml—indicative of moderate antioxidant potency. By comparison, the reference standard, ascorbic acid, exhibited a much lower IC_{50} of 13.25 µg/ml, confirming its far superior radical-quenching efficiency.

These findings align with literature reports: for instance, an ethanol extract of *Musa paradisiaca* peel evaluated via DPPH assay yielded an IC_{50} of 114.86 µg/ml, categorized as moderate antioxidant activity [33]. Additionally, a peel-off gel mask formulation containing *Musa paradisiaca* peel extract showed IC_{50} values of 112–115 ppm (µg/ml), similarly indicating moderate efficacy [34].

The comparatively inferior potency of the *Musa paradisiaca* extract relative to ascorbic acid is attributable to structural differences in active molecules. While ascorbic acid's enediol moiety enables rapid hydrogen donation to neutralize free radicals, the phenolic constituents—such as flavonoids and vitamin E—in the plant extract donate hydrogen more slowly. Nevertheless, the extract's appreciable levels of total phenolic compounds, flavonoids, and vitamin E contribute substantially to its antioxidant action.

Moreover, studies have shown that phytochemical analyses identified the key antioxidant constituents in *M. paradisiaca*, including gallic acid, syringic acid, ferulic acid, catechol, and others, particularly concentrated in the peel and pseudo stem, which contribute to its free-radical scavenging ability [35].

5.4 Effect of *EEMP* in haloperidol-induced cytotoxicity in SH-SY5Y Cell:

The MTT assay is a widely used colorimetric method for evaluating cell viability, proliferation, and cytotoxicity, and it is extensively applied in neurotoxicity and neuroprotection studies using neuronal cell models such as SH-SY5Y cells. The SH-SY5Y human neuroblastoma cell line is regarded as a robust in vitro model for neurodegenerative disease research, particularly Parkinson's disease, due to its dopaminergic properties and susceptibility to oxidative stress [36].

In the present study, the effects of the *EEMP* fruit peel on SH-SY5Y cells were evaluated using the MTT assay. A dose-dependent reduction in cell viability was observed, with 93.07±0.64 % viability at 6.25 µg/mL, decreasing to 30.90±3.47% at 100 µg/mL (Fig. 2, Table 6). According to the ISO 10993-5 guidelines, cell viability above 80% is considered non-cytotoxic, 80–60% weakly cytotoxic, 60–40% moderately cytotoxic, and below 40% strongly cytotoxic [37]. Based on this classification, *EEMP* at the highest concentration tested (100 µg/mL) exhibited strong cytotoxicity (30.9% viability) [37].

In the present study, the ethanolic extract of *Musa paradisiaca* fruit peel (*EEMP*) exhibited an IC_{50} value of 70.13 µg/mL against SH-SY5Y neuroblastoma cells, as determined by the MTT assay. According to the criteria established by the U.S. National Cancer Institute (NCI) for preliminary in vitro screening, crude plant extracts with IC_{50} values below 100 µg/mL are considered to demonstrate biologically significant cytotoxicity (Xia et al., 2011; Suffness & Pezzuto, 1990) [38, 39]. Therefore, the observed IC_{50} value of *EEMP* (70.13 µg/mL) suggests notable cytotoxic potential, consistent with previously reported plant extracts that exhibit dose-dependent reductions in SH-SY5Y cell viability.

Microscopic examination of SH-SY5Y cells treated with the ethanolic extract of *Musa paradisiaca* fruit peel (*EEMP*) revealed significant morphological alterations indicative of apoptosis. These changes included cell shrinkage, membrane blebbing, and nuclear fragmentation, consistent with apoptotic cell death pathways. Such morphological features have been well-documented in neuroblastoma cells subjected to oxidative stress. Our results align with previous studies Zhao *et al.,* demonstrated that hydrogen peroxide (H_2O_2) induces similar apoptotic characteristics in SH-SY5Y cells, including nuclear condensation and DNA fragmentation, as observed through DAPI staining and electron microscopy [40]. Han *et al*., reported that apoptosis in SH-SY5Y cells is often mediated by oxidative stress, leading to mitochondrial dysfunction, activation of caspases, and subsequent DNA fragmentation [41]. This cascade of events underscores the critical role of oxidative stress in neuronal cell death, indicating that the morphological changes observed in *EEMP*-treated SH-SY5Y cells align with those reported in literature for oxidative stress-induced apoptosis. *EEMP* likely exerts its cytotoxic effects via mechanisms involving oxidative stress and apoptotic pathways.

The cytotoxic effects observed in *EEMP*-treated SH-SY5Y cells may be mediated by its flavonoids and phenols, which induce apoptosis through mitochondrial dysfunction, ROS generation, modulation of Bcl-2 family proteins, and caspase activation, similar to mechanisms reported in cancer and neuronal cell studies [42]. Many flavonoids and phenolic compounds induce cell cycle arrest at G1/S

or G2/M, allowing DNA damage to accumulate. Persistent damage signals then activate p53, which promotes apoptosis via the mitochondrial pathway [43].

To confirm the *in-vitro* findings, the DPPH assay and SH-SY5Y cytotoxicity studies indicate that *EEMP* exhibits antioxidant and pro-apoptotic properties relevant to neuroprotection, and its established safety in acute oral toxicity testing supports further *in-vivo* evaluation of its antioxidant and neuroprotective potential.

Conclusion

The present study demonstrated that the ethanolic extract of *Musa paradisiaca* fruit peel (*EEMP*) possesses significant antioxidant and neuroprotective potential *in vitro*. The extract exhibited concentration-dependent DPPH radical scavenging activity and notable cytoprotective effects in SH-SY5Y human neuroblastoma cells. The presence of high levels of phenolics, flavonoids, and vitamins C and E supports its strong free radical–scavenging and redox-stabilizing capacity. The observed reduction in oxidative stress–induced cytotoxicity suggests that *Musa paradisiaca* fruit peel extract may mitigate dopaminergic neuronal damage associated with Parkinson's disease. These findings provide a scientific basis for the traditional use of banana peel as a natural antioxidant source and highlight its therapeutic relevance in neurodegenerative disorders.

Future Perspectives

To further substantiate these *in vitro* findings, *in vivo* studies are warranted to evaluate the neuroprotective efficacy of *EEMP* in animal models of Parkinson's disease. Future investigations should focus on assessing: *In vivo* antioxidant enzyme activity, Behavioural outcomes related to motor function, and Molecular markers of neurodegeneration, particularly α-synuclein expression and its modulation by *EEMP*. Comprehensive *in vivo* and molecular studies will provide deeper mechanistic insights into the role of *Musa paradisiaca* phytoconstituents in combating oxidative stress and neurodegeneration, potentially paving the way for novel, plant-based neuroprotective therapeutics.

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