Research Square

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Neuroprotective Potential of Vitamin E and Rutin against Paraquat-Induced Parkinson's Disease: Insights from Molecular Docking and In Vivo Studies

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Abstract

Oxidative stress–induced dopaminergic neurodegeneration plays a crucial role in the pathogenesis of Parkinson's disease. Natural antioxidants such as Vitamin E and Rutin have exhibited promising neuroprotective potential. The present study aimed to evaluate the protective effects of Vitamin E and Rutin, individually and in combination, against Paraquat-induced neurotoxicity using in silico and in vivo approaches. The results show that Rutin has a higher binding affinity (− 9.3 kcal/mol) than Vitamin E (− 7.3 kcal/mol) and the standard drug Levodopa (− 7.6 kcal/mol) in molecular docking studies (PyRx) against MAO-B (PDB ID: 2V5Z). In vivo, the combination-treated group (Group VI: Vitamin E 60 mg/kg + Rutin 10 mg/kg, p.o.) showed highly considerable improvements (***p < 0.001) over the only Paraquat-treated group (Group II), including significant increases in body weight (211.2 ± 2.151 g), enhanced rotarod performance (80.67 ± 4.055 sec), reduced catalepsy (3.833 ± 0.2261 sec), and marked enhancement in locomotor activity (7017 ± 29.00 mm; 18.00 ± 0.3919 crossings). Post-sacrifice analysis additionally confirmed significant brain weight recovery across treatment groups (Group IV–VI) (***p < 0.001). Biochemical results showed that combination therapy produced pronounced increases in dopamine levels (22.42 ± 0.444 u/mg), a striking reduction in lipid peroxidation (69.78 ± 0.562 u/mg), and elevated GSH levels (10.90 ± 0.178 u/mg) (***p < 0.001) versus Paraquat alone, with individual treatments displaying only partial efficacy. In conclusion, the superior neuroprotective efficacy of the Vitamin E and Rutin combination, driven by their combined antioxidant effects and dopaminergic neuron preservation, offers a promising therapeutic approach for managing Paraquat-induced neurotoxicity and Parkinsonian-like disorders.

Introduction

Parkinson's disease (PD) is a chronic neurodegenerative disorder characterised by the selective degeneration of dopaminergic neurons in the substantia nigra, leading to motor impairments such as tremors, rigidity, bradykinesia, and postural instability. Increasing evidence suggests that oxidative stress plays a central role in the pathogenesis of PD, causing neuronal damage through the generation of reactive oxygen species, lipid peroxidation, and depletion of endogenous antioxidant systems [1][2][3].

Environmental toxins, particularly herbicides such as Paraquat, have been implicated in the development of Parkinsonian symptoms [4]. Paraquat induces oxidative stress–mediated neurotoxicity by generating free radicals and disrupting mitochondrial function. It thus mimics key pathological features of PD in experimental models [5]. This makes Paraquat a widely used agent for studying neurodegeneration and evaluating potential neuroprotective interventions.

Monoamine oxidase-B (MAO-B), an enzyme responsible for the oxidative deamination of dopamine, is a significant therapeutic target in PD management [6]. Increased MAO-B activity contributes to oxidative stress and dopaminergic neuronal loss [7]. Although conventional therapies such as Levodopa-Carbidopa remain the gold standard for symptomatic treatment, their long-term use is associated with complications, including motor changes and reduced therapeutic efficacy [8]. Therefore, there is a

growing need to examine alternative or adjunct therapies with improved safety and neuroprotective potential.

Natural antioxidants have attracted considerable attention for their ability to counteract oxidative stress and protect neuronal integrity [9]. Vitamin E acts as a potent lipid-soluble antioxidant by scavenging free radicals [10], inhibiting lipid peroxidation [11], and protecting neuronal membranes from oxidative damage [12]. Rutin, a bioflavonoid, exhibits antioxidant [13] and anti-inflammatory [14] effects by reducing reactive oxygen species, enhancing endogenous antioxidant defences, and protecting dopaminergic neurons [16]. Their combined use may afford enhanced neuroprotection through synergistic antioxidant mechanisms.

In this context, the present study aimed to investigate the neuroprotective effects of Vitamin E and Rutin, individually and in combination, against Paraquat-induced neurotoxicity using both in silico and in vivo approaches. Molecular docking studies were performed to evaluate their interactions with the MAO-B enzyme, while behavioural and biochemical assessments were conducted to determine their ability to mitigate oxidative stress and restore dopaminergic function. This study intends to clarify whether Vitamin E and Rutin can enhance the therapeutic potential against Parkinson's disease, as evidenced by paraquat-induced toxicity. If proven effective, this combinatorial approach could provide a safer and more effective plan for managing Parkinson’s treatments with reduced side effects.

Materials and Methods

2.1 Molecular Docking Studies Against MAO-B Enzyme

PyRx (Python Prescription 0.8) was used in molecular docking research to assess the binding interactions with target proteins [17]. Based on a literature review, the protein structures were obtained from the Protein Data Bank (PDB). MAO-B (PDB ID: 2V5Z) was selected to study the antidepressant effects [18]. Ligand preparation was done using ChemDraw software (Professional 16.0). Protein preparation and optimisation were carried out using Discovery Studio Visualizer (v24.1.0.23298). Docking simulations were carried out in PyRx, utilising AutoDock Vina for docking score calculations. Additionally, Discovery Studio Visualizer was used to conduct 2D and 3D interaction evaluations of the docked complexes to evaluate binding affinities and interaction types. Additionally, a redocking experiment was carried out using AutoDock Vina in PyRx to validate the docking protocol. The docking accuracy was assessed by calculating the root-mean-square deviation (RMSD), with values below 2.0 Å considered acceptable, indicating reliable docking performance [19].

2.2 In Vivo Experimental Studies

2.2.1 Animal Selection and Approval

Male wistar rat (200 to 220 gms, 7 to 8 weeks’ age, n = 6) were used for the experiments. The animals were confined and quarantined in cages for 8–10 days. The animals were kept under normal laboratory

conditions, including a temperature of 25 ± 1°C, a humidity of 50–65%, and a 12 hrs. light-dark cycle. The experimental protocol was authorized by the IAE Committee of PRES's College of Pharmacy (For Women), Nashik, under registration number 1345/PO/Re/S/10/CPCSEA. The project proposal number is PRES-COPC-IAEC/2022-23/04 [20].

2.2.2 Preparation of Solutions

Paraquat dichloride hydrate (99.2%, Sigma Aldrich) 10 mg/kg solution prepared in water for injection [21]. Levodopa -carbidopa (100 – 10 mg, SYNDOPA, Sun Pharma Pvt Ltd) 15 mg /kg dose prepared by adding in distilled water [22], Vitamin E (400 mg, ALTIVIT-E, Altius Life Science Pvt Ltd) capsule content was given 60 mg / kg to the animals orally [23], Rutin (> 95%, Yucca enterprises, Mumbai, GPS location 25.30896,68.7387) solution prepared by adding 10 mg in 1 ml of distilled water [24].

2.2.3 Experimental Design and Treatment Protocol

Each group of animals received dose once for 28 days. Group I served as the vehicle control, receiving saline NaCl solution (0.9% w/v, p.o./day). Group II was given the inducer drug, Paraquat (10 mg/kg. i.p./2 times a week) and all remaining Groups III-VI received Paraquat at the same dose. Group III got the standard drug, Levodopa-Carbidopa (15 mg/kg. p.o./day). Group IV was the test group: Vitamin E (60 mg/kg p.o./day). Group V was the test group, which received Rutin (10 mg/kg, p.o./day). Group Vl was the combination group that received Vitamin E (60 mg/kg.p.o./day). together with Rutin (10 mg/kg, p.o./day). Behavioural assessments were carried out using the same experimental groups during the treatment period [25][26][27].

2.2.4 Behavioural Parameter

Measurement of Body Weight

The body weight of the animals was measured on the 1st and 28th days prior to paraquat administration. The percentage change in body weight was calculated by Equation No. 1 [27].

$$\%\ Change\ in\ Bodyweight = \frac{Present\ weight}{Initial\ weight}\ X\ 100$$ Equation no:1

Rotarod Test

Motor coordination and balance were evaluated using the rotarod apparatus (Orchid Scientific). The apparatus consisted of a rotating rod 75 mm in diameter and 40 cm in height, divided into four compartments. Prior to the experiment, animals were trained on the rotarod. During the test, rats were placed on the rotating rod at a constant speed of 25 rpm, and the latency to fall from the rod was recorded. The cut-off time was set at 180 seconds. The rotarod performance was assessed before paraquat administration on Day 1st and on Day 28th of treatment [28].

Catalepsy Test

Cataleptic behaviour was assessed using the bar test. Rats were placed in a half-rearing posture with both forepaws resting on a horizontal bar positioned 10 cm above the surface. The time taken by the animal to remove at least one forepaw from the bar was recorded as the catalepsy score. The maximum cut-off time was set at 180 seconds [29].

Open Field Test

The open field test was performed to evaluate locomotor and exploratory behaviour. The apparatus consisted of a square arena with outer dimensions of 42" × 42" and an inner chamber footprint of 19.5" × 19.5", divided into nine equal squares. Each rat was placed individually in the central square, and its activity was recorded for 5 minutes. Parameters such as travelled distance (mm) and the number of squares crossed were measured using Orchid's All Maze Version 5.0 video-tracking software [30].

2.2.5 Animal Euthanasia and Preparation of Homogenates: Evaluation of Rat Brain Biomarkers of Oxidative Stress and Neuroprotection.

On the 29th day, immediately after behavioural assessment, the animals were subjected to biochemical estimation. For tissue homogenate preparation, the animals were sacrificed via cervical dislocation. The animals were sacrificed via cervical dislocation. The brains, which were isolated for biochemical estimations, were then further rinsed in ice-cold isotonic saline (0.9% w/v). The hippocampus and striatum were isolated and homogenized in ice-cold 0.1 M phosphate-buffered saline (pH 7.4) to produce 10% w/v homogenates. These homogenates were further centrifuged at 4°C (5000 rpm) for 15 min, and the supernatant was used to estimate biochemical parameters. The supernatant was stored at -80°C. Evaluation of ELISA kits (Krishgen Biosystems) was used to measure Dopamine Level, Lipid Peroxide, and Reduced Glutathione (GSH) [31][32][33].

2.3 Statistical Analysis

All observations were expressed as mean ± SEM. Statistical analysis was performed using one-way ANOVA with GraphPad Prism (version 8.0.1). The number of animals in each group was n = 6. Statistical significance was considered at $^{*}p < 0.05$, $^{**}p < 0.01$and $^{***}p < 0.001$ when compared with the negative control and $^{\#\#\#}p < 0.001$ when compared with the normal control group.

Result and Discussion

3.1 Molecular docking study

The molecular docking study was conducted to evaluate the binding interactions of Rutin and Vitamin E with Monoamine Oxidase-B (MAO-B), an enzyme vital to dopamine metabolism and implicated in the pathophysiology of Parkinson's disease. The native ligand Levodopa was used as a reference compound for comparison [34].

The docking scores indicate that Rutin (-9.3 kcal/mol) exhibited a significantly stronger binding affinity toward MAO-B than both Levodopa (-7.6 kcal/mol) and Vitamin E (-7.3 kcal/mol) (Table 1). This suggests that Rutin may have a steadier and favourable interaction with the active site of MAO-B. The interaction analysis showed that Rutin formed multiple hydrogen bonds and hydrophobic interactions with key residues, including PHE103, ASP123, TYR112, and GLU483, which are likely responsible for its high binding affinity (Table 1 & Fig. 2). In contrast, Vitamin E demonstrated a moderate docking score and interacted with fewer amino acid residues, GLU391, TYR237, LEU250, and ARG36, indicating relatively weaker binding (Table 1 & Fig. 3). However, it still showed potential MAO-B inhibitory qualities through hydrogen and hydrophobic bonding. The native ligand Levodopa interacted with residues GLY11, GLY13, TYR393, and ALA35, in line with known active site interactions, and its docking score was consistent with its established therapeutic role in Parkinsonism (Table 1 & Fig. 1). The RMSD validation confirmed the reliability of the docking protocol, with values below 2.0 Å, indicating acceptable accuracy.

This evidence supports the hypothesis that natural compounds like Rutin could serve as potential MAO-B inhibitors, offering neuroprotective benefits in Parkinson's therapy by preserving dopaminergic function [35].

Table 1
Results of Molecular Docking Studies with MAO-B Enzyme

Sr. no	Compounds	Interacting with Amino Acids	Types of Bond	Docking Score (Kcal/mol)
1	Levodopa (Native Ligand)	GLY11, GLY13, TYR393, GLU34, GLY41, ALA35, and ILE264.	Hydrogen, Hydrophobic, Vander Waal's	-7.6
2	Vitamin E	GLU391, TYR237, LEU250, and ARG36.	Hydrogen, Hydrophobic, Vander Waal's	-7.3
3	Rutin	PHE103, ASP123, TYR112, THR478, ARG100, GLU483, and TRP119.	Hydrogen, Hydrophobic, Vander Waal's	-9.3

Table 2
Results of Behavioural Parameters in Parkinson's Disease

Groups	% Body Weight	Rotarod Test	Catalepsy Test	Open Field Test	Open Field Test
Groups	**% Change in Body weight (gm) Mean ± SEM**	**Fall of Time (sec) Mean ± SEM**	**Catalepsy Time (sec) Mean ± SEM**	**Travelled Distance Locomotion (mm) Mean ± SEM**	**Total Nos. of crossing Mean ± SEM**
Group I (Control Group)	220 ± 1.862	89.67 ± 4.492	0.9167 ± 0.238	8272 ± 188.6	21.54 ± 0.6769
Group II (Negative Control)	166.5 ± 2.766$^{###}$	27.17 ± 2.301$^{###}$	9.450 ± 0.2029$^{###}$	3788 ± 135.5$^{###}$	9.920 ± 0.2782$^{###}$
Group III (Positive Control)	214.5 ± 1.118***	81.17 ± 6.123***	2.950 ± 0.2975***	8475 ± 150.1***	21.02 ± 0.3765***
Group IV (Test Group I)	174.5 ± 1.384*	56.67 ± 3.029*	6.050 ± 0.4856 *	4045 ± 24.01*	10.05 ± 0.5939*
Group V (Test group II)	186.8 ± 1.851**	62.50 ± 2.012**	4.517 ± 0.4564**	5484 ± 130.1**	15.12 ± 0.2632***
Group VI (Test group III)	211.2 ± 2.151***	80.67 ± 4.055***	3.833 ± 0.2261***	7017 ± 29.00***	18.00 ± 0.3919***

All the observations were expressed as mean ± SEM. The data were analysed using one-way ANOVA, followed by the Sidak test for multiple comparisons, using GraphPad Prism software version 8.0.1. Statistical significance was considered at $^{*}p < 0.05$, $^{**}p < 0.01$, and $^{***}p < 0.001$ when compared with negative control. $^{###}p < 0.001$ when compared with the normal control.

Table 3
Effect of Treatments on Brain Weight and Oxidative Stress Markers

Groups	Brain Weight (gm) Mean ± SEM	Biochemical Estimation	Biochemical Estimation	Biochemical Estimation
Groups	**Brain Weight (gm) Mean ± SEM**	**Dopamine (u/mg) Mean ± SEM**	**Lipid Peroxidation (u/mg) Mean ± SEM**	**GSH (u/mg) Mean ± SEM**
Group I (Control Group)	1.615 ± 0.036	29.22 ± 0.734	64.19 ± 0.309	10.29 ± 0.623
Group II (Negative Control)	1.262 ± 0.015$^{###}$	9.120 ± 0.405$^{###}$	116.0 ± 1.086$^{###}$	4.377 ± 0.216$^{###}$
Group III (Positive Control)	1.062 ± 0.010***	28.51 ± 0.386***	64.03 ± 0.659***	10.11 ± 0.363***
Group IV (Test Group I)	1.667 ± 0.013***	12.04 ± 0.668*	98.82 ± 0.904*	6.675 ± 0.333**
Group V (Test group II)	1.695 ± 0.037***	16.32 ± 0.405***	88.50 ± 0.868**	8.138 ± 0.244***
Group VI (Test group III)	1.745 ± 0.015***	22.42 ± 0.444***	69.78 ± 0.562***	10.90 ± 0.178***

All the observations were expressed as mean ± SEM. The data were analysed using one-way ANOVA, followed by the Sidak test for multiple comparisons, using GraphPad Prism software version 8.0.1. Statistical significance was considered at ($^{*}p < 0.05$), ($^{**}p < 0.01$), and ($^{***}p < 0.001$) when compared with negative control. $^{###}p < 0.001$ when compared with the normal control.

The present study investigated the effects of different treatments on Paraquat-induced neurotoxicity by evaluating body weight, rotarod performance, catalepsy, and open-field activity across all experimental groups (Table 2).

Group I (control), treated with normal saline (0.9% NaCl, p.o.), maintained normal physiological and behavioral parameters, showing body weight (220 ± 1.862 gm), rotarod performance (89.67 ± 4.492 sec), minimal catalepsy (0.9167 ± 0.238 sec), and normal locomotor activity with travelled distance (8272 ± 188.6 mm) and number of crossings (21.54 ± 0.6769). In contrast, Group II (Paraquat, 10 mg/kg, i.p.) showed a meaningful decline in all parameters, with reduced body weight (166.5 ± 2.766 g; $^{###}p < 0.001$), decreased fall-off time (27.17 ± 2.301 sec; $^{###}p < 0.001$), increased catalepsy (9.450 ± 0.2029 sec; $^{###}p <$

0.001), and reduced locomotion (3788 ± 135.5 mm; 9.920 ± 0.2782 crossings; $^{###}p < 0.001$), indicating severe neurotoxicity, motor impairment, and dopaminergic dysfunction induced by oxidative stress [36] [37].

Group III (Levodopa-Carbidopa, 15 mg/kg, p.o.) significantly reversed these effects, restoring body weight (214.5 ± 1.118 gm; $^{***}p < 0.001$), improving rotarod performance (81.17 ± 6.123 sec; $^{***}p < 0.001$), reducing catalepsy (2.950 ± 0.2975 sec; $^{***}p < 0.001$), and raising locomotor activity (8475 ± 150.1 mm; 21.02 ± 0.3765 crossings; $^{***}p < 0.001$), therewith validating the experimental model and demonstrating effective neuroprotection [38].

Group IV (Vitamin E, 60 mg/kg, p.o.) showed partial protection with moderate improvement in body weight (174.5 ± 1.384 gm; $^{*}p < 0.05$), rotarod performance (56.67 ± 3.029 sec; $^{*}p < 0.05$), reduced catalepsy (6.050 ± 0.4856 sec; $^{*}p < 0.05$), and slight improvement in locomotor activity (4045 ± 24.01 mm; 10.05 ± 0.5939 crossings; $^{*}p < 0.05$), implying limited neuroprotection protection.

Group V (Rutin, 10 mg/kg, p.o.) demonstrated better efficacy compared to Vitamin E, with significant improvement in body weight (186.8 ± 1.851 gm; $^{**}p < 0.01$), rotarod performance (62.50 ± 2.012 sec; $^{**}p < 0.01$), reduction in catalepsy (4.517 ± 0.4564 sec; $^{**}p < 0.01$), and increased locomotor activity (5484 ± 130.1 mm; 15.12 ± 0.2632 crossings; $^{**}p < 0.01$), indicating moderate neuroprotective activity.

Importantly, Group VI (combination of Vitamin E 60 mg/kg + Rutin 10 mg/kg, p.o.) exhibited the most pronounced protective effect among test groups, with significant restoration of body weight (211.2 ± 2.151 gm; $^{***}p < 0.001$), rotarod performance (80.67 ± 4.055 sec; $^{***}p < 0.001$), reduction in catalepsy (3.833 ± 0.2261 sec; $^{***}p < 0.001$), and improved locomotor activity (7017 ± 29.00 mm; 18.00 ± 0.3919 crossings; $^{***}p < 0.001$). The results were comparable to the standard drug-treated group.

Further analyses of brain weight and homogenate levels of oxidative stress markers, including dopamine, lipid peroxidation, and GSH, were performed across all experimental groups (Table 3).

Group I (control), treated with normal saline (0.9% w/v NaCl, p.o.), showed normal brain weight (1.615 ± 0.036 gm) and biochemical parameters, including dopamine levels (29.22 ± 0.734 u/mg), lipid peroxidation (64.19 ± 0.309 u/mg), and GSH levels (10.29 ± 0.623 u/mg), indicating normal neuronal function and oxidative balance. In contrast, Group II (Paraquat, 10 mg/kg, i.p.) showed significant alterations, with decreased brain weight (1.262 ± 0.015 g; $^{###}p < 0.001$), marked reduction in dopamine levels (9.120 ± 0.405 u/mg; $^{###}p < 0.001$), increased lipid peroxidation (116.0 ± 1.086 u/mg; $^{###}p < 0.001$), and reduced GSH levels (4.377 ± 0.216 u/mg; $^{###}p < 0.001$). The results confirm severe oxidative stress and dopaminergic neurodegeneration induced by Paraquat.

Group III (Levodopa-Carbidopa, 15 mg/kg, p.o.) significantly restored biochemical balance, with dopamine levels (28.51 ± 0.386 u/mg; $^{***}p < 0.001$), lipid peroxidation reduced to near normal levels (64.03 ± 0.659 u/mg; $^{***}p < 0.001$), and GSH levels (10.11 ± 0.363 u/mg; $^{***}p < 0.001$). However, brain

weight (1.062 ± 0.010 g; ***p < 0.001) remained lower compared to control, indicating that although functional recovery was achieved, complete structural restoration may require longer duration or additional defensive mechanisms.

Group IV (Vitamin E, 60 mg/kg, p.o.) showed partial improvement, with increased dopamine levels (12.04 ± 0.668 u/mg; *p < 0.05), reduced lipid peroxidation (98.82 ± 0.904 u/mg; *p < 0.05), and improved GSH levels (6.675 ± 0.333 u/mg; **p < 0.01). Brain weight was significantly increased (1.667 ± 0.013 g; ***p < 0.001), suggesting some degree of neuroprotection, likely due to its antioxidant activity in reducing free radical–mediated damage [39].

Group V (Rutin, 10 mg/kg, p.o.) demonstrated better efficacy compared to Vitamin E, with significant improvement in dopamine levels (16.32 ± 0.405 u/mg; ***p < 0.001), further reduction in lipid peroxidation (88.50 ± 0.868 u/mg; **p < 0.01), and increased GSH levels (8.138 ± 0.244 u/mg; ***p < 0.001). Brain weight (1.695 ± 0.037 g; ***p < 0.001) was also significantly improved, signifying enhanced neuroprotective and antioxidant effects of Rutin [40].

Importantly, Group VI (combination of Vitamin E 60 mg/kg + Rutin 10 mg/kg, p.o.) showed the most pronounced protective effect among the test groups. This group exhibited significantly restored brain weight (1.745 ± 0.015 g; ***p < 0.001), improved dopamine levels (22.42 ± 0.444 u/mg; ***p < 0.001), markedly reduced lipid peroxidation (69.78 ± 0.562 u/mg; ***p < 0.001), and elevated GSH levels (10.90 ± 0.178 u/mg; ***p < 0.001).

Overall, Paraquat administration resulted in significant neurotoxicity characterized by both neurobehavioral deficits and biochemical alterations, including weight loss, deficient motor coordination, increased catalepsy, reduced locomotor activity, decreased dopamine levels, elevated lipid peroxidation, depletion of endogenous antioxidants (GSH), and reduced brain weight. These changes indicate severe oxidative stress and dopaminergic neuronal damage [41]. Treatment with Vitamin E and Rutin individually provided partial protection against these alterations, likely through their antioxidant and free-radical-scavenging mechanisms [39][40]. However, the combination therapy displayed superior success in restoring behavioural performance and biochemical balance, which may be attributed to synergistic antioxidant action, enhanced reduction of oxidative stress, and improved preservation of dopaminergic neurons. The combination treatment effectively improved motor function, normalized oxidative stress markers, and restored neurochemical levels, approaching the effects of the standard drug. The results strongly suggest that combined antioxidant therapy may serve as an effective strategy for the management of Paraquat-induced neurotoxicity and Parkinsonian-like symptoms by targeting both functional and biochemical aspects of neurodegeneration.

Conclusion

The present study shows that Paraquat produces significant neurotoxicity, characterized by behavioural impairments and biochemical alterations associated with oxidative stress and dopaminergic neuronal

damage. Treatment with Vitamin E and Rutin individually provided partial neuroprotection; however, their combination displayed superior potency in improving motor coordination, reducing catalepsy, restoring locomotor activity, and normalizing biochemical parameters, including dopamine, lipid peroxidation, and GSH levels. This enhanced effect may be attributed to synergistic antioxidant action and improved preservation of neuronal function. These results indicate that the combination therapy demonstrates promise as a feasible strategy for the management of Paraquat-induced neurotoxicity and Parkinsonian-like conditions.

Further studies are necessary to clarify the underlying molecular mechanisms, evaluate long-term safety and efficacy, and optimize dosage strategies. In addition, advanced investigations, including histopathological analysis, biomarker studies, and gene expression profiling, are required to better understand the neuroprotective pathways involved. Overall, this approach may contribute to the development of effective antioxidant-based therapies for neurodegenerative disorders.

Abbreviations

PD Parkinson's disease

MAO-B Monoamine Oxidase B

PyRx Python Prescription

PDB Protein Data Bank

cm Centimeter

gm Grams

mg milligrams

sec Seconds

ANOVA Analysis of Variance

SEM Standard Error of Mean

GSH Reduced Glutathione

Declarations

Conflict of interest

The author reports no conflicts of interest in this work.

Declaration

Ethics Approval and Participation Consent: Following approval from the Institutional Animal Ethics Committee (Approval No. PRES-COPC-IAEC/2022-23/04), the study was carried out in accordance with the principles set forth by the Committee for Control and Supervision of Experiments on Animals.

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Figures

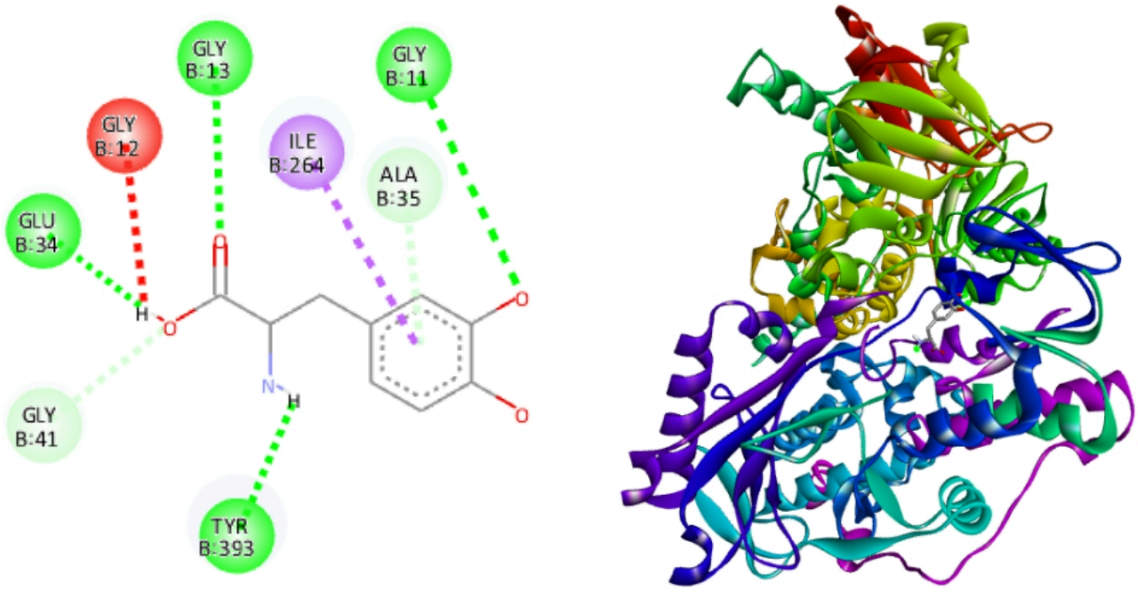


Figure 1

The 2D (A) and 3D (B) interaction of Levodopa with MAO-B Enzyme

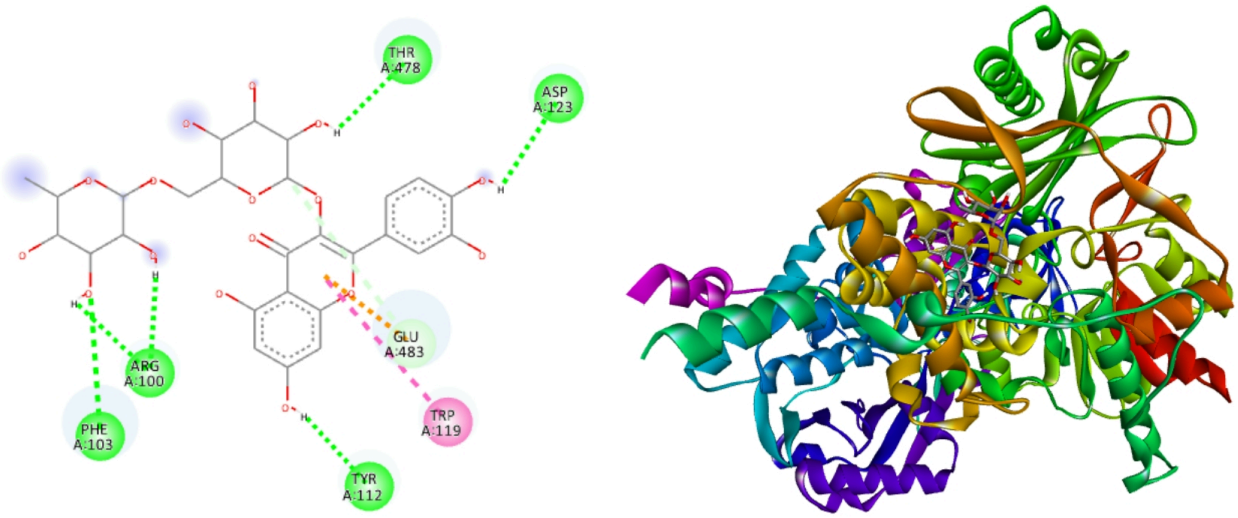


Figure 2

The 2D (A) and 3D (B) interaction of Rutin with MAO-B Enzyme

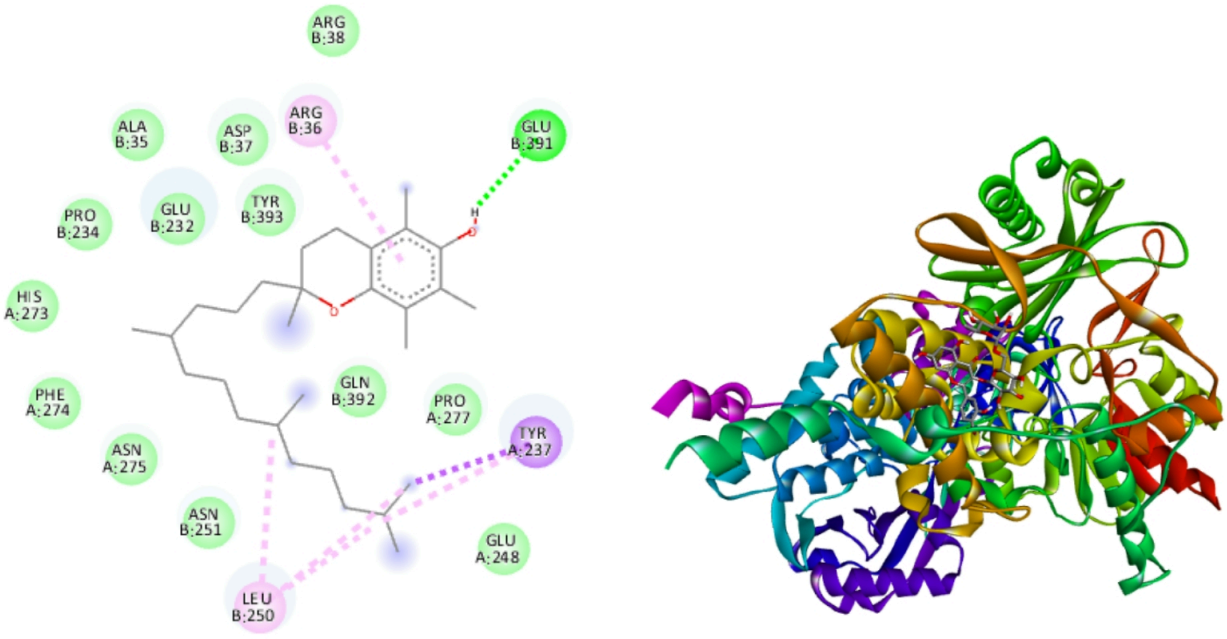


Figure 3

The 2D (A) and 3D (B) interaction of Vitamin E with MAO-B Enzyme