Vitamin B-Complex Mitigates Sub-Chronic Methamphetamine-Induced Oxidative Stress and Neurobehavioral Deficits in Adolescent Wistar Rats

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ABSTRACT

Methamphetamine (METH) abuse is a growing public health concern, particularly among Nigerian youths, where it is often consumed for its stimulant and euphoric effects but is associated with severe neurotoxic and psychiatric consequences. This study evaluated the neuroprotective potential of vitamin B-complex against METH-induced cerebellar and cerebral toxicity in adolescent male Wistar rats. Fifty-eight rats weighing 115–128 grams were used, with 28 employed for toxicity testing and 30 randomized into six experimental groups (n = 5). Group A (Negative Control) and received feed and distilled water only. Group B received 8 mg/kg of methamphetamine. Group C and D received 50 mg/kg and 100mg/kg of vitamin B-complex respectively. Group E received a co-administration of 8 mg/kg methamphetamine and 50 mg/kg of vitamin B-complex, while Group F received a co-administration of 8 mg/kg of methamphetamine and 100 mg/kg of vitamin B-complex. Treatments were administered orally for 28 days. Neurobehavioral evaluations (Morris water maze and hanging wire test) were conducted during days 24–28 to capture sub-chronic functional outcomes. At termination, animals were anesthetized, brains harvested, and tissues processed for biochemical and histological analysis. Results showed that METH-treated rats exhibited significant ($p < 0.05$) weight loss, prolonged escape latencies, impaired motor strength, increased lipid peroxidation, and reduced antioxidant markers (SOD, GSH), with histology revealing neuronal degeneration. In contrast, vitamin B-complex supplementation, alone or co-administered with METH, improved body weight, enhanced behavioral performance, normalized oxidative stress indices, and preserved cerebellar and cerebral histoarchitecture. These findings suggest that vitamin B-complex offers significant protection against METH-induced neurotoxicity, supporting its potential as an adjunctive therapeutic strategy for substance-related neurological disorders.

Keywords: Adolescent, Methamphetamine, Vitamin B-complex, Neuroprotection, Wistar rats

INTRODUCTION

Methamphetamine (METH), commonly known as “ice,” “crystal,” or locally as *Mkpurummiri* in South-East Nigeria, is a highly addictive psychostimulant and a major global public health concern (1, 2). Structurally related to amphetamine, which is used clinically in attention-deficit hyperactivity disorder (ADHD) and narcolepsy, METH is largely abused recreationally due to its potent, long-lasting euphoric effects that are stronger and cheaper than cocaine (3, 4). It can be ingested orally, snorted, injected, or smoked, with smoking

being the most common route (4). Rising use continues to impose devastating effects on individuals, families, and healthcare systems worldwide (2).

Chronic METH exposure produces oxidative stress, excitotoxicity, neuroinflammation, and neuronal apoptosis (1, 5). Neuroimaging reveals reduced dopamine levels, decreased dopamine transporter (DAT) density, and microglial activation in the striatum, resembling Parkinson's disease pathology (6). These changes underpin deficits in cognition, memory, and psychomotor function. Importantly, only partial dopaminergic recovery occurs after abstinence, highlighting METH's persistent neurotoxic footprint (1). Clinically, METH abuse is linked with paranoia, hallucinations, delusions, and psychosis, while withdrawal features depression, anxiety, hypersomnolence, and agitation. Some symptoms resolve quickly, but cognitive and affective deficits often persist, correlating with ongoing neuronal damage (5, 7).

Mechanistically, METH primarily damages dopaminergic and serotonergic terminals rather than cell bodies. Excessive dopamine release drives oxidative stress, lipid peroxidation, mitochondrial dysfunction, and excitotoxicity, while hyperthermia worsens injury (5, 8). These processes impair executive function and motor coordination, with meta-analyses confirming deficits in working memory, processing speed, and impulse control (1).

Another critical dimension of METH abuse is nutritional compromise. Substance use disorders often cause deficiencies in essential vitamins, especially B vitamins, which are vital for energy metabolism and neurotransmitter synthesis (9). METH disrupts utilization of thiamine (B1), pyridoxine (B6), and cobalamin (B12), exacerbating oxidative stress and neurotoxicity. Addressing these deficits through supplementation may provide therapeutic benefit.

Vitamin B complex, consisting of eight water-soluble vitamins, plays central roles in neuronal repair, neurotransmitter regulation, and homocysteine metabolism (10, 11). Deficiencies are strongly associated with depression, anxiety, and cognitive decline (12). Experimental studies indicate that B vitamins attenuate apoptosis, gliosis, and oxidative damage in models of METH exposure and diabetes-related neurodegeneration (10, 13).

Given the central role of the cerebrum in higher cognitive functions and the cerebellum in motor control and coordination, and their known vulnerability to oxidative and excitotoxic injury (14), investigating the protective role of vitamin B complex against methamphetamine-induced neurotoxicity in these brain regions is highly justified. This is particularly relevant in adolescence, a critical stage of brain maturation and heightened susceptibility to substance-induced damage (3).

Therefore, this study evaluates the neuroprotective effects of vitamin B complex against METH-induced cerebellar toxicity in adolescent male Wistar rats. By targeting oxidative stress, neurotransmitter imbalance, and energy deficits, B-complex supplementation may offer a safe and accessible strategy to mitigate METH-related neurological injury.

MATERIALS AND METHODS

Procurement and Housing of Experimental Animals

This study was conducted at the Department of Anatomy, Faculty of Basic Medical Sciences, Chukwuemeka Odumegwu Ojukwu University, Uli Campus, Anambra State. Fifty-eight (58) adolescent male albino Wistar rats (postnatal day 28–42; 115–128 g) were sourced from the Research Enterprise, University of Ibadan, Nigeria. The animals were acclimatized for two weeks under standard laboratory conditions, housed in well ventilated cages at room temperature with a 12-hour light/dark cycle, and maintained on standard rat chow (Agro Feed Mill, Nigeria Ltd.) and distilled water *ad libitum*. The use of animals at this age and weight corresponds to the adolescent stage of rat development, which is marked by rapid brain maturation and increased vulnerability to neurotoxic insults, making them appropriate for this study. All experimental procedures complied with the National Institute of Health Guide for the Care and Use of Laboratory Animals

(15). Twenty-eight rats were assigned to toxicity testing, while fifty-six were used for the main experimental protocol.

Drug Procurement, Preparation, and Toxicity tests

Methamphetamine (METH) was obtained through the National Drug Law Enforcement Agency (NDLEA), while vitamin B-complex was purchased from a licensed pharmaceutical supplier. METH was reconstituted in distilled water following Madden et al.'s method (16), and vitamin B-complex prepared according to the manufacturer's instructions; stock solutions were freshly prepared daily, and dosages calculated relative to body weight (mg/kg).

Acute oral toxicity (LD_{50}) of METH and vitamin B-complex was assessed using Lorke's method (17), modified by Doera et al. (18) and involved two phases. In phase one, three groups of two rats each received 10, 100, and 1000 mg/kg, and were observed for 72 hours for toxicity signs and mortality. In phase two, four groups of two rats each received 1200, 1600, 2900, and 5000 mg/kg. The LD_{50} of METH was determined as 32.5 mg/kg, while vitamin B-complex showed no mortality up to 5000 mg/kg, indicating a wide margin of safety.

Experimental Design and Treatment Protocol

Thirty (30) of the acclimatized adolescent male Wistar rats were randomly assigned into six groups (A–F) of 5 rats each. Group A (Negative Control) received distilled water. Group B received 8 mg/kg of methamphetamine. Group C and D received 50 mg/kg and 100mg/kg of vitamin B-complex respectively. Group E received a co-administration of 8 mg/kg methamphetamine and 50 mg/kg of vitamin B-complex, while Group F received a co-administration of 8 mg/kg of methamphetamine and 100 mg/kg of vitamin B-complex. Administration was carried out orally using an orogastric cannula at the designated doses for each experimental group.

Neurobehavioral Assessments

Neurobehavioral assessments were scheduled near the end of the treatment period to evaluate chronic effects. Morris water maze training was conducted on days 24–26 with a probe trial on day 27; the hanging wire test was performed on day 28 immediately prior to sacrifice.

Hanging Wire Test was used to assess motor strength and balance by recording the time rats could cling to a suspended wire (19).

Morris Water Maze test involved pre-training with a visible platform followed by hidden platform trials in opaque water to assess spatial learning and memory (20).

Termination of Experiment and Sample Collection

Twenty-four hours after the final treatment (day 29), the animals were fasted overnight and anesthetized with ketamine hydrochloride (40 mg/kg, intraperitoneally). Blood samples were obtained via ocular puncture and transferred into plain, sterilized glass tubes without anticoagulant for biochemical assays. The blood was centrifuged using a laboratory ultracentrifuge (New Life model), and the resulting serum was separated and stored under refrigeration until analysis.

While still under deep anesthesia, the animals were humanely sacrificed in accordance with institutional ethical guidelines. The skull was carefully opened, and the brain was excised. The cerebellum and cerebrum were dissected, rinsed in cold normal saline to remove blood residues, blotted dry, and weighed. Portions designated (one gram each of cerebellum and cerebrum) for biochemical assays were homogenized in 10 ml of 0.9% saline, centrifuged at 3000 rpm for 20 minutes, and the supernatant stored at 2 °C until analysis, while samples for histological examination were fixed in 10% formal saline contained in universal bottles for routine hematoxylin and eosin (H&E) and Cresyl Violet (Nissl) staining.

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Biochemical Assays

The following biochemical markers were determined:

Lipid Peroxidation (MDA) was measured using the thiobarbituric acid reactive substances (TBARS) method (21) with absorbance set at 530 nm. Results were expressed as nmol MDA/h/g tissue.

Reduced Glutathione (GSH) was determined using Ellman's method with DTNB; absorbance at 412 nm and expressed as µmol/g tissue (22).

Superoxide Dismutase (SOD) was measured by monitoring NBT reduction; absorbance at 560 nm and expressed as µmol/min/mg protein (23).

Histological Processing and Staining

Routine Histopathological Examination Using H&E Staining

Fixed portions of the brain tissues (cerebrum and cerebellum) were processed using standard histological techniques. Briefly, samples were dehydrated in ascending grades of ethanol (50%, 70%, 95%, and absolute), cleared in xylene, and infiltrated with molten paraffin wax at 75 °C before embedding in paraffin blocks at 58–60 °C. Serial sections of 5 µm thickness were cut on a rotary microtome, floated on a warm water bath, mounted on clean glass slides, and oven-dried to remove residual paraffin.

Staining was carried out using the hematoxylin and eosin (H&E) method (24). Sections were dewaxed in xylene, rehydrated through descending grades of alcohol, and rinsed in distilled water. Hematoxylin staining (15 min) was followed by acid–alcohol differentiation, bluing, eosin counterstaining (1 min), dehydration in ascending grades of ethanol, clearing in xylene, and mounting with DPX. The sections were examined under a light microscope for general cytoarchitecture and cellular alterations following standard histological protocols (25, 26).

Histological Analysis by Cresyl Violet (Nissl) Staining

Brain tissues were fixed in 10% neutral-buffered formalin, processed through graded alcohols, cleared in xylene, and embedded in paraffin wax. Serial sections of 5 µm thickness were cut using a rotary microtome and mounted on clean glass slides. After deparaffinization and hydration, the sections were stained with 0.1% cresyl violet solution for 5–10 minutes, rinsed briefly in distilled water, and differentiated in 95% ethanol. Slides were dehydrated, cleared in xylene, and coverslipped with DPX mounting medium. The stained sections were examined under a light microscope to assess neuronal morphology, including Nissl substance distribution, chromatolysis, and integrity of pyramidal and Purkinje cells. The procedure followed standard histological protocols (26, 27).

Data Analysis

Data obtained from the study were analyzed using the Statistical Package for the Social Sciences (SPSS), version 27.0.1 (IBM Corp., Armonk, NY, USA). Results were expressed as mean ± standard deviation (SD). Group comparisons were performed using one-way analysis of variance (ANOVA), and statistical significance was set at $p \leq 0.05$.

RESULTS

Effect of Methamphetamine and Vitamin B Complex on Body Weight

As shown in Table 1, the control group (A) recorded an increase in body weight between the initial and final measurements. Group B, treated with methamphetamine, showed significant reduction in body weight. Groups C and D, treated with vitamin B complex, exhibited significant weight increases. Groups E and F, which received combined treatments, showed moderate increases compared with their initial weights.

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Table 1. Effect of methamphetamine and vitamin B complex on body weight of experimental Wistar rats

GROUPS	WEIGHT (g)	MEAN± SEM	p-value
GROUP A	Initial	140.47±1.32	0.005
	Final	160.33±0.05	
GROUP B	Initial	125.06±0.33	0.001
	Final	100.56±0.41	
GROUP C	Initial	138.10±0.33	0.001
	Final	156.00±0.00	
GROUP D	Initial	128.07±0.02	0.000
	Final	150.76±2.31	
GROUP E	Initial	123.65±3.21	0.000
	Final	130.45±5.31	
GROUP F	Initial	120.65±3.02	0.001
	Final	131.75±0.02	

Values are presented as mean ± SEM (g). Statistical analysis was performed using one-way ANOVA; $p \leq 0.05$ was considered significant.

Effect of Methamphetamine and Vitamin B-Complex on Relative Brain Weight

Table 2 presents the relative brain weights of rats across experimental groups. Significant decreases were observed in Groups B, and F compared to the control ($p < 0.05$). No significant differences were recorded in Groups C, D, and E. The one-way ANOVA confirmed an overall group effect ($F = 17.43$).

Table 2: Effect of Methamphetamine and Vitamin B-Complex on Relative Brain Weight

	Groups	MEAN ± SEM	p-value	f-value
Relative Brain weight (g)	Group A	1.80 ± 0.045		17.43
	Group B	1.16 ± 0.040	0.001*	
	Group C	1.66 ± 0.055	0.59	
	Group D	1.74 ± 0.085	0.96	
	Group E	1.52 ± 0.010	0.075	
	Group F	1.37 ± 0.045	0.008*	

Values are expressed as mean ± SEM ($n = 5$). One-way ANOVA was used to compare groups; $p < 0.05$ was considered statistically significant.

Effect of Methamphetamine and Vitamin B-Complex on Motor Coordination and Muscle Strength (Hanging Wire Test)

The results of the hanging wire test (Table 3) showed significant impairment in motor strength and coordination in Groups B (methamphetamine only), with markedly reduced hanging times compared to the control group. Conversely, Groups C and D (vitamin B-complex low and high dose) demonstrated enhanced performance, particularly the high-dose group. Groups E and F (combined treatments) exhibited reduced but non-significant hanging times relative to the control.

Table 3: Hanging Wire Test Performance in Experimental Groups

	Groups	MEAN ± SEM	p-value	f-value
Hanging Wire test (seconds)	Group A	87.50 ± 9.5	16.21	16.21
	Group B	13.50 ± 4.5*	0.04	
	Group C	109.00 ± 5.0	0.86	

	Group D	127.50 ± 20.5*	0.35	
	Group E	25.00 ± 18.0	0.08	
	Group F	24.50 ± 11.5	0.07	

Values are expressed as Mean ± SEM (n = 5). Statistical analysis was performed using one-way ANOVA; $p < 0.05$ was considered statistically significant compared with control and represented with*.

Effect of Methamphetamine and Vitamin B-Complex on Spatial Learning and Memory (Morris Water Maze Test)

The mean escape latency times of the rats in the Morris water maze are presented in Table 4. Control animals (Group A) recorded an average latency of 22.16 ± 2.93 seconds. Rats administered methamphetamine alone (Groups B) exhibited significantly prolonged escape latencies (39.66 ± 11.23 seconds; $p < 0.05$) compared to the control. In contrast, animals treated with vitamin B-complex alone (Groups C and D) or in combination with methamphetamine (Groups E and F) demonstrated latency times (23.20 ± 8.50, 23.60 ± 3.20, 23.33 ± 2.30, and 23.40 ± 0.12 seconds, respectively) that were comparable to the control group. One-way ANOVA yielded a significant overall effect across groups ($F = 8.023$, $p < 0.05$).

Table 4: Morris Water Maze Test (Escape Latency)

	Groups	Mean ± SEM	p-value	F-value
Morris Water Maze Test- Escape latency (Seconds)	Group A	22.16 ± 2.93		8.023
	Group B	39.66± 11.23	0.000	
	Group C	23.20± 8.50	0.002	
	Group D	23.60± 3.20	0.000	
	Group E	23.33± 2.30	0.004	
	Group F	23.40± 0.12	0.003	

Values are expressed as Mean ± SEM (n = 5). Statistical significance was determined using one-way ANOVA; $p \leq 0.05$ considered significant.

Effect of Methamphetamine and Vitamin B-Complex on Oxidative Stress Markers

Table 5 shows the effects of methamphetamine and vitamin B-complex on oxidative stress biomarkers in the cerebrum and cerebellum of Wistar rats. Methamphetamine significantly increased malondialdehyde (MDA) levels compared with the control, while co-treatment with vitamin B-complex attenuated this effect. Superoxide dismutase (SOD) activity was significantly altered across groups, whereas reduced glutathione (GSH) concentrations did not differ significantly among the treatment groups.

Table 5: Effect of Methamphetamine and Vitamin B-Complex on Oxidative Stress Markers

	Groups	Mean ± SEM	p-value	F-value
MDA (mm^{-1})	Group A	3.60 ± 0.01		23.25
	Group B	3.96± 0.06	0.000	
	Group C	3.62±0.01	0.000	
	Group D	3.64±0.03	0.000	
	Group E	3.68±0.02	0.001	
	Group F	3.52±0.04	0.003	
GSH (mm^{-1})	Group A	1.75 ± 0.02		0.23
	Group B	1.43 ± 0.48	0.002	
	Group C	1.79 ± 0.27	0.001	

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	Group D	1.71±0.09	0.000	
	Group E	1.79±1.64	0.015	
	Group F	1.76±3.53	0.023	
SOD (mm^{-1})	Group A	8.56 ± 0.02		5.04
	Group B	7.20 ± 0.41	0.000	
	Group C	8.60 ± 0.01	0.000	
	Group D	8.63±0.54	0.000	
	Group E	8.34±0.64	0.024	
	Group F	8.51±0.71	0.045	

Values are expressed as mean ± SEM (n = 5). One-way ANOVA was used to compare groups; $p \leq 0.05$ was considered statistically significant.

Histological Findings

H&E-stained cerebellar sections revealed normal cortical architecture in the control group (A), showing well-defined molecular (A), Purkinje (C), and granular layers (B) with intact Purkinje cells and clear nuclei. The methamphetamine-treated group (B) exhibited severe neuronal degeneration, with pyknotic and karyorrhectic Purkinje cells (PKP), disrupted layering, and marked vacuolation (V). Groups C and D (Vitamin B complex only) displayed preserved cerebellar architecture and well-organized Purkinje cells (P), though group D showed slight irregularity within the Purkinje cell layer. Co-treated groups (E and F) demonstrated improved cerebellar morphology such as well-defined molecular (A) and Granular (B) layers compared with the methamphetamine group, characterized by reduced degeneration, better cell alignment, and restoration of normal laminar organization, which was most prominent in group F.

Cresyl violet–stained cerebellar sections showed clear differences across groups. The control group (A) displayed normal trilaminar architecture with well-outlined Purkinje cells (red arrows) and intense Nissl staining. The methamphetamine-treated group (B) exhibited severe neuronal degeneration with pyknotic and karyorrhectic Purkinje cells (black arrows), disorganized layers, and reduced staining intensity. Groups C and D (Vitamin B complex only) maintained normal cerebellar structure and deeply stained Purkinje cells (red arrows), though slight scattering of the Purkinje layer was observed in group D. Co-treated groups (E and F) showed partial to near-complete recovery of neuronal organization, with mild to pronounced aggregation of Purkinje cells (red arrows) and deeper Nissl staining across the layers, especially in group F.

H&E-stained sections of the cerebrum showed normal cortical organization in the control group (A), with well-arranged neurons, clear nuclei (N), and intact neuropil. The methamphetamine-treated group (B) displayed prominent degenerative changes, including neuronal shrinkage (NS), nuclear pyknosis, perineuronal vacuolation, and disrupted cortical layers. Groups C and D (Vitamin B complex only) revealed normal histoarchitecture comparable to the control, with preserved neuronal outlines, clear nuclei (N) and distinct cortical layering. In the co-treated groups (E and F), neuronal morphology appeared improved relative to the methamphetamine group, showing reduced vacuolation, fewer pyknotic cells, clear nuclei (N) and more organized cortical structure, with group F exhibiting the greatest degree of preservation.

Cresyl violet–stained sections of the cerebrum revealed normal neuronal architecture in the control group (A), characterized by distinct pyramidal neurons with well-defined nuclei and cytoplasm (red arrows). The methamphetamine-treated group (B) showed scanty degeneration of pyramidal neurons (red arrows) within the cortical region. Groups C and D (Vitamin B complex only) displayed intensely stained pyramidal neurons and dendrites with deeply stained Nissl substance, indicating essentially normal neurons (red arrows). In the co-treated groups (E and F), pyramidal neurons appeared aggregated with increased color intensity (red arrows), more pronounced in group F, showing compact neuronal arrangements and strong staining reaction.

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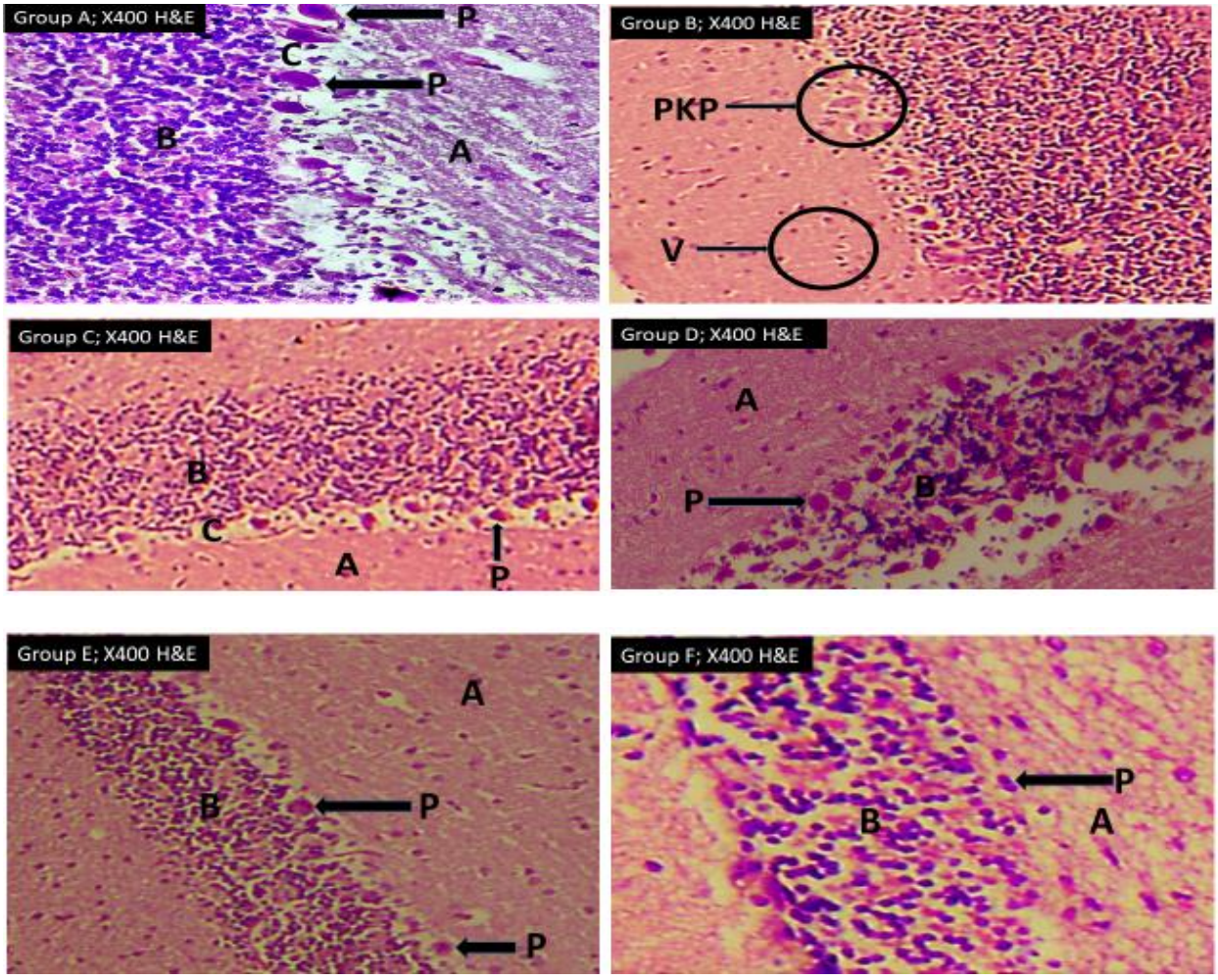
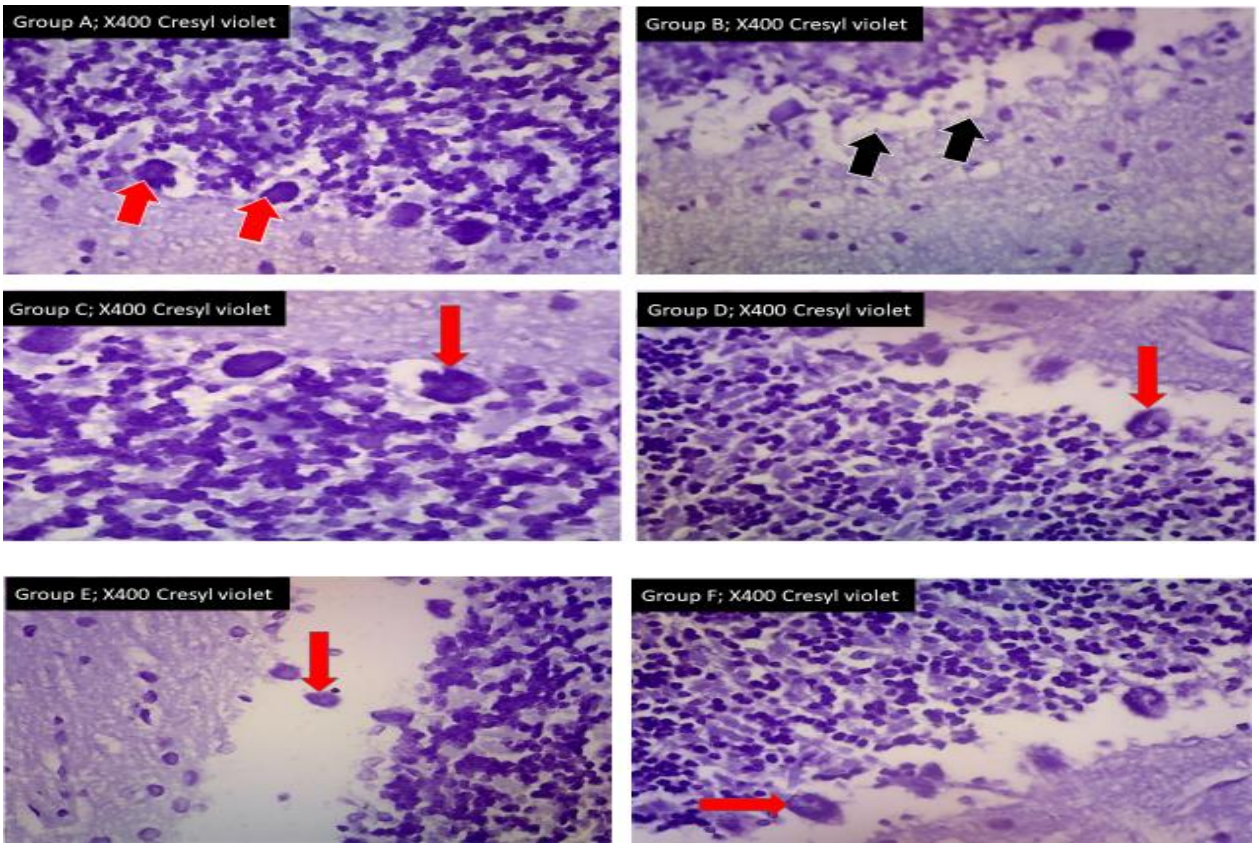
Cerebellum (H&E)



Cerebellum (cresyl violet)



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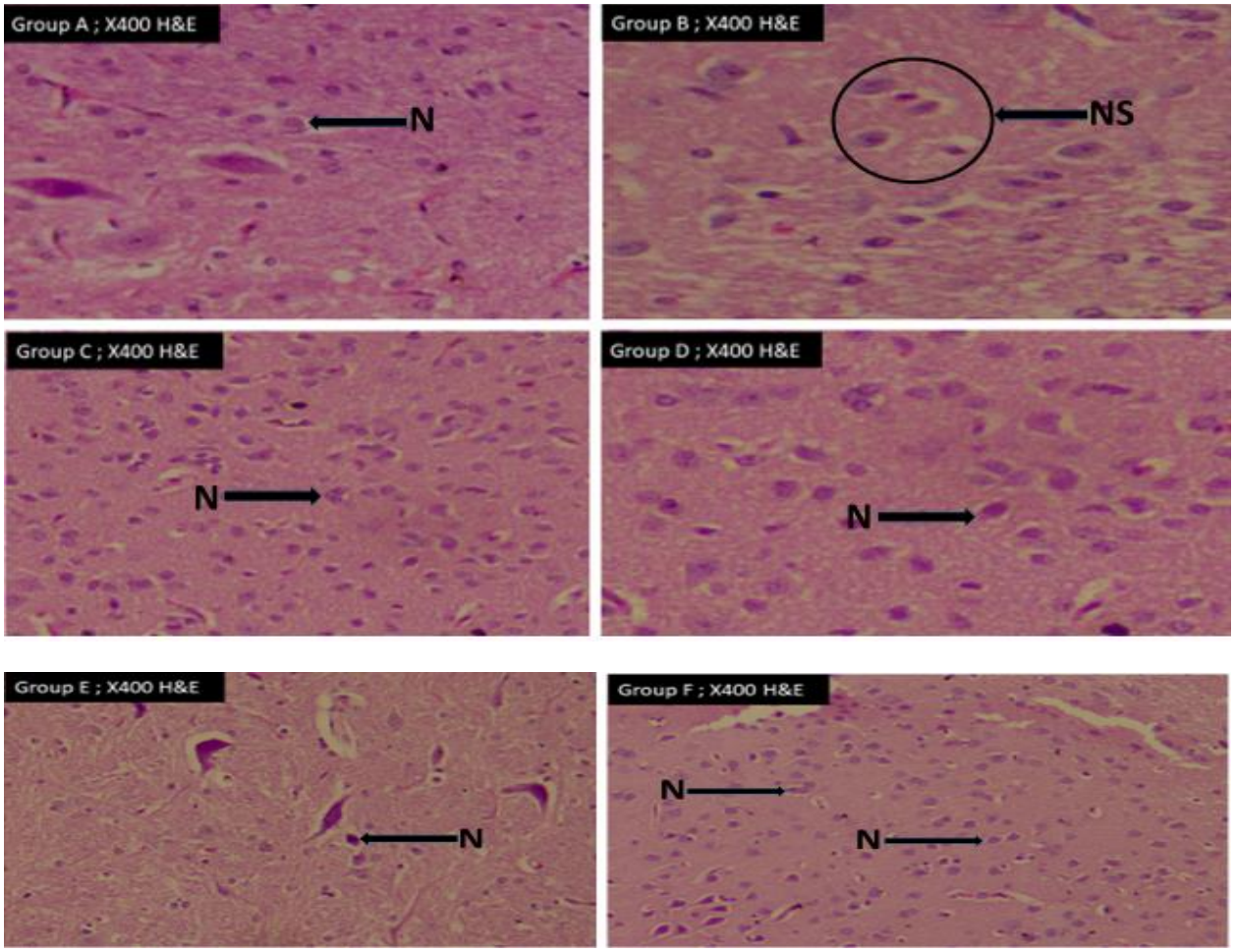
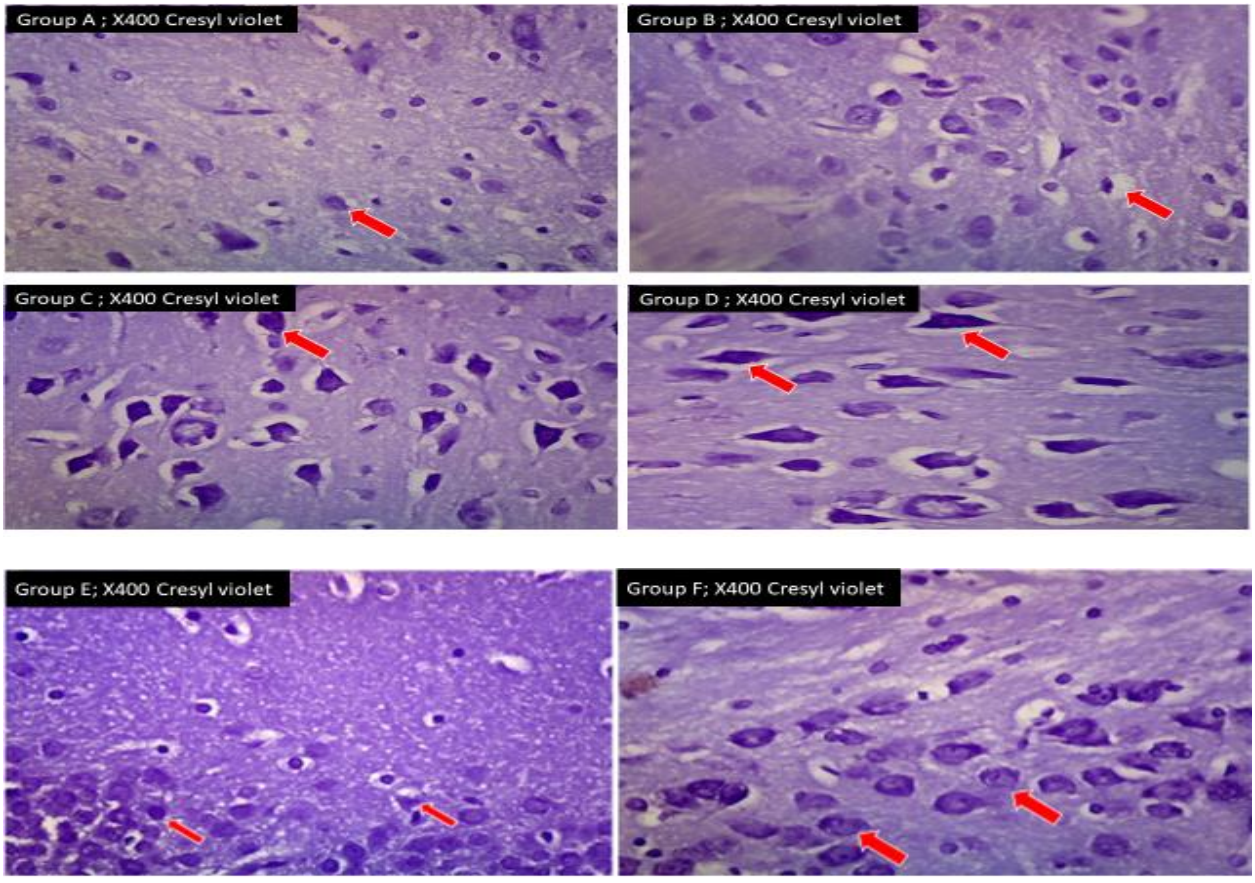
Cerebrum (H&E)



Cerebrum (cresyl violet stain)



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DISCUSSION

Methamphetamine (METH) is a potent psychostimulant widely abused for its stimulant and euphoric properties despite its well-documented neurotoxic effects mediated through oxidative stress, excitotoxicity, and neuroinflammation (1, 5). In this study, METH administration in adolescent Wistar rats produced significant reductions in body weight, consistent with earlier reports linking psychostimulant exposure to catabolic changes and metabolic disruption (3, 28). Methamphetamine increases synaptic levels of dopamine, norepinephrine, and serotonin, which collectively suppress appetite and diminish the rewarding value of food in both animal and human models, resulting in reduced caloric intake and body weight loss (29). Interestingly, vitamin B-complex supplementation promoted weight gain when administered alone and partially restored growth in co-treated groups, indicating its potential role in counteracting METH-induced metabolic dysregulation.

Regarding brain weight, methamphetamine has been documented to induce neurodegenerative alterations involving dopaminergic and serotonergic neuronal loss, particularly within the striatum, hippocampus, and cortex. These effects are mediated by oxidative stress and mitochondrial dysfunction, leading to neuronal apoptosis and structural damage. Additionally, methamphetamine provokes microglial activation and neuroinflammatory responses that contribute to tissue shrinkage and neural injury through reduced protein synthesis and cellular dehydration (30, 31). The reduction in brain weight observed in the present study may therefore reflect these underlying neuropathological processes associated with METH exposure.

Biochemical analyses further demonstrated that METH exposure elevated malondialdehyde (MDA) while reducing superoxide dismutase (SOD) and glutathione (GSH), reflecting increased lipid peroxidation and weakened antioxidant defenses. These alterations corroborate previous studies identifying mitochondrial dysfunction, free radical generation, and oxidative stress as major drivers of METH-induced neuronal damage (8, 32). Supplementation with vitamin B-complex reversed these changes, restoring antioxidant enzyme activity and reducing lipid peroxidation, consistent with evidence of its antioxidant and anti-inflammatory properties (13).

Neurobehavioral assessments revealed that METH impaired motor coordination in the hanging wire test and prolonged escape latency in the Morris water maze, indicating deficits in motor control and spatial learning. In contrast, rats treated with vitamin B-complex, either alone or alongside METH, performed significantly better, supporting the view that B vitamins enhance redox homeostasis, modulate neurotransmitter synthesis, and protect against cognitive and motor decline (12).

Histological evaluation provided further confirmation of METH neurotoxicity, with evidence of Purkinje cell degeneration, chromatolysis, and neuronal disruption, in agreement with previous reports of damage to dopaminergic and serotonergic terminals (1, 33). Notably, B-complex supplementation preserved neuronal integrity and maintained Nissl substance density, suggesting structural and functional resilience against METH-induced injury. The protective actions of B vitamins may be attributed to their metabolic functions, as pyridoxine supports serotonin synthesis, folate and cobalamin regulate homocysteine metabolism, and thiamine and riboflavin contribute to energy metabolism (11, 12).

A limitation of this study is that behavioral assessments were carried out only at the end of the 28-day experiment. While this timing allowed for the evaluation of chronic outcomes, it did not capture the progression of changes over time. Future studies should therefore incorporate both interim and terminal assessments to better distinguish acute from long-term effects of METH exposure and vitamin B-complex supplementation.

CONCLUSION

This study shows that methamphetamine exposure in adolescent Wistar rats induces neurotoxic effects, including reduced body and brain weights, elevated oxidative stress, impaired antioxidant defenses, neuronal degeneration, and deficits in motor and cognitive performance. Supplementation with vitamin B-complex, however, was associated with improved antioxidant status, preservation of neuronal morphology, and

enhanced behavioral outcomes. These findings indicate that methamphetamine disrupts cerebral and cerebellar integrity, while vitamin B-complex confers measurable protective effects that support neuronal function under neurotoxic conditions.

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Competing Interest: The Authors declare no competing interest.

Author's Contribution: EKOH Augustine Alobu, NWAKANMA Agnes Akudo and ELEMUO Chukwuebuka Stanley were primarily responsible for animal feeding and oral administration of treatments. EKOH Augustine Alobu, NWAKANMA Agnes Akudo, OFOEGO Uzozie Chikere and OJEMENI Gloria Chinenye were involved in the procurement of substances used, statistical analyses, and other technical aspects of the study. All authors participated in proofreading and finalizing the manuscript. The financial costs of the research were jointly covered by all authors.

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